High Bandwidth 802.11 Communications Link for Undersea Applications

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***Abstract*—This paper describes the development of an 802.11 based communications link for use with an autonomous underwater vehicle (AUV) docking system. The paper will show that 802.11 systems are not only practicable in seawater, but that they can also provide a reliable high-bandwidth link over a short distance using standard commercial components.**

***Index Terms*—Electromagnetic propagation in absorbing media, attenuation, underwater antennas, underwater communication**

I. Introduction

AUTONOMOUS underwater vehicles (AUVs) have been under development and in use for several decades. An underwater dock where the AUV can recharge it's batteries and communicate with operators on shore is a logical accessory to an AUV. MBARI's recently deployed docking system is a gimbaled cone mounted to a benthic stand that includes an acoustic homing system, an inductive power transfer system, an Ethernet camera with light and the wireless communications link presented in this paper.

The reliability analysis of MBARI's AUV dock design revealed that wired transfers between the dock and AUV were a significant source of unreliability. Further, developers at Florida Atlantic University (FAU) had already demonstrated a low-bandwidth 802.11b (2.4GHz) link and inductive power transfer between their dock and AUV [1], so an existing wireless link could be adapted to MBARI's purpose. Unfortunately the FAU link was a low-bandwidth link, reportedly 100 kBps across <2.54 cm, and a higher bandwidth link with further separation was desired. The primary challenge with the link was increasing the bandwidth while simultaneously increasing the antennae separation.

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FAU developers had already demonstrated a 2.4 GHz link using 802.11b, and there were several options for further development. The primary design variables were frequency, antennae and power amplifier. No consideration was given to developing a custom protocol, since 802.11 is compatible with widely used Ethernet infrastructure.

5 GHz, 802.11a, options were also commercially available for air, and initial testing focused on demonstrating a 5 GHz link through seawater. Using the 5 GHz link from a dual-band wireless access point (WAP) would also allow the unused 2.4 GHz link to easily be used for auxiliary AUV communications such as direct communications with a notebook computer.

General misunderstandings have led to the opinion that since seawater is a good conductor at RF frequencies, it's not worth pursuing RF transmissions under or through seawater. However, that depends on how far the two ends of the link must be separated, the transmitted power and the receiver sensitivity. It's a basic signal-to-noise problem that demands thorough analysis of all aspects of the problem.

The attenuation of electromagnetic (EM) energy passing through a medium such as seawater is described by Maxwell's equation [3]:

$$E = E_0 \exp^{-\alpha x} \tag{1}$$

where x, in meters, is the separation distance between transmitter and receiver antennae, and α is the attenuation coefficient in dB/m.

Testing included multiple antennae at both 2.4GHz and 5GHz, mounted on a moveable rack to facilitate a known antennae separation, (Fig. 1). The antennae were also tested in a cross-polarization and linear offset mode.

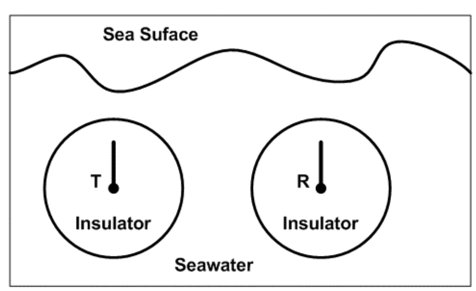

Fig. 1. Antennae test configuration where T is the transmitter and R is the receiver.

Additional scientific and commercial applications exist for such a link and will certainly benefit from the developed solution [4].

II. Skin Depth & Other Measures Of Attenuation

Many sources provide approximate equations that may be manipulated to describe the attenuation of RF energy as it passes through seawater. However, as Griffiths has explained, it is patently incorrect to use these equations without considering the frequency dependence of seawater conductivity [8]. Siegel and King have published more accurate theoretical equations [19], but only validated them up to 14 MHz.

Generally these equations use the permeability, μ, permittivity, ε, and conductivity, σ, of seawater to come up with some value of attenuation, typically specified in terms of dB/m or skin depth. As Moore points out, the conductivity is also dependent on location in the ocean, since the value can range from less than 2 in the arctic to more than 8 in other land-locked seas.

As an example of these equations Griffiths gives the following equation [8]:

$$\delta = \sqrt{\frac{1}{\pi f \sigma \mu}}\ \text{(m)} \tag{2}$$

where f is frequency (Hz).

Horvat has described attenuation with [10]:

$$\alpha = 8.686\omega \sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]}\ \text{(dB/m)} \tag{3}$$

Moore has described a “frequency independent” attenuation as [7]:

$$\alpha = \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}}\ \text{(Np/m)} \tag{4}$$

which is valid only if “a high enough frequency were used that the displacement current greatly exceeded conduction current.” This works out to be 84 Np/m (7.30 dB/cm) and a corresponding skin depth of 1.19cm.

Furthermore, even the “typical” properties of seawater that are presented in the various texts don’t match. For instance Moore uses 4 S/m as a typical value of conductivity while Griffiths uses 5 S/m.

When McBride used the various equations to calculate attenuation, and skin depth, a range of 17.9 dB/cm to 8.6 dB/cm, corresponding to 0.24 cm to 0.50 cm, was calculated at 2.4 GHz and a range of 26.2 dB/cm to 8.6 dB/cm, corresponding to 0.17 cm to 0.50 cm, was calculated at 5 GHz. These values were calculated using $\mu = 4\pi \times 10^{-7}$ N/A^2, $\sigma = 4.3497$ S/m and $\varepsilon = 6\text{x}10^{-10}$ C^2/N m^2.

Given the wide variation in calculated attenuation, it came as no surprise to the authors that their peers exhibited varying degrees of pessimism concerning the ultimate success of the development effort. It was also quite apparent that attenuation would need to be measured empirically to justify the theoretical calculations.

III. Link Margin Budget

Establishing a link budget requires parameters for the transmitter and receiver, the antennae, and expected path absorption which is described by (4).

Two D-Link DWL-7100AP wireless access points (WAPs) were used to form the bridge through seawater. The specification sheet for the DWL-7100AP lists the maximum transmit power as +18dBm for both 2.4GHz and 5GHz. The receiver sensitivity changes dynamically with overall bandwidth and is listed in Table I.

The transmission frequencies are either:

- (802.11g) 2.4-2.4835GHz
- (802.11a) 5.15-5.35GHz and 5.725-5.825GHz

An initial literature survey of empirical attenuation at these frequencies in water revealed very few sources. By interpolation, one empirical source indicated that the attenuation would be about 10dB/cm at both frequencies [6]. Our target distance was something greater than 2.5cm.

Using 11Mbps as an example the budgeted link margin is shown in Table II.

TABLE I
DWL-7100AP RECEIVER SENSITIVITY AT BANDWIDTH AND FREQUENCY

Bandwidth	2.4GHz	5GHz
108 Mbps	-73 dBm	-73 dBm
54 Mbps	-72 dBm	-71 dBm
48 Mbps	-72 dBm	-71 dBm
36 Mbps	-73 dBm	-76 dBm
24 Mbps	-77 dBm	-80 dBm
18 Mbps	-80 dBm	-83 dBm
12 Mbps	-80 dBm	-85 dBm
11 Mbps	-88 dBm	-88 dBm
9 Mbps	-85 dBm	-86 dBm
6 Mbps	-87 dBm	-87 dBm
5.5 Mbps	-89 dBm	
2 Mbps	-91 dBm	
1 Mbps	-95 dBm	

TABLE II
11Mbps LINK MARGIN BUDGET FOR BOTH 2.4 AND 5 GHZ

Maximum Tx Power	+18 dBm
Feed-line Losses	-3.0 dBm
Antenna Gain	0.0 dBm
Path Loss for 9.0cm	-90.0 dBm
Antenna Gain	0.0 dBm
Feed-line Losses	-3.0 dBm
Rx Signal Strength	-78 dBm
Rx Sensitivity	-88 dBm
Link Margin	**10 dBm**

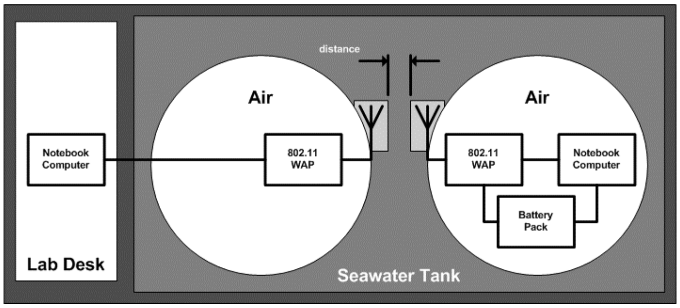

Fig. 2. Tank test block diagram for network bandwidth testing.

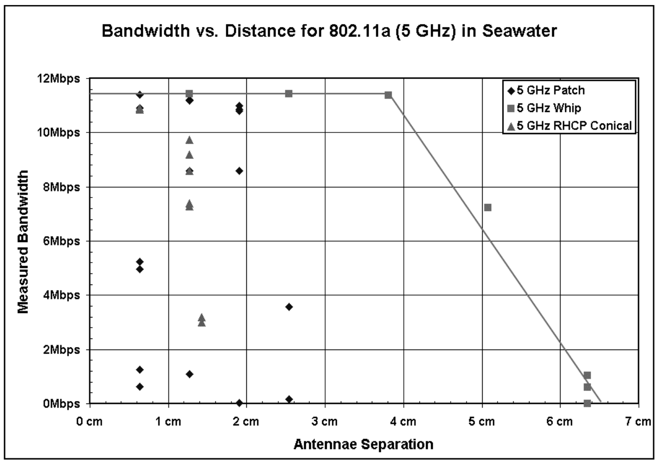

Fig. 3. Initial test results from testing several antennae over distance using network throughput as a metric.

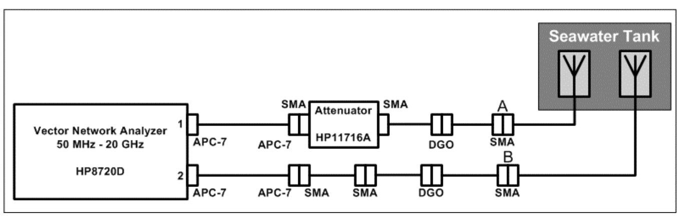

Fig. 4. Instrumentation block diagram used to measure path loss.

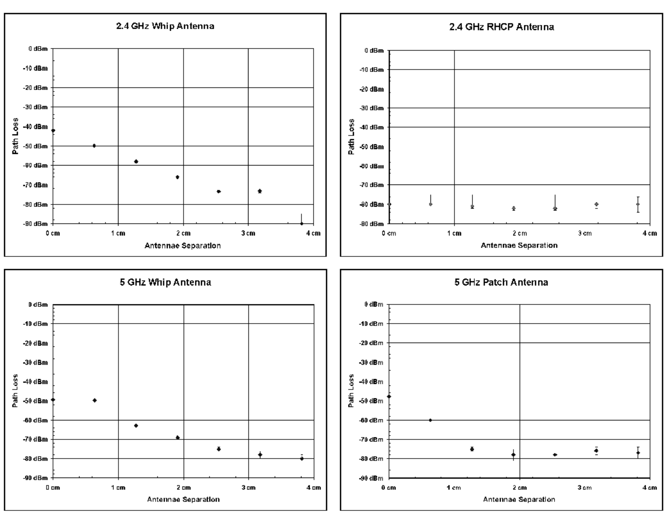

Fig. 5. Path loss results at 2.4 GHz and 5 GHz for several antennae.

IV. Network Bandwidth Testing

Initial tests, targeted at proving the concept, were conducted using a battery powered notebook and client-side WAP inside an airtight sphere. The server-side WAP was located inside another airtight sphere with a network and power cable extending to another notebook computer on a laboratory desk. The two WAP antennae were cast in a clear epoxy (η=1.5725) and ABS plastic block to facilitate mounting on our AUV and dock structure. Fig. 2 shows a basic block diagram of the testing apparatus.

The test plan involved moving a given antenna pair as close as possible, establishing a link and transferring both large and small files between the client and server using ftp to establish a measure of network bandwidth. After a successful transfer at a given separation, the antennae would be separated farther and the test repeated until the link could no longer be established or the bandwidth fell below an acceptable level. Tests were conducted using both a Hyperlink Technologies patch antenna (model HG5311P) and the whip antenna provided with the DWL-7100AP. Tests in air indicated that the maximum bandwidth was between 8Mbps and 11Mbps due to the network card used in the battery powered notebook computer.

Fig. 3 shows that the omnidirectional whip antenna performed the best in this test. The first set of patch antennae leaked, and although they showed promising results initially, the performance degraded quickly due to corrosion. The second set of patch antennae were waterproofed correctly, but didn't perform as well. Fig. 3 shows that it was certainly possible to achieve a high bandwidth 11 Mbps link across 3.5 cm of seawater using these stock 802.11 components.

V. Path Loss Testing

After showing that a high bandwidth was certainly achievable, further analysis revealed that the link wasn't achieving the budgeted distance. The bandwidth should have been 11 Mbps at greater than 9 cm, but was only achieving less than 4 cm.

After connecting point A to point B, in Fig. 4, feed-line losses from port 1 to port 2 on the cables connected to the HP 8720D vector network analyzer were measured at 3.57dB @ 2.4GHz and 1.51dB @ 5GHz.

Measurements were first made at 5GHz using both the D-Link whip antennae and the Hyperlink patch antennae. Then measurements were made at 2.4GHz using another whip antenna provided with the DWL-7100AP and a RHCP helical antenna, FRC Component Products model SLH10. The network analyzer was configured to deliver its maximum +5dBm. The baseline noise level was between -70dBm and -80dBm. The results are shown in Figs. 5-6.

It became quite clear that neither the patch nor helical antennae were optimal but that the whip antennae were best matched for the application. It was also readily apparent that transmission at 2.4GHz offers the least overall attenuation.

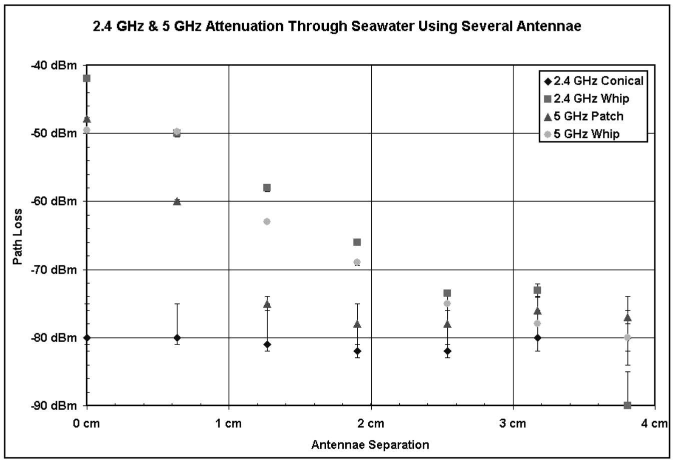

Fig. 6. Summary of path loss measurements for several antennae at both 2.4 GHz and 5 GHz.

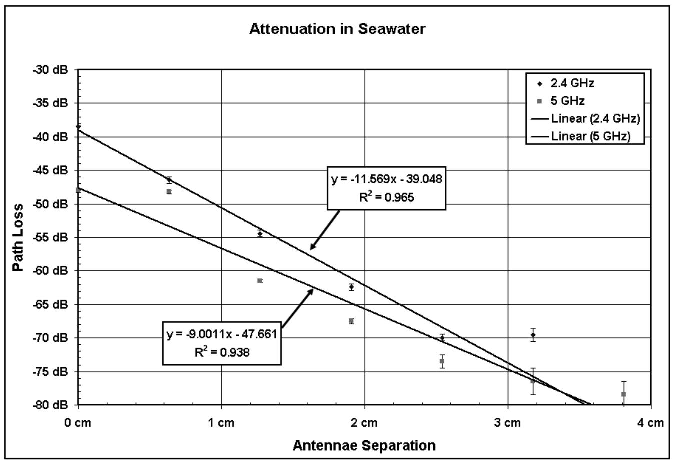

Fig. 7. Measured path loss between antennae in seawater.

TABLE III
REVISED 11Mbps LINK MARGIN FOR 2.4 GHZ WITH AMPLIFIER

Maximum Tx Power	+18 dBm
Feed-line Losses	-1.8 dB
Tx Amplifier Gain	+12 dB
Antenna Gain	-19.5 dB
Path Loss for 6.35cm	-73.7 dB
Antenna Gain	-19.5 dB
Rx Amplifier Gain	+20 dB
Feed-line Losses	-1.8 dB
Rx Signal Strength	-66.3 dBm
Rx Sensitivity @ 11Mbps	-88 dBm
Link Margin @ 11Mbps	**21.7 dB**

TABLE IV
STOCK WHIP ANTENNA WAVELENGTHS

Frequency	Length	Air	Saltwater
@ 2.44 GHz	2.68 cm	0.22 λ	0.29 λ
@ 5.49 GHz	2.32 cm	0.42 λ	0.57 λ

From this testing it was also possible to get a better number for the path loss attenuation over distance and antennae gain or loss. As shown in Fig. 7, the attenuation at 2.5 GHz was measured to be 11.6 dB/cm with 39.0 dB lost at the antennae interfaces when the signal was injected into the water. At 5 GHz, the attenuation was measured at 9.0 dB/cm with an injection loss of 47.7 dB. As Moore had predicted, a significant portion of the energy is lost directly at the antennae [11].

The temperature in the tank during testing was measured at 18.0 °C. Salinity is measured at a depth of 10m and was measured at 32.90 PSU, 3 weeks prior to the testing. It was measured at 32.60 PSU 3 months prior to that, 32.45 PSU 2 months prior to that and 32.50 PSU 2 months prior to that.

VI. Revised Link Budget

Using the measured attenuation, it was now possible to develop a more realistic link budget. It became apparent that amplifiers placed at each end of the link would provide a sufficient link margin to guarantee a link over the desired separation. The desired separation had also increased to at least 3.8cm.

The amplifier chosen was an RF Linx Antennafier 2400 CAE. The relevant specifications for the amplifier are:

Tx Gain	Up to +30dBm
Rx Gain	+20dB
Rx Noise Figure	2.5dB

The revised link budget is shown in Table III with a safety margin of an additional 2.5cm added to the antennae separation distance.

VII. Antennae

Four antennae pair were tested. Two whip antennae that came with the DWL-7100AP, a 5GHz patch antennae from Hyperlink Technologies and a 2.4GHz RHCP helical antenna from FRC Component Products.

The 2.4GHz antenna was simply a piece of RG-128 with the shield cut back 2.68cm. This resulted in a 0.22 wavelength whip in air. The antenna was cast in a solid block of ABS plastic using Loctite E-30CL (η=1.5725).

The 5GHz whip was similar to the 2.4GHz whip, but employed an additional sir-core choke. The stub length was 2.32cm resulting in a 0.42 wavelength whip in air. Like the 2.4GHz antenna, the antenna was cast in a groove milled into a solid block of ABS and sealed using E-30CL. Table IV shows the whip length with the wavelengths in air and seawater.

The back PVC panel of the 5GHz patch antenna was removed and then cast in place using the E-30CL.

Since the mounting base of the RHCP helical antenna was connected to the TNC connector's shield, the base was cast in 3M Scotchcast to keep it isolated from seawater.

During the path loss testing, the HP 8720D vector network analyzer was calibrated and used to measure the impedance and SWR of the various antennae. Fig. 8, the smith chart for the 2.4 GHz whip antenna, shows that the impedance is very nearly 50 ohms without an equalization network.

Using an HP Infinium oscilloscope, model 54845A, it was also possible to measure the amplitude of the RF signal going to the antenna, which is shown in Fig. 9.

VIII. Specific Antenna Testing Required for Docking

After analyzing the results of the path loss compared to the antenna design, two 2.4GHz whip antennae were built to test the impact of multiple wavelength antennae on the performance. The antennae lengths were based on the geometrical requirements of the docking system. One antenna, which might be used in the dock, was lengthened to 46.0cm and the other antenna, which might be used on the vehicle, was lengthened to 15.6cm. The path loss using this antennae pair dropped to -83 dB in less than 1 cm, a considerable drop in performance, and these antennae were not tested again. It is worth noting that these longer antennae performed worse than the shorter antennae with a higher current density. This is somewhat surprising given Siegel & King's results [20] using insulated dipole antennae.

Cross polarization is a value commonly used in the calculation of a link budget. Our testing using the whip antennae in a cross polarization orientation indicated that cross polarization would eliminate any communications beyond 0.00cm separation. The link dropped off too quickly for us to measure with our equipment. It is recommended that this polarization not be implemented using this type of whip antennae.

The orientation of the antennae in the dock and AUV allows the antennae to slip past each other until the vehicle stops. In this situation, the separation is the same in one axis, but changes in another which creates a change in the way the transmitted field overlaps the receiving antenna. We were concerned that this slip might cause a problem by adding to the overall antennae separation. Using the 5 GHz whip antennae, we saw no drop in the link until the antennae had slipped beyond 8cm.

IX. The Final 2.4 GHz Solution

Due to the relatively insignificant performance improvement gained by using 5 GHz technology vs. using 2.4 GHz technology, and the mass availability and inexpensive nature of 2.4 GHz technology, we decided to base our final solution around 2.4 GHz. We tested inline 2.4 GHz amplifiers with the stock 0.22 λ_{air} whip antennae, mentioned in Table IV, and Fig. 10 shows that the path loss could be improved using these amplifiers. Based on the improved path loss using the amplifiers, we tested the bandwidth of the 2.4 GHz link with and without the amplifiers, Fig. 11. An unexpected result of the bandwidth testing was that the bandwidth was low both near and far and that there was a range of high-bandwidth vs. distance. Fig. 9 also shows that the amplifier actually degrades the network performance but extends the distance a little on

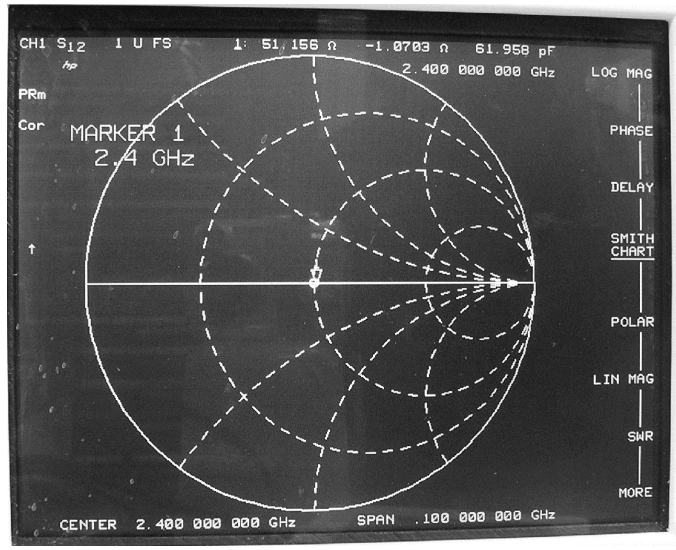

Fig. 8. Smith chart showing the 50 ohm impedance of the 2.4 GHz whip antenna pair being tested in the saltwater tank.

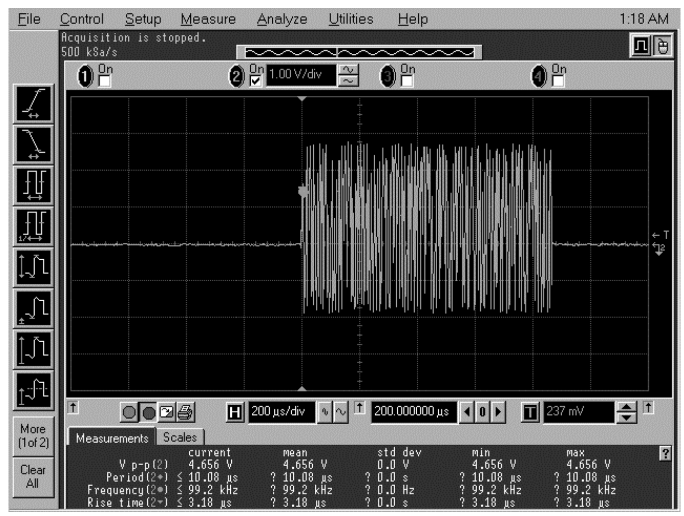

Fig. 9. The RF signal envelope measured at the antenna port and terminated into 50 ohms.

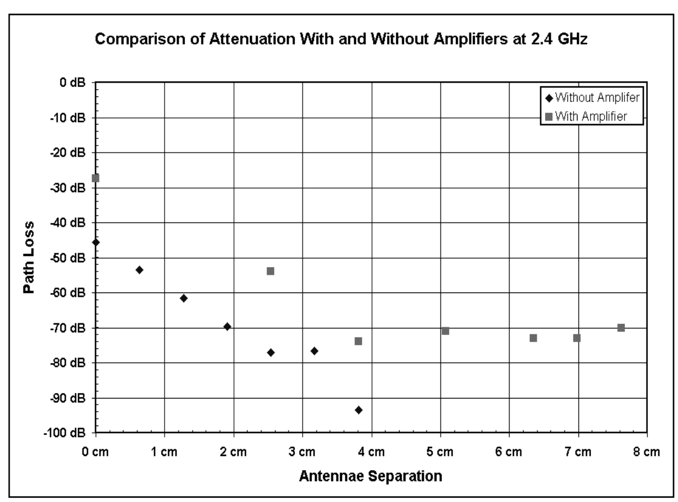

Fig. 10. 2.4 GHz path loss with and without inline bi-directional amplifiers.

the right-hand side of the graph.

X. System Integration & Test Results At Sea

The antennae and WAPs were integrated into the AUV and dock systems. The system was initially tested in a 12m deep seawater test tank and the network connection was 100% reliable through the duration of the docking testing.

The entire docking system was tested at sea in a shallow surf zone, which is subject to biofouling. The system was deployed for five months. The wireless networking system facilitated reliable underwater communications from the shore to the AUV while the vehicle was in the dock, as shown in Fig. 12.

While the vehicle was in the dock, the wireless network provided communications to the vehicle's main computer. During testing, the vehicle was completely shut down in the dock and restarted using the wireless link to establish communications. Also, while the vehicle was in the dock, a recursive ping script, using the ICMP protocol, provided a measure of the reliability and turn-around time of the packet transmission across the link.

Table V lists the deployed system specifications and final deployed results.

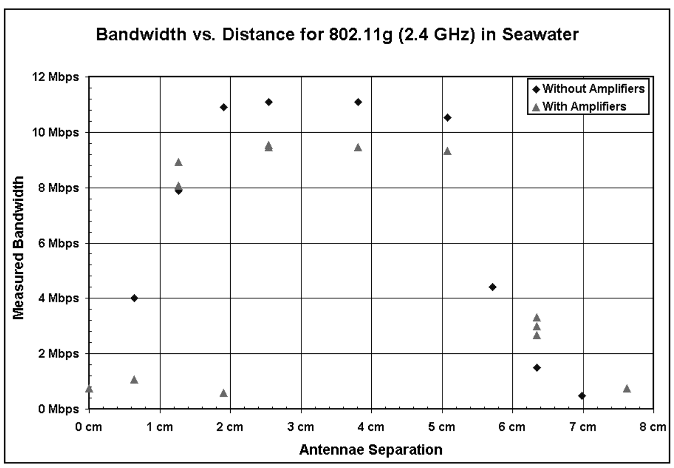

Fig. 11. 2.4 GHz bandwidth vs distance comparison between using bi-directional amplifiers and not using bi-directional amplifiers.

TABLE V
DEPLOYE D SYSTEM PERFORMANCE SPECIFICATIONS

Protocol	802.11g
Transmission Frequency	2.4 GHz
RF Power	1W
Antenna	0.22 λ_{air} whip
RF Link Margin	21.7 dB
Through seawater transmission distance	1.5" (deployed) 2.5" (demonstrated)
ICMP Trasmission Success Rate	98.95%
Average ICMP time	4 ms
Bandwidth	9.5 Mbps

Fig. 12. The AUV has docked autonomously in the underwater dock, deployed at sea in a surf zone, and is using the underwater 802.11 link to communicate to shore.

XI. Price Of The System

Excluding the development costs and the pressure casing, Table VI provides a detailed account of the expenses in the wireless system. As shown in the table, a significant portion of the price comes from the underwater RF connectors, $860.

TABLE VI
COMPONENT PRICES

Dock Components	
D-Link DWL-7100AP Bridging WAP	$112.99
RF Linx 2400SAE-1W Amplifier	259.95
D.G. O'Brien 1100001-101 Bulkhead RF Connector	119.00
D.G. O'Brien 1150446-103 RG-58 Plug Cable Assembly	430.00
ABS plastic block material for antenna	7.75
Loctite E-30CL tube	11.00
Pasternack Enterprises N connector	12.95
Pasternack Enterprises N connector with 18" RG-58 whip	10.80
Vehicle Components	
D-Link DWL-7100AP Bridging WAP	112.99
RF Linx 2400SAE-1W Amplifier	259.95
D.G. O'Brien 1100001-101 Bulkhead RF Connector	119.00
D.G. O'Brien 1150446-103 RG-58 Plug Cable Assembly	430.00
ABS plastic block material	7.75
Loctite E-30CL tube	11.00
Pasternack Enterprises N connector	12.95
Pasternack Enterprises N connector with 18" RG-58 whip	10.80
Total	**$1926.90**

XII. Conclusions

This paper has shown how an affordable 9.5 Mbps underwater 2.4 GHz 802.11g link was developed using COTS components and how it performed. As expected, the performance of this link is directly related to the path length, as it is in air. There does not appear to be any significant advantage to using 5 GHz technology underwater, and there are several advantages of using 2.4 GHz.

Acknowledgment

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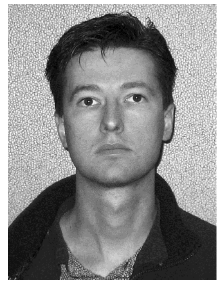

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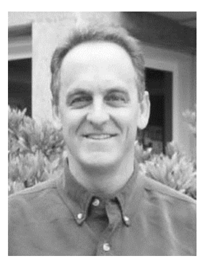
Since graduating in 1996, he has worked in the fields of network engineering, particle acceleration, high speed video electronics and oceanographic equipment. He is currently an Electrical Engineer working in the Research and Development: Instrumentation Division at the Monterey Bay Aquarium Research Institute (MBARI) in California. His professional interests include low-power electronics, imaging systems, human interface technology and circuit card design.

Mr. McBride has been a member of the Association for Computing Machinery (ACM) and was a licensed Microsoft Certified Systems Engineer (MCSE). Mr. McBride was the president of his IEEE student body his senior year at Walla Walla College, and he was awarded 3rd place for his IEEE student entry at the Columbia Basin Technical Conference and Trade Show in 1996. Mr. McBride has authored and co-authored numerous publications for the IEEE Oceanic Engineering Society and other publications.

James T. Scholfield received the B.S. degree in oceanography from the University of Washington in 1971.

He was a Q.C., metrology, and mechanical technician for Boeing in Seattle, WA. Following his work with Boeing he was a mechanical technician at the Naval Postgraduate School in Monterey, CA. He is currently a senior mechanical technician working in the Technical Support Division at the Monterey Bay Aquarium Research Institute (MBARI).

He has been a member of the Marine Technology Society (MTS) since 2000.



Brett Hobson (M'98) received the B.S. degree in mechanical engineering from California State University, San Francisco in 1989.

Prior to joining MBARI he helped start Nekton Research, a Navy R&D contractor specializing in small underwater vehicles. He started designing, building and operating undersea systems at Deep Ocean Engineering and Deep Sea Discoveries. He is currently working in the Research and Development: Platforms Group at the Monterey Bay Aquarium Research Institute (MBARI).

He is a member of the Marine Technology Society and American Geophysical Union.

Thomas T. Hoover (M'06) completed Naval Nuclear Propulsion School in 1985, and went to sea on the USS San Francisco (SSN-711). He received the received the BS degree in electrical engineering technology from Old Dominion University, Norfolk, VA in 1998.

While attending college he was a Field Engineer for Symmetron Inc in Fairfax VA applying low signature technologies to naval platforms. After completing his degree he worked as a Test Engineer for Space Systems / Loral in Palo Alto CA. In 2003 he returned to active duty in the Navy to deploy a robotics repair facility to Iraq in support of EOD forces. He is currently working in the Research and Development: Science division at the Monterey Bay Aquarium Research Institute on Autonomous Unmanned Vehicles.