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PERFORMANCE EVALUATION OF MIMO OFDM SYSTEMS IN ON-SHIP BELOW-DECK ENVIRONMENTS

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Abstract- For more than a decade, there has been increased interest in characterizing electromagnetic propagation in below-deck environments of naval vessels for the purpose of deploying wireless networks. This work focus on the measured the received power, power delay profile and RMS delay spread of a wireless channel over multiple decks of a merchant ship. The measurements in were used to estimate coherence bandwidth and delay spread, which can be used to calculate the maximum rate at which narrowband communication technique scan transmit data without experiencing Inter Symbol Interference (ISI). Orthogonal Frequency Division Multiplexing (OFDM) is suitable for this type of environment as a means to mitigate frequency selectivity that may reduce the role of coherence bandwidth as a limiting factor in wireless communications throughput. Multiple Input Multiple Output (MIMO) communications and multiple antenna techniques can also improve radio performance by exploiting spatially uncorrelated fading of wireless channels common in multipath-rich environments to improve throughput and reliability. Also this work evidence that multi antenna technologies can improve communications performance over SISO techniques in a below-deck environment. MIMO technologies offer improved capacity and less variation in system performance despite changing environmental factors. The PP-SNR values presented show the improvement in reliability can be provided by space-time coding. Estimation of Shannon channel capacity demonstrates that multipath scattering can be exploited by spatial multiplexing to improve performance and increase throughput. The achievable throughput was as high as 36 Mb/s in spite of the reverberant conditions limiting the coherence bandwidth. On the poorest-quality link, SISO communications were restricted to 6 Mb/s in the engine room, while MIMO physical layers were able to operate at 12 Mb/s, thereby doubling the link throughput. Similar performance gains were observed in the coupled compartments with doors open.

Index Terms - Inter Symbol Interference, Orthogonal Frequency Division Multiplexing, Multiple Input Multiple Output

I. INTRODUCTION

For more than a decade, there has been increased interest in characterizing electromagnetic propagation in below-deck environments of naval vessels for the purpose of deploying wireless networks. Below-deck spaces are predominantly metal structures. These spaces constitute multipath-rich environments that introduce distinct challenges for deploying wireless networks. The RF spectrum on ships also introduces active radar and communication signals, emissions from working machinery and interference by personnel on board. Still, deploying wireless networks in below-deck spaces is desirable as it offers significant potential in augmenting and in some applications, replacing current wired network infrastructure. Previous works focused on received power and path loss, as well as the effects of opening/closing doors. This work focus on the measured the received power, power delay profile and RMS delay spread of a wireless channel over multiple decks of a merchant ship.

The rest of this paper is organized as follows. Section II describes the existing system and its drawbacks. Section III presents the proposed system techniques. The capacity for each physical layer (MIMO SM, SISO) and capacity for each physical layer (I.I.D, MIMO) is analysed in Section IV. The simulation results are given in Section V. Finally, the conclusions are drawn in Section VI.

II. EXISTING SYSTEM AND ITS DRAWBACKS

The survey on these work show that the current shipboard monitoring systems use extensive lengths of cables to connect sensors to control units. Replacing wired connections by wireless ones may be an efficient solution to reduce the ship weight and cost. Ships are characterized by a specific metallic environment which can severely decrease the efficiency of wireless networks due to signal attenuation and multipath effects. In this paper, we present a feasibility study of a Wireless Sensor Network (WSN) using ubiquitous technologies on board vessels. A measurement campaign has been

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conducted on board a ferry to investigate the radio propagation challenges of wireless communications in this particular environment. Path loss models have been obtained for typical shipboard environments. Engineering rules concerning the placement and the number of communication nodes needed to cover the decks and maintain the network connectivity have been determined. Based on these results, an IEEE 802.15.4 compliant WSN has been tested on board the same ferry. Sensor nodes have been placed on the four decks of the ferry and the base station has been placed in the control room located in the bottom deck. Results show an excellent reliability with respect to transmission ratio of sensor nodes and a significant connectivity between nodes located in different compartments and decks separated by metallic watertight doors.

The major disadvantage associated with the existing system are Desired throughput is not achieved, decreases the network performance and Shannon channel capacity is not measured.

III. PROPOSED SYSTEM TECHNIQUES

The proposed system uses Orthogonal Frequency-Division Multiplexing (OFDM) which is suitable for this type of environment as a means to mitigate frequency selectivity that may reduce the role of coherence bandwidth as a limiting factor in wireless communications throughput. MIMO communications and multiple antenna techniques can also improve radio performance by exploiting spatially uncorrelated fading of wireless channels common in multipath-rich environments to improve throughput and reliability. Data symbols using Quadrature Phase Shift Keying (QPSK) demodulation based on the sampled and enhanced multipath response.

MIMO communication and multiple antenna techniques can also improve radio performance by exploiting spatially uncorrelated fading of wireless channels. The major advantages of proposed system are desired throughput is achieved and improves network performance. A mathematical treatment of OFDM involves, the Fourier transform, the use of the Fast Fourier Transform in OFDM and the guard interval and its implementation

After the qualitative description of the system, it is valuable to discuss the mathematical definition of the modulation system. This allows us to see how the signal is generated and how receiver must operate, and it gives us a tool to understand the effects of imperfections in the transmission channel. OFDM transmits a large number of narrowband carriers, closely spaced in the frequency domain. In order to avoid a large number of modulators and filters at the transmitter and complementary filters and demodulators at the receiver, it is desirable to be able to use modern digital signal processing techniques, such as fast Fourier transform (FFT).

Mathematically, each carrier can be described as a complex wave:

$$s_c(t) = A_c(t)e^{j[\omega_c t+\phi_c(t)]} \qquad (1)$$

The real signal is the real part of $s_c(t)$. Both $A_c(t)$ and f ${}_c(t)$, the amplitude and phase of the carrier, can vary on a symbol by symbol basis. The values of the parameters are constant over the symbol duration period t.

OFDM consists of many carriers. Thus the complex signals $s_s(t)$is represented by:

$$s_s(t) = \frac{1}{N}\sum_{n=0}^{N-1} A_n(t)e^{j[\omega_n t+\phi_n(t)]} \qquad (2)$$

Where

$$\omega_n = \omega_0 + n\Delta\omega$$

This is of course a continuous signal. If we consider the waveforms of each component of the signal over one symbol period, then the variables Ac(t) and f c(t) take on fixed values, which depend on the frequency of that particular carrier and so can be rewritten:

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$$\phi_n(t) \Rightarrow \phi_n$$
$$A_n(t) \Rightarrow A_n$$

If the signal is sampled using a sampling frequency of 1/T, then the resulting signal is represented by:

$$s_s(kT) = \frac{1}{N}\sum_{n=0}^{N-1} A_n e^{j[(\omega_0 + n\Delta\omega)kT + \phi_n]} \tag{3}$$

At this point, we have restricted the time over which we analyze the signal to N samples. It is convenient to sample over the period of one data symbol. Thus we have a relationship: t =NT

If simplifying eqn. 3, without a loss of generality by letting w 0=0, then the signal becomes:

$$s_s(kT) = \frac{1}{N}\sum_{n=0}^{N-1} A_n e^{j\phi_n} e^{j(n\Delta\omega)kT} \tag{4}$$

Now Eq. 4 can be compared with the general form of the inverse Fourier transform:

$$g(kT) = \frac{1}{N}\sum_{n=0}^{N-1} G\left(\frac{n}{NT}\right) e^{j2\pi nk/N} \tag{5}$$

In eq. 4, the function $A_n e^{j\phi_n}$ is no more than a definition of the signal in the sampled frequency domain, and s(kT) is the time domain representation. Eqns. 4 and 5 are equivalent if:

$$\Delta f = \frac{\Delta\omega}{2\pi} = \frac{1}{NT} = \frac{1}{\tau} \tag{6}$$

This is the same condition that was required for orthogonality. Thus, one consequence of maintaining orthogonality is that the OFDM signal can be defined by using Fourier transform procedures.

CAPACITY FOR EACH PHYSICAL LAYER

MIMO is the use of multiple antennas at both the transmitter and receiver to improve communication performance. It is one of several forms of smart antenna technology. Note that the terms input and output refer to the radio channel carrying the signal, not to the devices having antennas. New techniques, which account for the extra spatial dimension, have been adopted to realize these gains in new and previously existing systems. MIMO technology has attracted attention in wireless communications, because it offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. It achieves this goal by spreading the same total transmit power over the antennas to achieve an array gain that improves the spectral efficiency (more bits per second per hertz of bandwidth) or to achieve a diversity gain that improves the link reliability (reduced fading). Because of these properties, MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wifi), 4G, 3GPP Long Term Evolution, WiMAX and HSPA+.

Spatial multiplexing requires MIMO antenna configuration. In spatial multiplexing, a high rate signal is split into multiple lower rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. If these signals arrive at the receiver antenna array with sufficiently different spatial signatures, the receiver can separate these streams into (almost) parallel channels. Spatial multiplexing is a very powerful technique for increasing channel capacity at higher Signal-to-Noise Ratios (SNR). The maximum number of spatial streams is limited by the lesser of the number of antennas at the transmitter or receiver. Spatial multiplexing can be used with or without transmit channel knowledge. Spatial multiplexing can also be used for simultaneous transmission to multiple receivers, known as Space Division Multiple Accesses. The scheduling of receivers with different spatial signatures allows good separability.

A. Single Input Single Output (SISO)

It refers to a wireless communications system in which one antenna is used at the source (transmitter) and one antenna is used at the destination (receiver). SISO is the simplest antenna technology. In some

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environments, SISO systems are vulnerable to problems caused by multipath effects. When an electromagnetic field is met with obstructions such as hills, canyons, buildings, and utility wires, the wave fronts are scattered, and thus they take many paths to reach the destination. The late arrival of scattered portions of the signal causes problems such as fading, cut-out (cliff effect) and intermittent reception (picket fencing). In a digital communications system, it can cause a reduction in data speed and an increase in the number of errors. In order to minimize or eliminate problems caused by multipath wave propagation, smart antenna technology is used. There are three forms of smart antenna, known as SIMO (Single Input, Multiple Output), MISO (Multiple Input, Single Output), and MIMO (Multiple Input, Multiple Output).

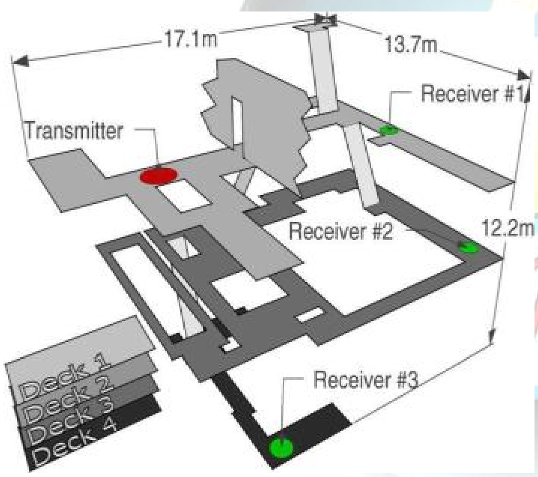

Fig.1. Floor-plan sketch of the aft engine room.

To evaluate the performance of each physical layer, an analysis of the channel capacity is provided. Estimation of Shannon capacity illustrates the effects of changing channel conditions on throughput. The Shannon channel capacity is defined as the tightest upper bound on the amount of information that can be transmitted over a communication channel, in bps/Hz. It is the limiting rate at which data can be transmitted with arbitrarily small probability of bit error. For a flat fading channel, the capacity is defined as

$$C=\log_2\left(1+\frac{P_{\mathrm{Tx}}|h|^2}{N_0}\right) \tag{7}$$

Where, P_{Tx} is transmit power, $|h|$ is the complex channel gain and N_0 is the noise power in the channel.

For an OFDM link with K subcarriers, there are K narrow band flat fading channels. The channel capacity becomes the summation of the capacities of each subcarrier.

$$C=\sum_{K=1}^{K}\log_2\left(1+\frac{P_{Tx}|h|^2}{N_0}\right) \tag{8}$$

This expression can be further expanded for MIMO as

$$C=\sum_{K=1}^{K}\log_2\left[\det\left(I_{mn}+\frac{P_{Tx,k}}{mN_{0,k}}H_kH_k^{+}\right)\right] \tag{9}$$

Where H_k is an $m\times n$ channel matrix with m transmit antennas and n receive antennas. The entries hi,j represent the complex channel gain from Tx antenna to Rx antenna . To compare Shannon capacity fairly from experiments using separate physical layers, the channel gains are normalized such that $|H|_{Frobenius}= mn$.

PP-SNR has also been used as a metric to characterize channel quality .We define PP-SNR as the ratio of signal power to signal error, namely

$$\text{PP-SNR}=\mathrm{E}\left[\|x\|^2/\left\|\hat{x}-x\right\|^2\right],$$

PP-SNR is similar to SNR, but sources of error affecting PP-SNR include nonlinear distortion in the radio transceiver, error in channel estimation, and noise enhancement from equalization. Given a PP-SNR, the Symbol Error Rate (SER) can be estimated statistically from the Receiver Operating Characteristic (ROC) curve of the hard decision bit decoder.

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Conversely, for a given SER constraint, the maximum modulation order can be calculated to estimate achievable throughput.

B. Engine Room

Engine Room Number 2 is a multi deck compartment toward the stern of the hip, housing one of the two main engines for ship propulsion. This compartment was selected as a location for testing because it is a contiguous space with largely metal construction. Thus, signal scattering was expected to be quite high. Furthermore, this space was seen as a prime candidate for implementing a wireless sensor network to monitor the status of vital ship machinery. Average capacities for the various physical layers used in the engine room are shown as a function of average SNR. The capacity is averaged over all receivers for each type of physical layer tested. The water-filling solution represents the upper bound of capacity for the link, while independent, identically distributed channels represent the highest theoretical gain achievable in any MIMO link of equal channel norm. Since the channels are normalized with respect to gain per receiver, the effect of spatial correlation is isolated in the MIMO channel on Shannon capacity. As demonstrated, the channel is spatially decor related enough to support the use of MIMO techniques to improve performance over SISO techniques. The capacity is approximately doubled by using MIMO-SM over SISO. PP-SNR for each physical layer and receiver location is shown, being the shortest link and nearest to line-of-sight, has the highest PP-SNR.

C. Coupled Compartments

A cluster of spaces in an interior deck of the ship was used to analyze the coupling between adjacent and near-adjacent compartments. A key objective was to determine the effect of closing watertight doors on signal integrity. Fig. 2 shows the layout of these coupled compartments as well as the locations of the nodes used in the experiment. The transmitter node was located in compartment A, and the two receiver nodes were located in compartments B and C. Compartment A includes an emergency escape scuttle into compartment C (this scuttle was closed for the duration of the testing) and an exhaust duct with vents connects compartments A and B. While the doors and hatches are watertight, there exist ventilation ducts, piping and other protrusions that create an effective aperture for electromagnetic signals to propagate between the compartments.

D. Independent and Identically Distributed (I.I.D.)

IID refers to sequences of random variables. IID implies an element in the sequence is independent of the random variables that came before it. In this way, an IID sequence is different from a Markov sequence, where the probability distribution for the nth random variable is a function of the previous random variable in the sequence (for a first order Markov sequence). An IID sequence does not imply the probabilities for all elements of the sample space or event space must be the same. For example, repeated throws of loaded dice will produce a sequence that is IID, despite the outcomes being biased.

E. MIMO Maximal-Ratio Combining (MRC)

MIMO stands for Multiple Input and Multiple Output, and refers to the technology where there are multiple antennas at the base station and multiple antennas at the mobile device. Typical usage of multiple antenna technology includes cellular phones with two antennas, laptops with two antennas (e.g. built in the left and right side of the screen), as well as CPE devices with multiple sprouting antennas. The predominant cellular network implementation is to have multiple antennas at the base station and a single

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antenna on the mobile device. This minimizes the cost of the mobile radio. MRC is a method of diversity combining in which the signals from each channel are added together, the gain of each channel is made proportional to the RMS signal level and inversely proportional to the mean square noise level in that channel. Different proportionality constants are used for each channel. It is also known as ratio-squared combining and pre-detection combining. Maximal-ratio combining is the optimum combiner for independent AWGN channels..

It shows the layout of the relevant decks in the main engine room and the specific location of each radio node. Tests were performed in the engine room with nodes located on three of the four decks over which the compartment spans. The void space between receivers 2 and 3 was occupied by the engine and exhaust stack, which spanned all decks. The radio locations were chosen to represent a combination of line-of sight and non-line-of-sight links and to gain an understanding of coverage rein a contiguous space spanning multiple decks.

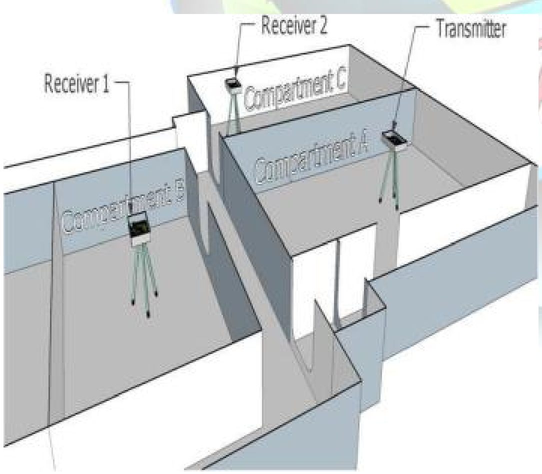

Fig 2: Floor plan of the adjacent compartments used for the coupled compartment measurements.

The measurements in the coupled compartments show two distinct behaviors emerging from differences in physical layout. As shown in Fig. 2, the Transmitter is separated from Receiver 1 by two bulkheads and a hallway. The primary pathway for the signal is through this hallway when the doors are open, but it must propagate through apertures in the bulkheads when they are closed. However, the Transmitter is separated from Receiver 2 by a single bulkhead. When the doors are open, there is a single long pathway for the signal to propagate to the receiver via the hallway. The capacity for the channel between the Transmitter and Receiver 1 improves for SISO when the doors are closed. Since the path loss from the channel is normalized, this improvement indicates the channel has a flatter response (less frequency selectivity). This is consistent with a decrease in multipath signals arriving at Receiver 1 and an increase in the dominance of the signals arriving via ductwork connecting the two spaces.

Since MIMO techniques mitigate frequency selectivity through antenna diversity, the negligible change in the capacity of these schemes would indicate that the channel correlation (a major factor in capacity) does not change in a significant way when the doors are opened or closed. The capacity for the channel between the Transmitter and Receiver 2 improves for both SISO and MIMO schemes when the doors are closed. The improvement for SISO indicates that frequency selectivity decreases, similar to the effect seen at Receiver 1. The improvement for MIMO indicates that the channel correlation also decreases, in contrast to the effect seen at Receiver 1. The signal integrity decreases for Receiver 1when the doors are closed. Despite the crease infrequency selectivity, the attenuation of the signal when the doors are closed still results in an overall decrease in integrity. PP-SNR increases for Receiver 2 when the doors are closed consistent with the dominant signal component coming through apertures in the bulk head and the multipath signal from the hall way deconstructive interfering when the doors are open.

SIMULATION RESULTS

Simulation is done with Matlab 7.0 (Matrix Laboratory), a high-performance language for scientific and technological calculations. It integrates computation, visualization and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. It is a complete environment for high-level programming, as well as interactive data analysis.

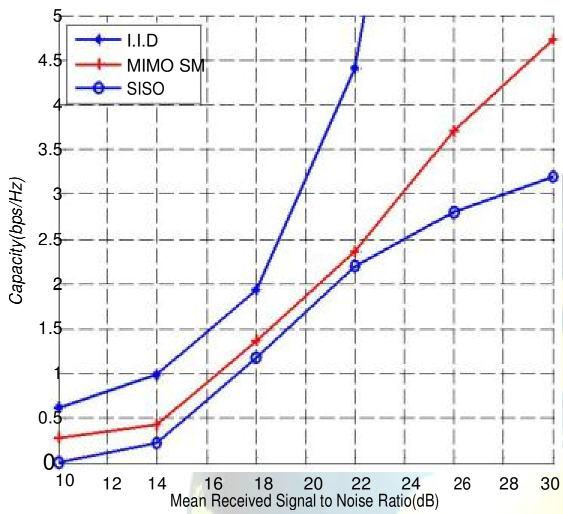

Fig. 3: Mean Received Signal to Noise Ratio Vs Capacity (IID, MIMO & SISO)

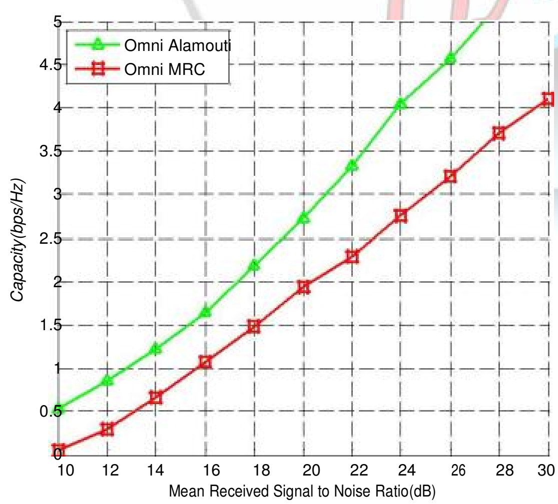

Fig. 4: Mean Received Signal to Noise Ratio Vs Capacity (Omni Alamouti & MRC)

CONCLUSION

This work evidence that multi antenna technologies can improve communications performance over SISO techniques in a below-deck environment. MIMO technologies offer improved capacity and less variation in system performance despite changing environmental factors. The PP-SNR values presented show the improvement in reliability that can be provided by space-time coding. Estimation of Shannon channel capacity demonstrates that multipath scattering can be exploited by spatial multiplexing to improve performance and increase throughput. The achievable throughput was as high as 36 Mb/s in spite of the reverberant conditions limiting the coherence bandwidth. On the poorest-quality link, SISO communications were restricted to 6 Mb/s in the engine room, while MIMO physical layers were able to operate at 12 Mb/s, thereby doubling the link throughput. Similar performance gains were observed in the coupled compartments with doors open.

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