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Effects of Reconfigurable Antennas On Wireless Network Performance Within A *Ticonderoga*-Class Engine Room

ABSTRACT

Wireless communication within spaces aboard naval ships is being studied. The objective is low-cost, easy-to-install augmentation of data flow to and from sensors and control equipment. Wireless communications has the potential advantage over wired communication of not jeopardizing watertight integrity. However, due to the highly reverberant nature of ship interiors, RF signals below decks are subject to fading and other multi-path effects that limit their usefulness. In order to mitigate these potential performance limitations, we examine the utility of alternative antennas on the infrastructure side of the wireless links. The impact of using electrically reconfigurable antennas for the transmitter was characterized by measuring received signal quality and estimating the Shannon channel capacity of various wireless links within the engine room aboard *Thomas S. Gates* (CG 51). This ship is a decommissioned *Ticonderoga*-class cruiser. The wireless measurement system employed the Wireless Open-Access Research Platform (WARP) hardware with a packet structure closely resembling the IEEE 802.11g standard. Reconfigurable antennas were found to improve communication performance and reliability when compared to omnidirectional antennas.

I. INTRODUCTION

There is ongoing interest in installing and operating wireless networks aboard ships [1–3]. Unlike traditional wired networks, wireless communication can easily augment connectivity in existing spaces with relatively low cost and little disruption to the structure or watertight integrity of the bulkheads. Wireless networks have been proposed for monitoring, controlling and automating many operations aboard ships, particularly in engineering spaces [4–6].

The below-decks environment of a ship presents significant challenges to wireless communication. The solid metal structure that is necessary to maintain watertight integrity impedes wireless signals from propagating between compartments. Moreover, the highly multipath nature of a space such as an engine room may lead to signal distortion that degrades communication. These effects have been studied at length (e.g., [7–9]) during attempts to quantify the impact of the multipath environment on communication performance.

A study by Mehmood and Wallace [10] proposed using reconfigurable antennas as a means for reducing multipath interference in highly reflective environments. A reconfigurable antenna allows for dynamically changing the radiation pattern which alters the wireless channel between communicating nodes. Interference is mitigated by selecting a configuration for the antenna which produces the most favorable channel conditions [11]. The performance gains possible with this type of antenna have only been assessed via simulation in [10] and similar studies (e.g., [12]), however. Other studies, such as [13–15], make actual performance measurements with software-defined radios, but the reported experiments were conducted in typical lab or office environments. In a previous study, we observed the communication performance gains from the use of reconfigurable antennas over conventional antennas in a reverberation chamber [16]. Although this type of environment is able to emulate electromagnetic properties similar to below-decks spaces, no attempts have been made to ascertain communications performance of reconfigurable antennas in an actual below-decks setting.

The current study examines the communication performance benefits of electronically reconfigurable antennas in the RF-challenging environment of an engine room aboard *Thomas S. Gates* (CG 51) [17], a decommissioned *Ticonderoga*-class cruiser. An IEEE 802.11g wireless network was constructed using a software defined radio architecture and MATLAB. Post-processing signal-to-noise ratio (PP-SNR), channel capacity, and achievable throughput were calculated from measurements taken between a transmitter and two receiver nodes placed in the engine room.

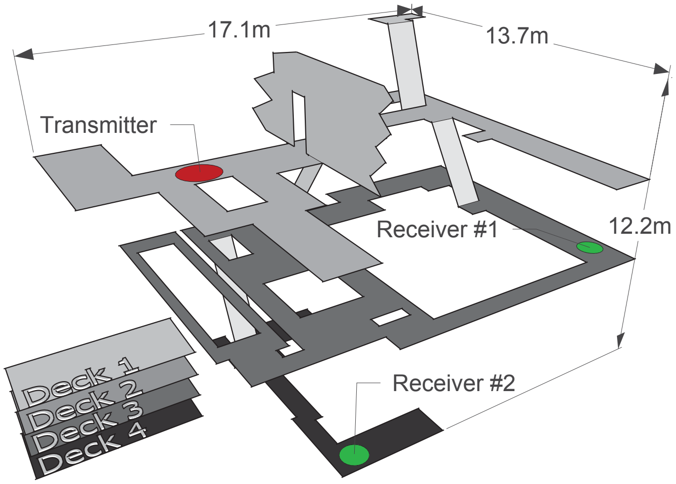

Figure 1. Cross-section of the measurement scenario showing the layout of the engine room and the placement of the transmit and receive nodes.

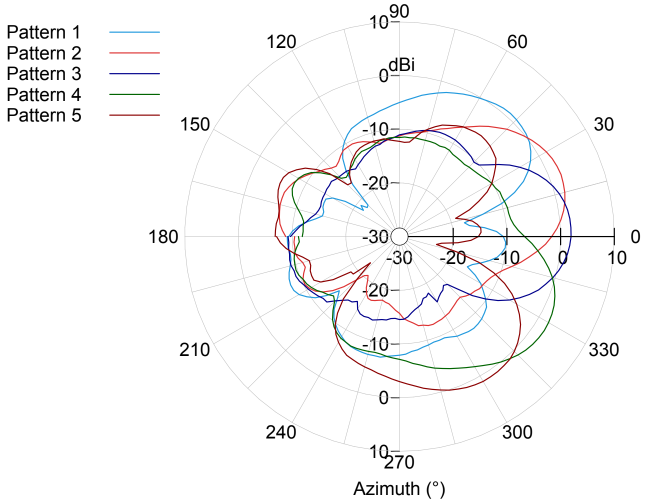

Figure 2. Radiation patterns of the reconfigurable antenna electrically selected for experimentation.

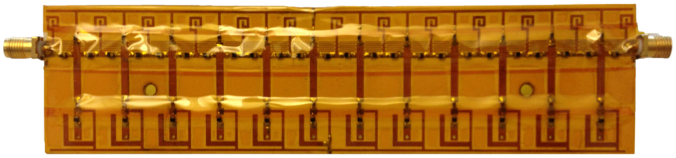

Figure 3. Electrically reconfigurable, leaky wave antenna described in [21]. Total size is 5×16 cm.

II. MEASUREMENT SCENARIO

The Aft Engine Room in *Thomas S. Gates* is a multi-deck compartment towards the stern of the ship. It houses one of the two main engines for ship propulsion. The compartment was selected as the measurement location, because it is a large, contiguous space containing a number of metal objects and features. Thus, signal scattering was expected to be high. Furthermore, the space is a prime candidate for implementing a wireless sensor network to monitor the status of vital ship machinery.

The layout of the Aft Engine Room and the placement of the nodes are shown in Figure 1. The compartment spans four decks. A series of ladders, walkways, and instrument panels surround the centrally-located engine and exhaust stack which comprises the majority of the volume of the compartment. The Transmitter was positioned on Deck 2 with Receiver 1 on Deck 3 and Receiver 2 on Deck 4. The receiver positions were chosen to assess communication quality for typical wireless coverage in a contiguous space over non-line-of-sight links.

III. EXPERIMENTAL SETUP

A. Test Platform

A MATLAB-based IEEE 802.11g OFDM measurement platform was developed for the WARP v3 Kit, a software-defined FPGA radio [18]. The platform was configured to use the Single-Input, Single-Output (SISO) and 1×2 receive-side Maximal Ratio Combining (MRC) [19] physical layer schemes. The transmitter and receiver subsystems were implemented in MATLAB. This process is described more fully in [20]. The FPGA radio was only used for transmission and reception of the raw waveforms.

B. Antennas

A commercial, off-the-shelf dual-band (2.4/5.8 GHz) omnidirectional antenna (model HG2458RD-SM, manufactured by L-com) and a reconfigurable, leaky wave antenna described in [21] were selected for comparison. The reconfigurable antenna (pictured in Figure 3) has two ports that are electrically beam-steerable. The ports are connected through a series of 10 DC bias networks. The beams of the ports can be steered by altering the voltage supplied to the DC bias networks. Five configurations were selected for this experiment. The radiation patterns produced by these configurations are shown in Figure 2.

C. Test Protocol

The WARP software-defined radio has two radio ports. The omnidirectional antenna and the reconfigurable antenna were both attached to one of the radio ports (Figure 4). The ports were calibrated to ensure equalized output power. Since the wireless channel is time-varying,

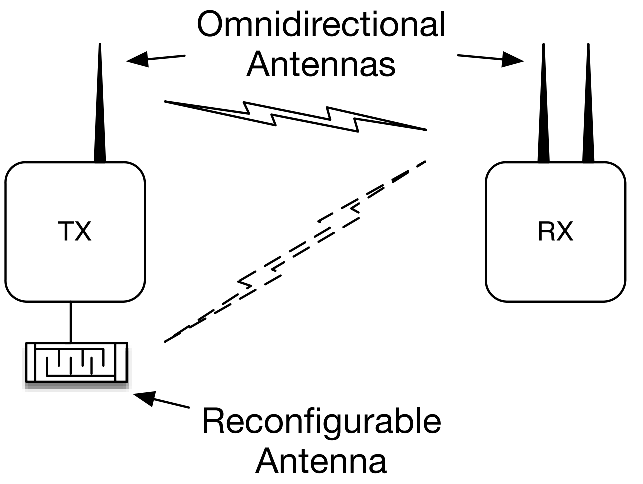

Figure 4. The transmitter had one omnidirectional antenna and one reconfigurable antenna connected to its radio ports. The receivers were equipped with two omnidirectional antennas. Transmissions alternated between the omnidirectional antenna and the reconfigurable antenna.

transmissions were alternated between the omnidirectional antenna and the reconfigurable antenna to improve the basis of comparison.

Each trial consisted of six total transmissions—one for the omnidirectional antenna and one for each of the five reconfigurable antenna patterns. The full experiment contained 2,400 trials. As shown in Figure 4, the receivers had omnidirectional antennas connected to both of their radio ports and received two streams for each transmission. SISO and MRC could then both be decoded from a single transmission. Only one received signal was used for SISO decoding while both were used for MRC decoding.

D. Source Stirring

The measurement scenario represents a primarily static wireless environment. In normal ship operation, the movement of equipment, humans, and the ship itself would result in dynamic, time-varying channel conditions. To mimic such an environment, the transmitter (or "source") was moved to multiple positions within 1 meter of the starting position. The repositioning effectively alters, or "stirs," the electromagnetic field inside the compartment. Source stirring produces equivalent changes that would be observed by either mechanical mode stirring or frequency stirring [22]. The stirring only occurred in between trials, so it does not affect the channel correlation and comparison of successive transmissions within a trial. Sets of 400 trials were performed at each position.

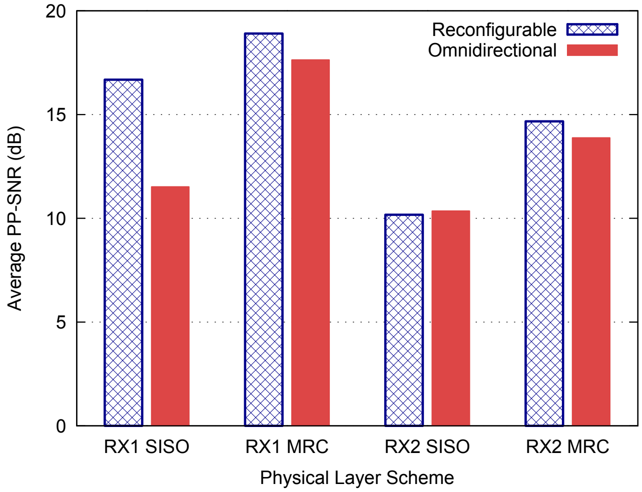

Figure 5. PP-SNR with optimal reconfigurable antenna pattern selected.

E. Performance Metrics

The Post-Processing, Signal-to-Noise Ratio (**PP-SNR**) is a link-level measure of signal integrity. It is the ratio of the transmitted signal power to the signal error at the receiver (evaluated in dB). While PP-SNR is similar to SNR, it is hardware-specific as it takes into account the gains and losses introduced by each element of the transmitter and receiver subsystems.

Channel **capacity** is the theoretical upper bound on the amount of information that can be carried over a channel with an arbitrarily small amount of error [23]. It is calculated (in bits/sec per unit bandwidth) from the normalized channel gain estimates such that the effects of path loss are removed. In an OFDM system, the channel capacity is the sum of the capacities of each subcarrier.

The **achievable throughput** of a link is the highest rate of data transfer that can be attained given SNR and bit error rate constraints. Higher PP-SNR values indicate more accurate data symbol reception, allowing for higher-order modulations to be used. Moving from BPSK to QPSK (QAM-4) effectively doubles throughput levels from 6 to 12 Mbps. Using QAM-16 increases throughput to 24 Mbps, while QAM-64 allows a rate of 36 Mbps.

IV. RESULTS

Small changes in the positioning of the transmitter antennas caused large variance in the signal integrity at the

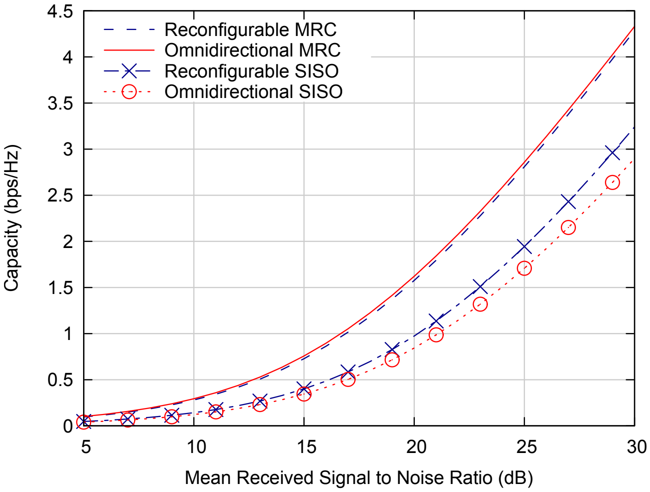

Figure 6. Capacity for Receiver 1

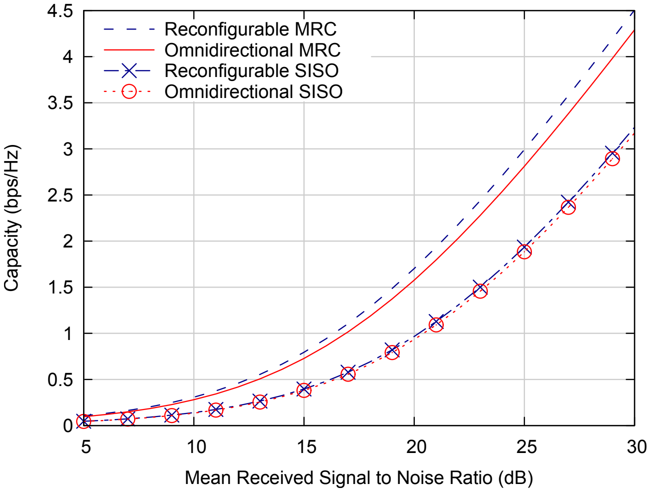

Figure 7. Capacity for Receiver 2

receiver. The variance was less for MRC transmissions than SISO, because the receiver diversity used by MRC appears to mitigate channel fluctuations. Regardless of the receiver or physical layer scheme, the best performing antenna type and configuration changed frequently over the course of the transmissions. The reconfigurable antenna can capitalize on this characteristic by modifying its configuration frequently to maximize the PP-SNR.

For each transmission of reconfigurable antenna, the configuration that maximized the PP-SNR was chosen from the five configurations tested. The performance of this optimal configuration was compared to that of the omnidirectional antenna. The optimal configuration provides an upper bound on the improvement possible with the reconfigurable antenna.

Table 1. Achievable throughput (Mbps) for Receiver 1 with bit error rate limited to 10^{-6}.

	Physical Layer Scheme	
Antenna	SISO	MRC
Reconfigurable	24	36
Omnidirectional	12	24

Table 2. Achievable throughput (Mbps) for Receiver 2 with bit error rate limited to 10^{-6}.

	Physical Layer Scheme	
Antenna	SISO	MRC
Reconfigurable	12	24
Omnidirectional	12	12

Figure 5 shows the average PP-SNR values for the reconfigurable antenna and the omnidirectional antenna for both SISO and MRC at each receiver. For both schemes of Receiver 1, and for the MRC scheme of Receiver 2, the reconfigurable antenna had a higher PP-SNR level. Only for the SISO scheme of Receiver 2 does the omnidirectional antenna have a higher signal integrity than the reconfigurable antenna, and then only by less than 0.2 dB. The SISO scheme for Receiver 1 shows a gain of more than 5 dB by using the reconfigurable antenna over the omnidirectional antenna.

The measured capacities of each transmit scheme are shown in Figures 6 and 7 for Receivers 1 and 2, respectively. The reconfigurable antenna has higher capacities for every transmit scheme except for the MRC scheme of Receiver 1, where the difference between the two antennas is negligible.

The observed gains in PP-SNR have a practical impact on communications due to the corresponding increase in throughput. As PP-SNR increases, higher-order modulation levels may be used. This will directly increase the data throughput of the communication link.

Achievable throughput rates were calculated by using the highest modulation order that still resulted in bit error rates less than 10^{-6}. For Receiver 1 (Table 1), using the reconfigurable antenna allows for data rates of 12 Mbps higher than when using omnidirectional antennas. Similar trends are observed for Receiver 2 for MRC (Table 2). With Receiver 2 SISO, the advantages of the reconfigurable antenna were not sufficient to allow for increased throughput.

V. CONCLUSIONS

The use of an electrically reconfigurable antenna in our experiments improved communication quality. While the use of a standard, omnidirectional antenna sometimes resulted in the best performance, there were many states of the electromagnetic environment where better performance was achieved by one of the configurations available via an electrically reconfigurable antenna. When the omnidirectional antenna performed quantifiably better, the margin of improvement in signal integrity was less than 0.2 dB. In contrast, the reconfigurable antenna had gains in signal integrity up to 5.2 dB over the omnidirectional antenna in some scenarios.

Clearly, communication performance in our experiments improved by a greater margin by moving from SISO to MRC. However, many wireless clients do not have the ability to implement diversity schemes such as MRC (e.g., wireless sensor nodes that are designed for low-complexity and low-cost). Systems incorporating such clients would benefit by using a reconfigurable antenna at the access point. This change could be made without any hardware modifications to the client devices. Even if a client does incorporate additional diversity schemes, the reconfigurable antenna will still sometimes outperform the omnidirectional antenna. Performance never significantly diminished as a result of using the reconfigurable antenna at the transmitter. It appears that a reconfigurable antenna may be beneficial for use aboard ships where wireless networks are being considered.

ACKNOWLEDGMENT

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