Performance of Reconfigurable Antennas in a Below-Decks Environment

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***Abstract*—Reconfigurable antennas have been proposed for mitigating multipath interference and increasing channel capacity in wireless networks. The majority of studies which have investigated these claims do so either in simulation or through the use of software defined radios in lab or office environments. There has been little work in quantifying experimentally the performance gains of a reconfigurable antenna in highly metallic environments representative of military and industrial applications. This letter quantifies the performance gains provided by the use of electrically reconfigurable antennas in the place of omnidirectional antennas given varying environmental and system configurations. Wireless measurements for various 802.11-like physical layers were performed in a set of multideck, coupled compartments aboard *Thomas S. Gates* (CG 51), a decommissioned *Ticonderoga*-class U.S. Navy cruiser. The reconfigurable antennas were observed to provide higher channel capacities than omnidirectional antennas. When the bulkhead doors connecting the coupled compartments were left open, the postprocessing signal to noise ratio (PP-SNRs) of signals received from reconfigurable antennas were up to 4 dB higher than what was observed when using omnidirectional antennas. As the compartments became less electrically coupled (i.e., bulkhead doors were closed), the benefit provided via the antenna pattern diversity of the reconfigurable antennas diminished.**

***Index Terms*—Electromagnetically reflective spaces, MIMO, OFDM, reconfigurable antennas, shipboard propagation.**

I. INTRODUCTION

ELECTRICALLY reconfigurable antennas have gained popularity because of the increased flexibility that they provide in wireless radio architectures. Since the radiation pattern of this type of antenna may be dynamically altered, the antenna may be adapted to meet changing channel conditions. Electrically reconfigurable antennas have been proposed for mitigating multipath interference and for increasing system capacity in wireless networks [1]. The majority of reconfigurable antenna studies that demonstrated performance benefits were, however, conducted in simulation (e.g., [2]) or used with software defined radios in lab or office environments (e.g., [3]). There is ongoing desire to deploy wireless networks in highly metallic environments encountered often in military and industrial settings such as below-deck spaces on naval vessels. In these environments, reconfigurable antennas may be especially useful [4]. The defining electromagnetic characteristics of below-deck environments have been studied (e.g., [5]), and they exhibit high multipath propagation and high path loss between adjoining compartments. The added pattern diversity of reconfigurable antennas may provide a means for reducing the effects of such interference. Still, only little experimental testing has been performed to demonstrate that potential advantage.

In a previous study of below-deck spaces [6], we sought to quantify the performance of a selection of physical layers using only omnidirectional antennas over different wireless links and environment states (i.e., opening and closing bulkhead doors). The current study focuses on evaluating performance gains when using reconfigurable antennas at the transmitter node in place of omnidirectional antennas. These performance gains are evaluated for a selection of physical layer configurations and across multiple transmitter/receiver links. This variation is important, as certain system architectures may be infeasible due to hardware or policy constraints at the receivers. To this end, wireless communication performance was assessed between four nearly adjacent compartments aboard *Thomas S. Gates* (CG 51) [7], a decommissioned *Ticonderoga*-class U.S. Navy cruiser. Two metrics—system capacity and postprocessing signal-to-noise ratio—were experimentally measured for three wireless links and four 802.11 based physical layers. These three metrics provided an estimate of the performance gains provided by the use of reconfigurable antennas over a broad scale, while also illustrating link-specific performance.

The remainder of the letter is organized as follows. In Section II we discuss the experimental platform used for assessing communications performance, the models of antennas that were investigated, and the performance metrics used to evaluate them. In Section III we discuss the physical layout and network topology of the investigated multicompartment setup. The results of the study are presented in Section IV, documenting the performance gain of the reconfigurable antenna with the bulkhead doors open and closed.

II. EXPERIMENTAL SETUP

This study compares the performance of a wireless communication system employing a reconfigurable antenna to that of the same system with an omnidirectional antenna. The comparison was conducted for 24 distinct cases. Three different wireless links were each combined with four different physical layer

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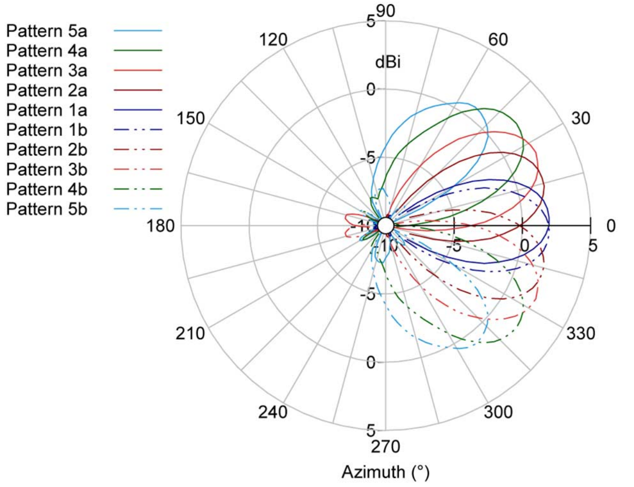


Fig. 1. Radiation patterns of the reconfigurable antenna. Solid-line "a" patterns are from the first port of the antenna, while the dashed-line "b" patterns are from the second port.

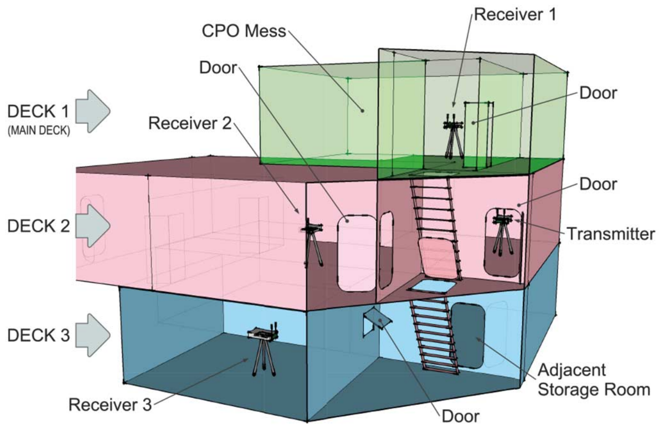


Fig. 2. Floor plan sketch of the coupled compartments scenario. One receiver node was placed on each of the three decks. A transmitter node was placed on Deck 2 (middle deck, right side). Scenarios indicated as "doors open" were performed with the doors indicated in this figure fully open. Scenarios indicated as "doors closed" were performed with these doors closed.

schemes. These twelve cases were each used twice, first testing communications through open doors in the environment and then with closed doors.

A. *Wireless System*

The omnidirectional antenna used in this study was a commercial, off-the-shelf dual band (2.4/5.8 GHz) antenna manufactured by L-com (model #HG2458RD-SM). Similar to monopole antennas that are commonly used for commercial wireless access points, this antenna served as the basis for comparison to reconfigurable antennas. Two omnidirectional antennas were used on each receiver and the omnidirectional transmitter with 10-in spacing.

The reconfigurable antenna used for the reconfigurable transmitter was the leaky wave antenna (LWA) developed by the Drexel University Wireless Systems Laboratory. This two-port composite right/left handed LWA, described in [8], is able to steer two distinct RF beams electrically via a series of 12 metamaterial unit cells. Five beam configurations (i.e., patterns) were selected for this experiment. These patterns (shown in Fig. 1) steer a 35°-wide beam in five distinct directions spread over a 90° sector. MIMO tests were performed with the five pairs of patterns 1a/1b, 2a/2b, 3a/3b, 4a/4b, and 5a/5b. SISO tests were performed with the five patterns 5a, 3a, 1a, 3b, and 5b.

Four 802.11-like OFDM physical layers were investigated by this effort: SISO, Maximal Ratio Combining (MRC) 1×2[9], Alamouti space-time block coding 2×2[10], and Vertical-Bell Laboratories Layered Space-Time (VBLAST) spatial multiplexing 2×2[11]. The transmitter and receiver subsystems were implemented in MATLAB according to the experimental methodology proposed in [12]. Wireless Open-Access Research Platform (WARP) software defined radios [13], [14] were used for the wireless transmission and reception of the waveforms. The experiment was performed on 802.11b/g/n channel 11 (2.462 GHz). Total power delivered to the antennas after transmitter calibration averaged -3.2 dBm for the omnidirectional antennas and -3.6 dBm for the reconfigurable antenna (transmit power was optimized for consistency given the gain resolution on the WARP boards).

B. *Testing Protocol*

To mitigate the impact of the time-varying nature of the wireless channel on the results, transmissions were alternated between the omnidirectional antenna and the LWA. This task was accomplished by using two WARP nodes placed at the transmitter location; one node had the omnidirectional antennas connected, the other had the LWA connected. The radio gains of each WARP node were equalized using an Agilent U2001H USB power sensor [15]. A single trial of the experiment consisted of six consecutive transmissions. The first transmission used omnidirectional antennas while the remaining five transmissions each used one of the five LWA configuration patterns each. For each physical layer, 2400 trials were performed with the doors open and another 2400 trials were performed with the doors closed.

The measurement scenario investigated here consists of a largely static wireless environment. During normal ship operations, the movement of humans and equipment throughout the spaces would result in time-varying channel conditions. To emulate such channel variations, the transmitter was moved to multiple positions within one meter of the starting position. This repositioning of the transmitter alters the electromagnetic field inside the measurement area. For each measurement case, sets of 400 trials were performed at each transmitter position.

III. MEASUREMENT LOCATION

The multideck, coupled compartments scenario of this study was setup in four compartments near the middle of the ship on Decks 1–3 of the *Thomas S. Gates*, and is shown in Fig. 2. A single transmitter was positioned on Deck 2 with three receivers located in three adjoining compartments. Receiver 1 was positioned directly one deck above the transmitter (i.e., on Deck 1) in the Chief Petty Officer (CPO) mess. The door on Deck 1 that was opened and closed was the metallic, nonwatertight door from the CPO mess opening into the passageway.

Receiver 2 was positioned on the same deck as the transmitter (i.e., on Deck 2) in an adjacent compartment. A single bulkhead separated the two compartments, and two watertight doors opening into the common passageway were opened and closed. Line-of-sight (LOS) did not exist between the transmitter and Receiver 2. Receiver 3 was positioned on the deck below the transmitter (i.e., on Deck 3). A bulkhead door at the bottom of the ladder (opening to storage space adjacent to Receiver 3) remained closed throughout testing, while a metallic, nonwatertight hatch (a service window) was opened and closed. The watertight hatches at each ladder between decks remained open throughout testing.

A. *Performance Metrics*

Similar to the study in [6], communication performance was evaluated using two metrics: system capacity and postprocessing signal-to-noise ratio (PP-SNR).

System capacity is the theoretical upper bound on the achievable data rate of the system over a wireless link with an arbitrarily small amount of error [9]. As opposed to wireless channel capacity, system capacity also takes into account the signal processing (e.g., coding scheme, carrier phase offset correction, etc.) applied at the transmitter and receiver. In this study, it is calculated in bits per second (bps) per unit of bandwidth, using estimated channel state information from each transmission. The channel state information is also normalized such that the Frobenius norm of the channel matrix is equal to the number of transmitters times the number of receivers [16]. An increase in capacity may indicate a decrease in either frequency selectivity or spatial correlation.

PP-SNR is defined as the root-mean-square (RMS) average of the transmitter signal power divided by the RMS average of the error vector magnitude between transmitted and received signals (i.e., the inverse of the error vector magnitude as defined in [17]). PP-SNR is analogous to the SNR of the channel, however it takes into account hardware-specific characteristics of the transmitter and receiver subsystems.

IV. RESULTS

In order to compare the performance of the LWA with the omnidirectional antenna, a selection algorithm was used to choose a single LWA pattern configuration from the five configurations tested at each trial of the experiment. Here, we used an ideal selection algorithm which chooses the LWA pattern configuration so as to yield the highest PP-SNR for each trial. The results presented can thus be interpreted as upper bounds on the performance gains possible with the LWA used in this measurement scenario. In other work [18], we have reported practical selection algorithms for reconfigurable antenna systems.

Fig. 3 depicts the gains provided by switching from the omnidirectional antenna to the LWA in each of the 24 cases studied. A significant increase (more than 1 dB gain) in PP-SNR was observed by moving to the LWA in 10 out of the 24 cases under study. The largest PP-SNR gains (up to 4 dB) were observed with the doors open in the links for Receivers 2 and 3. These gains suggest that the LWA is able to direct more RF energy to these receivers than the single-pattern omnidirectional antenna.

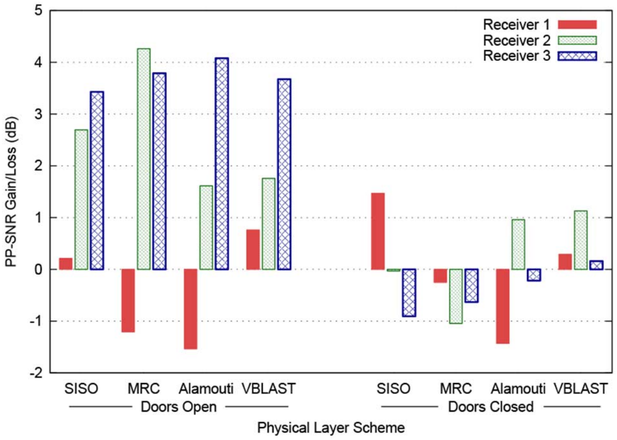


Fig. 3. PP-SNR gains (in dB) realized by switching from an omnidirectional antenna to a reconfigurable antenna at the transmitter. Gains are presented for each physical layer scheme and each receiver link with both the doors open and closed. For 10 out of 24 cases, gains of more than 1 dB are observed; For eight out of 24 cases, losses in signal quality are observed.

TABLE I
RECONFIGURABLE ANTENNA PP-SNR (dB) FOR EACH PHYSICAL LAYER, RECEIVER LOCATION AND DOORS STATE

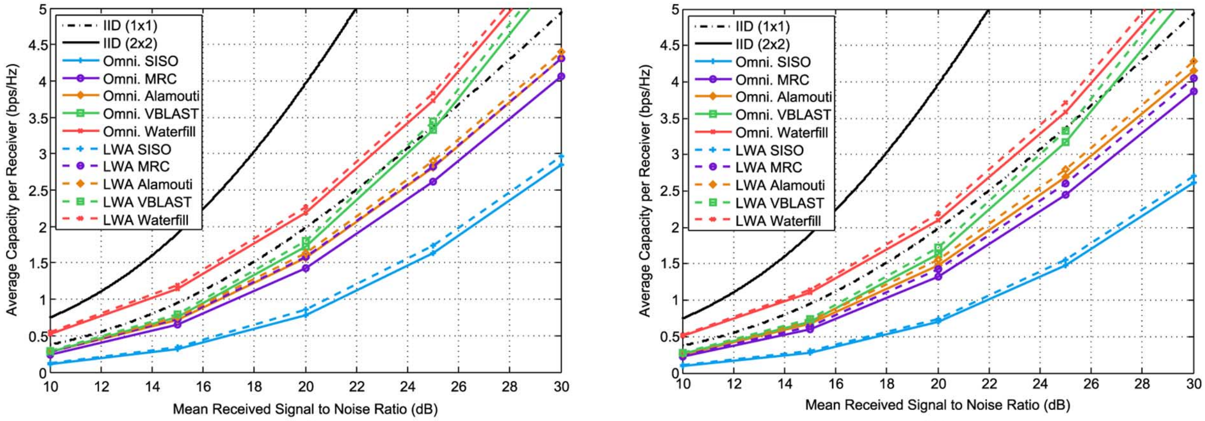
	Doors Open				Doors Closed			
Location	SISO	MRC	ALA.	VBLAST	SISO	MRC	ALA.	VBLAST
RX 1	16.6	19.4	18.0	13.4	12.1	15.8	15.4	9.5
RX 2	23.2	26.0	24.4	19.3	12.6	16.3	17.3	10.8
RX 3	21.0	24.4	23.7	17.7	13.1	17.7	17.9	11.5

When the doors were open, the PP-SNR gains from using the LWA over the omnidirectional antenna are lowest at Receiver 1; in two cases, the PP-SNR actually went down when using the LWA compared to using the omnidirectional antenna. This pattern suggests that the best-case LWA pattern directs less energy than the omnidirectional antenna into the compartment directly above the transmitter. This trend supports our intuition, since the signal pathways to Receiver 1 are the longest and most indirect of the three receivers.

When the doors were closed, switching to the LWA provided gains in PP-SNR that were generally less than those observed when the doors were open. Only for SISO at Receiver 1 did the PP-SNR improve a greater amount with the doors closed. Positive gains were realized by switching to the LWA in five of the 12 doors-closed cases (only three of those cases improved by 1 dB or greater). In the other seven of the 12 doors-closed cases, the omnidirectional antenna performed as well or better than the LWA. In only two cases was there a loss of more than 1 dB by switching to the LWA. These results indicate that as the compartments become more decoupled (the doors move from an open to a closed state), there is less advantage to reconfiguring the LWA radiation pattern.

For each case presented in Fig. 3, the corresponding absolute PP-SNR values when using the LWA are presented in Table I. As expected, closing the bulkhead doors reduces the PP-SNR for all receivers and physical layers.

Fig. 4 shows estimated system capacity in bps/Hz versus the total received SNR in dB. Fig. 4(a) shows the estimated system capacities when the doors were open, while Fig. 4(b) shows the



(a) (b)

Fig. 4. Observed system capacities (bps/Hz) when using either the omnidirectional (Omni.) antenna or LWA versus total received SNR. Capacities are shown for each of the investigated physical layers, and have been averaged over all three receiver links. Capacities for the 1×1 and 2×2 independent and identically distributed (IID) cases are shown for comparison. (a) Case 1: Doors open. (b) Case 2: Doors closed.

estimated system capacities when the doors were closed. The system capacities for the LWA and omnidirectional antenna are shown for the SISO, MRC, Alamouti, and VBLAST physical layers. The channel capacities for an independent, identically distributed channel matrix and for a water filling algorithm [9] are also shown for comparison. Observed channel capacities were similar across the three receivers, hence Fig. 4 shows the average channel capacity across all links. As expected, closing the bulkhead doors results in slightly lower channel capacities for both antennas and all physical layers. The use of the LWA, however, was observed to produce a capacity increase for all physical layers, with the doors both doors and closed. For our experimental setup, this trend suggests that the use of the LWA reduced the frequency selectivity and/or spatial correlation in the channel, mitigating multipath interference.

V. CONCLUSION

The wireless measurements presented here quantify the performance gains of an electrically reconfigurable antenna over an omnidirectional antenna in the practical, highly multipath environment of a naval ship. Regardless of opening or closing bulkhead doors, gains in channel capacity were observed when using the leaky wave antenna (LWA) of [8] over an omnidirectional antenna. PP-SNR gains of up to 4 dB were also observed when the bulkhead doors were left open, most likely because of the beam steering capability of the LWA. When the bulkhead doors were closed, the positive observed gains were fewer and smaller in magnitude, and the relative advantage of the LWA disappeared.

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