SHIPBOARD RADIO FREQUENCY PROPAGATION MEASUREMENTS FOR WIRELESS NETWORKS

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ABSTRACT

This paper discusses several in-hull RF propagation studies on board one decommissioned and several active Naval ships in the 0.8 – 2.5 GHz range. During these tests, it was repeatedly demonstrated that radio signals will propagate from one compartment to another even when the watertight doors (hatches) are shut and sealed. In fact, signals have been received across several bulkheads. Results indicate approximately 20 dB of attenuation is associated with transmission through a bulkhead/watertight door. It has also been found that the wireless channel aboard Naval vessels does not show good correspondence with a Ricean channel.

Finite element modeling of a shipboard compartment has been performed and supports the hypothesis that rubber door gaskets and other non-conductive structures may be the source of bulkhead penetration/leakage.

For comparison, ultra-wideband channel measurements within the hull of a ship have also been taken. These measurements will be used to characterize the propagation within a single compartment as well as through a sealed bulkhead/watertight door.

INTRODUCTION

To best suit the internal communication needs of Naval vessels, a wireless system has many advantages. Electric wiring and fiber optic cable introduce limitations. They must be planned into the ship, they cost money, and they must be maintained. They also must be passed from compartment to compartment. This requires holes to be made in the bulkheads, which consequently must be made thicker in order to withstand the same amount of stress. Finally, the cables themselves are subject to damage. In the event of a casualty due to an accident or an attack, the signal path could be destroyed at the time that the communication system is needed the most. Wireless transmissions, however, need only space to propagate. Space does not cost money, need to be maintained, or need to be planned into ships, and space cannot be destroyed.

However, there are several factors that limit the capabilities of wireless systems aboard ships. The most obvious is that the structure of the ship is made entirely of steel—a very good conductor. When an electric field enters a perfect conductor, it collapses entirely [1]. If it enters a material with high, though finite, conductivity—such as steel—it is severely attenuated [2]. However, there are many non-conductive objects imbedded into bulkheads, such as rubber seals around hatches, which attenuate the transmission less than the conductive steel.

Another obstacle to wireless communication is the fact that a ship is a multipath environment. Any signal transmitted aboard a ship is reflected or diffracted by many different objects, resulting in multiple copies of the signal arriving at the receiver at different times. Since communication systems traditionally have relied on coherent waveforms, these multiple copies of the signal may cancel each other out and block the signal entirely at the receiver [3].

Channel sounding has been performed since the advent of radio communication, and continues today. Outdoor studies attempt to describe large-scale environments [4 - 5]. When wireless systems began to be used within buildings, indoor channel sounding began, some studies focusing on specific devices [6], some on frequency ranges [7 - 8], some on building types [9 - 11]. Several studies have been performed to determine the performance of commercial off-the-shelf (COTS) wireless components aboard ships [12 - 14], but did not attempt to describe the channel. Another study, performed on the *ex-USS Shadwell*, attempted to identify the propagation modes of the wireless signals [15]. This study reached no major conclusions, but did show that communication was possible through closed hatches and across decks.

This project attempted to characterize the wireless channel aboard naval ships in the frequency range of 0.8 – 2.5 GHz using narrowband measurement techniques, as well as ultra-wideband technology. Channel modeling was also done to investigate the propagation path from compartment to compartment.

NARROWBAND TESTING

The narrowband tests performed during this study consisted of placing a transmitter in a compartment (room) aboard a vessel and measuring the received signal strength in various locations within and near that compartment. At the receiver, the signal strength was sampled at regular intervals over a short distance (Fig 1). The assumption was made that, due to the multipath effect, the average power and variation along one dimension would be equal to those along other dimensions in the same location. Therefore, only one measurement was made at each frequency in each location.

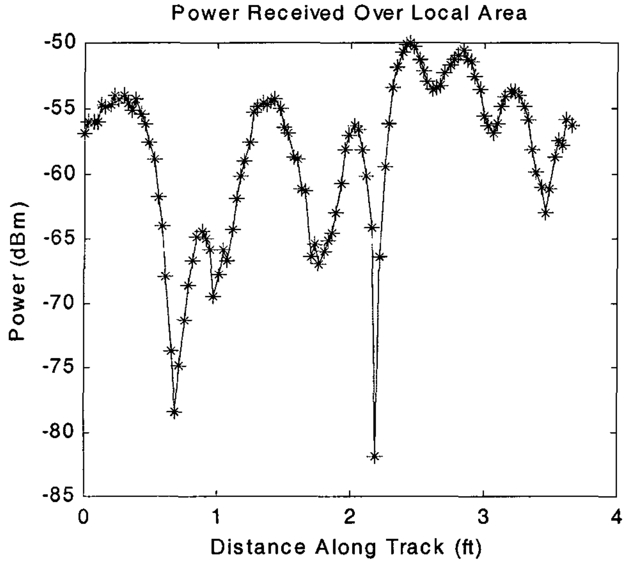

Figure 1. Received Signal Variation Due To Multipath

This was done in order to gather information about the multipath effect. From this technique, a statistical description of the received power could be made, including the average power, standard deviation, and the Ricean *K* factor, the ratio of power transmitted in the line-of-sight path to that transmitted by diffuse paths. The average received power from different locations was compared to determine the effect of bulkheads and hatches on the transmission path.

The *K* factor was estimated by finding the best-fit Ricean curve to match the received power levels in each location (Fig. 2). The best-fit curve was that which had the smallest mean square error (mse) from the data distribution curve. No apparent trend was found in the Ricean *K* value with respect to frequency or location. The distribution curves of some measurements did not demonstrate good correspondence with Ricean power distributions. That is, the mse of the best-fit curve was greater than 0.0005 [16]. This could be due to objects near the equipment causing sharp-edged shadowing or transmission patterns.

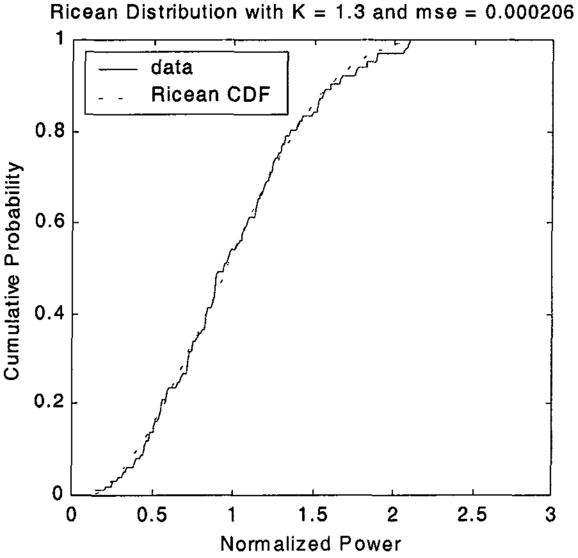

Figure 2. Received Power Distribution and Best-Fit Ricean Curve

Preliminary testing on the hangar deck aboard the *ex-USS America*, a decommissioned aircraft carrier in Philadelphia, demonstrated that signals could be transmitted across bulkheads and closed hatches. The tests aboard *America* showed approximately 16 dB attenuation per bulkhead.

The effect of bulkheads on the transmission was determined by finding the difference (in dB) between the measured signal power on the near and far sides of the bulkhead. The effect of hatches was determined by finding the difference between the power received with the hatch open and that with the hatch shut.

$A_B = P_{near} - P_{far}$ Attenuation of bulkhead in dB

$A_H = P_{open} - P_{shut}$ Attenuation of hatch in dB

The following data is based on measurements made on board the destroyer *USS Ross* and the frigate *USS Carr*, both active vessels based out of Norfolk, Virginia. The average bulkhead attenuation across all frequencies is 25 dB. The difference in results between these tests and the tests aboard *America* can be attributed to the more cluttered environment and stronger (thicker) bulkheads in the engine rooms as compared to the hangar deck of a carrier.

Attenuation across bulkhead, open hatch near direct path	10 dB
Attenuation across bulkhead, open hatch far from direct path	20 dB
Attenuation across bulkhead, no open hatches	25 dB
Loss due to shutting hatch near direct path	15 dB
Loss due to shutting hatch far from direct path	5 dB

Additionally, a test aboard *USS Oscar Austin* demonstrated that a signal can be received on a different deck from the transmitter. The receiver was placed in Main Engine Room 2, one deck directly below the transmitter in the Central Control Station. The signal was received despite the fact that the antennas used—whip antennas—transmit no energy in the vertical direction. In this test, the multipath environment of the ship enhanced the capabilities of the communication system.

ULTRA-WIDEBAND TESTING

In addition to the narrowband testing technique, this project also performed some ultra-wideband measurements. These measurements were made with a prototype communication system [17] that transmits pulses whose spectral content is spread from 0.8 to 2.5 GHz. The system utilizes pulse-position modulation in a pseudo-random fashion, which further spreads information over a greater bandwidth. This allows the system to reject interference and to cause minimal interference to other communication systems.

The receiver has the capability of storing copies of received pulses on an attached computer. Therefore, whenever this system is communicating, it provides a measurement of the channel impulse response, which can be analyzed to yield information about the time dispersion and frequency characteristics of the channel.

This system was used to measure the attenuation across one closed hatch in the hangar bay of the *America*. An average of approximately 17.4 dB attenuation was measured across this particular hatch. This agrees with the results of the narrowband tests done on the *America*, which showed 17.0 dB attenuation across this hatch. The results of both of these tests are shown in Figure 3. The attenuation measured by the narrowband system (red points) lie very near the attenuation measured by the UWB system (blue curve). The red dashed line corresponds to the average value of the attenuation measured by the UWB system.

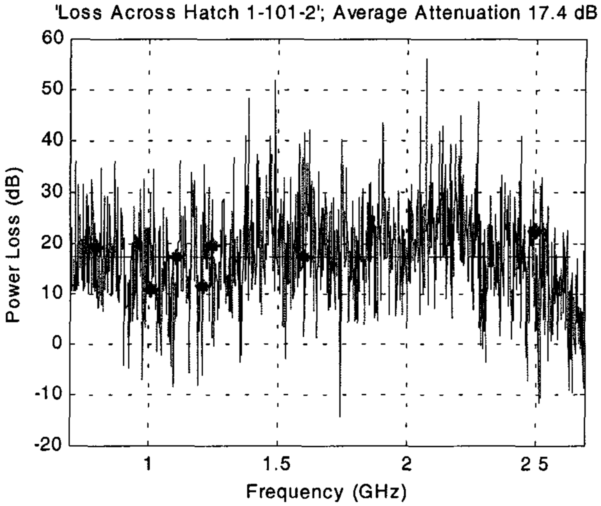

Figure 3. Attenuation Across Hatch

The UWB equipment was also used to characterize a single compartment. Whereas the transmission from one compartment to another is vastly different from land-based scenarios, transmission within one compartment shows a high degree of similarity to land based measurements made within one room.

The most common time dispersion parameters used to describe a channel are mean excess delay (μ_τ) and rms delay spread (σ_τ), shown in Figure 4. Excess delay (τ) is the time it takes for reflected energy to reach the receiver *after* the most-direct signal is detected. Mean excess delay, then, is the average time delay of all received energy. The rms delay spread is the standard deviation of the time delay [3].

τ_k	Excess delay (time after first received signal)
$P(\tau_k)$	Power received at τ_k

$$\mu_\tau = \frac{\sum_k P(\tau_k)\cdot\tau_k}{\sum_k P(\tau_k)}$$ Mean excess delay

$$\sigma_\tau = \sqrt{\frac{\sum_k P(\tau_k)\cdot(\tau_k - \mu_k)^2}{\sum_k P(\tau_k)}}$$ rms delay spread

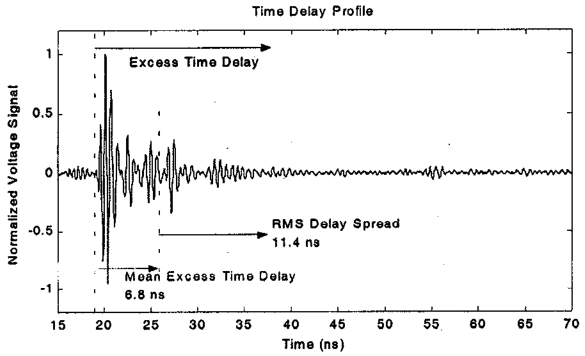

Figure 4 Example Time Delay Profile, τ, μ_τ, and σ_τ

The mean excess delay and rms delay spread of the compartment were determined to be 83.9 ns and 82.6 ns, respectively.

Also of interest is the path loss exponent, n, of the wireless channel. The received power of a wireless signal decays exponentially with distance [3]. More specifically, the power received, P_r, at distance d can be related to the power received at another distance d_0 according to:

$$P_r(d) = P_r(d_0)\cdot\left(\frac{d}{d_0}\right)^{-n}, \text{ or}$$

$$P_r(d)(dB) = P_r(d_0)(dB) - 10n\log\left(\frac{d}{d_0}\right)$$

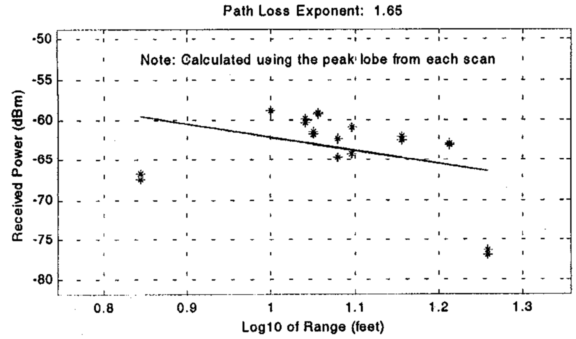

Figure 5. Path Loss Within Compartment 1-21-1-Q

The path loss exponent in the compartment was measured as 1.65 (Fig. 5), which is less than the free space path loss exponent of 2. This is to be expected, as the confined volume tends to contain the transmission, and is typical for indoor measurements taken with a line of sight path between the transmitter and receiver [3].

INTER-COMPARTMENT PROPAGATION

These tests have demonstrated that communication is possible from one compartment to another, but have not addressed the path that the signal takes through the bulkhead. To investigate this, computer modeling has been done.

Two scenarios have been investigated. The first consisted of an antenna transmitting an electromagnetic wave through approximately ten wavelengths of free space, to a perfectly conductive plate, simulating a steel bulkhead. The second simulation included a rubber slit in the plate, simulating a hatch seal (Fig. 6).

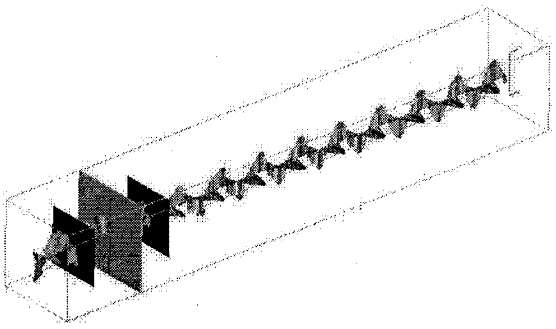

Figure 6. EM wave propagating through slit bulkhead

The power contained in each of these waves on each side of the bulkhead was compared. The wave that was transmitted through the solid steel was blocked entirely, an attenuation value of ∞. The wave that propagated through the bulkhead with the slit experienced only 29.3 dB attenuation. This value is higher than the attenuation measured aboard Navy vessels, which can be explained by the presence of more than one transmission path aboard ships, resulting in a stronger signal at the receiver.

CONCLUSION

Communication is possible from one compartment to another aboard ships, despite the fact that a ship is a multipath environment and that the bulkheads are made almost entirely of steel. The average attenuation per bulkhead within the engineering spaces of the Navy's surface combatant ships is 10 - 25 dB, depending on the geometry of the transmission path, over the frequency range of 0.8 - 2.5 GHz.

Within a compartment, the signal experienced a path loss exponent of 1.65 and an rms delay spread of 82.6 ns.

The non-conductive structures in the bulkheads—such as hatch seals and insulation around pipes—appear to be responsible for passing the energy from one compartment to the next.

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