Multipath Fading in Airframes at 2.4 GHz

Christopher Fitzhugh, Jeff
Frolik and Richard Ketcham
University of Vermont
Burlington, VT 05405

John Covell
Goodrich Fuel and Utility
Systems
Vergennes, VT 05491

Tom Meyer
Goodrich Aerospace Lighting
Systems
Oldsmar, FL 34677

***Abstract*- Wireless sensor networks offer the potential of weight reduction, higher reliability and improved safety for aircraft support systems. However airframes, being an enclosed metal environment, can produce severe multipath effects. Thus to enable the development of high integrity systems, the physical layer constraints due to such environments must be understood. This paper presents results of a characterization of two common commercial aircraft at the 2.4 GHz ISM band. In addition, we present empirical results that show the effectiveness of diversity techniques to mitigate fading effects. Results are compared to predicts using *M*-independent Rayleigh channel selection diversity.**

I. INTRODUCTION

In recent years, the diverse potential applications for wireless sensor networks (WSN) have been touted by researchers [1, 2] and the general press [3]. In general, WSN are seen as an enabling technology for the distributed monitoring of industrial, military and natural environments. While much work to date has focused on low-cost, energy efficient hardware designs, architectures and algorithms for WSN, very little effort has been dedicated to characterizing the channel environment for applications [4, 5]. WSN are unique due to extremely varied deployments (e.g., near-ground, underground, at air/water boundaries or embedded in composite structures) and as such current propagation models for other wireless systems (e.g., cellular or satellite communications) are not applicable. This paper presents the results of work characterizing the multipath fading characteristics for one specific WSN environment, namely, that of an airframe.

Although attention has recently focused on passenger entertainment services linked to passenger laptops via wireless IEEE 802.11 links (e.g., Boeing's Connexion system [6]), other wireless systems related to aircraft functions and operations have also been deployed. These include wireless links on aircraft LANs for use with electronic checklists and logs, links to weather reports and maps for pilots, and intra-crew communications. In addition, other FCC Part 15 wireless systems are being used for smoke detection [7], video security [8], and for control of emergency lighting [9]. WSN in particular show promise for systems that provide non-essential (for aircraft flight) but highly desirable information. For example, a system of distributed accelerometers and/or strain gauges could be valuable for conditional maintenance. However, commercial aircraft already have 2000 to 5000 pounds of wiring, thus the added weight of a *wired* sensor network is not desirable. Furthermore, wiring is vulnerable to vibration, hardening, and breakage. Moisture, temperature cycling, exposure to fungus, and aviation chemicals cause wiring insulation to degrade thus leading to potential shorting or intermittent performance [10]. Faults of this type are extremely difficult to localize, and work is being done to develop sensing systems to find such insulation problems [11]. In addition, wiring is also a primary entry point for electromagnetic effects (e.g., lightening) that can disrupt or damage aircraft electrical/electronic systems. Hence, a distributed WSN certainly offers advantages in terms of reduced weight and complexity.

Airframes, however, are far from being a free space environment due to reflections occurring from the enclosed, metallic structure. In addition, each type of aircraft has unique dimensions and thus can be expected to have its own unique multipath characteristics. As such, our motivation was to understand the extent that multipath can be expected to effect wireless communications for sensor networks. The work considers two common commercial aircraft and the 2.4 GHz ISM band that has garnered interest for WSN applications particularly due to the recently introduced IEEE 802.15.4/ZigBee hardware. The work investigates the frequency selective fading introduced by the environments and explores the effectiveness of employing spatial, polarization and channel diversity in order to mitigate these fading effects.

The paper is organized as follows. In Section 2 we present the environments characterized and the test methodology, along with typical data. In Section 3, we analyze the effectiveness of diversity techniques based on our empirical results. Section 4 concludes with the key results and directions for future work.

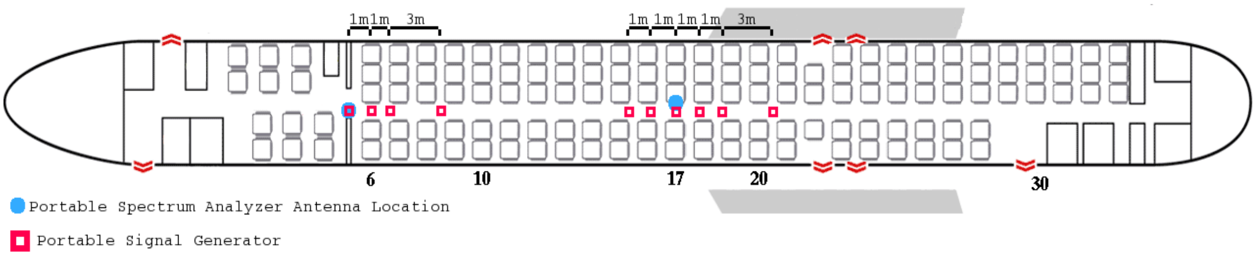

Figure 1. MD-90 floor plan and representative test locations (Seat plan obtained from seatguru.com)

II. TEST METHODOLOGY AND RESULTS

Two test environments were chosen as being representative of typical narrow-body and wide-body commercial aircraft. Respectively, the aircraft were an MD-90 (Fig. 1) and a 747-400 configured with seating but having no passengers.

The 2.4 GHz ISM (industrial, scientific and medical) band was swept using a portable signal generator (PSG), an A-System PSG27, and a portable spectrum analyzer (PSA), an Anritsu MS2711B. A planar, directional antenna connected to the PSA was mounted on the cabin ceiling. An omni-directional antenna was connected to the PSG which was moved to various test locations. PSG test locations included on the aisle floor, on seat backs and inside open stowage bins. Sample test positions are illustrated in Fig. 1.

The PSG was configured to step in 100 kHz increments from 2400 MHz to 2480 MHz and the PSA was set to a resolution bandwidth of 1.0 MHz. These frequency sweeps were performed in 43 different locations in both the narrow-body and the wide-body airframes. Note: due to setup constraints only magnitude response data was captured.

Fig. 2 illustrates a representative case in which the multipath effects are seen to be severe. In this 747-400 data, wideband degradation (> 5 MHz) is shown to be at least 15 dB in many places. Furthermore, narrower band degradation (< 1 MHz) exceeds 30 dB in places. Across the band, the standard deviation is 6.75 dB. In contrast, Fig. 3 shows more typical fading that was observed. In this MD90 data, wideband degradation is limited to around 10 dB, while degradation in the narrower band is limited to less than 20 dB. In comparison to Fig. 2, the across band standard deviation is a significantly smaller 5.36 dB.

To illustrate the uniqueness of the multipath environments of these two airframes, 18 records of the 747-400 and 16 records of the MD-90 were used to calculate the standard deviation across the band (~ 300 data points between 2400-2480 MHz). The inband variation for the 747-400 records were in the 6.08-8.44 dB range, while those for the MD-90 were in the 5.14-7.42 dB range indicating that overall the wide body environment is more severe.

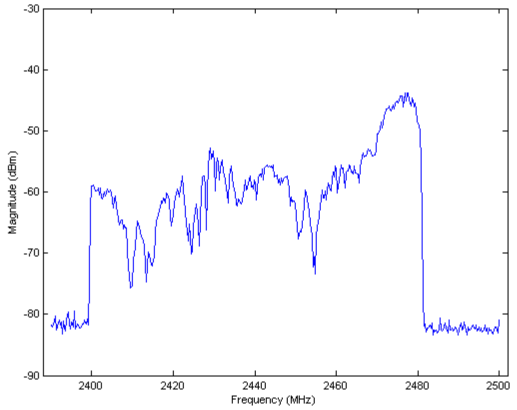

Figure 2. Severe fading effects noted

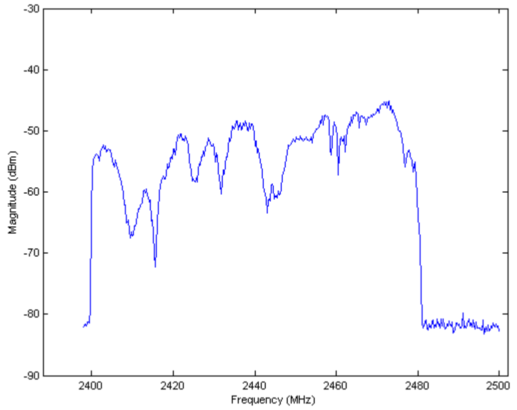

Figure 3. Typical fading effects noted

In the next section we discuss our empirical results showing diversity techniques can be used to mitigate these frequency selective fading effects, often to greater extent than predicted using common fading models.

III. DIVERSITY GAINS

From Figs. 2 and 3, it is clear that frequency diversity would be effective in combating fading effects. However, frequency diversity affects spectral efficiency and also requires coordination among all possible users. In WSN deployments, the number of users (sensor nodes) could be significantly high, thus limiting the ability to choose among multiple channels. As such, we first explore the improvement of using spatial or polarization *selection* diversity.

It has been shown [12], that if M-independent Rayleigh paths can be utilized in a communication link, then simply choosing the best path results in an expected improvement (gain, γ) which can be calculated as follows:

$$\gamma = \sum_{k=1}^{M} \frac{1}{k} \tag{1}$$

where k is the path index. Thus, theoretically, two different paths should provide a gain of 1.50 (1.76 dB) over the average received signal strength.

To ascertain the effectiveness of antenna diversity for airframe applications, data was collected with the PSG's antenna oriented in one of four different configurations.

1. Vertically oriented
2. Horizontally oriented
3. Horizontally oriented but with a 90º azimuth rotation from orientation no. 2
4. Vertically oriented but shifted 6.0 cm (~5λ/4) relative to orientation no. 1

Representative data for these cases and resulting selection diversity improvements are presented in the following subsections.

A. Vertical vs. Horizontal selection diversity

The top image of Fig. 4 compares multipath environments for a fixed location in which the only change is the orientation of the PSG antenna from vertical to horizontal.

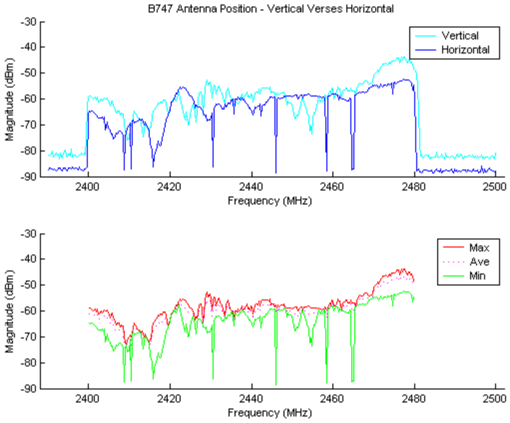

Figure 4. Polarization diversity data

The bottom panel of Fig. 4 shows three curves obtained from the measured data. The top curve is the max of both polarization (i.e., the power level selection diversity would provide). The bottom curve is the minimum of both polarizations and the middle curve is the average of the maximum and minimum curves. Using the 18 inband measurements for the wide-body airframe, indicates an average selection diversity gain of 2.13 dB or ~0.35 dB greater than predicted from (1). The narrow-body airframe cases (using the 16 measurements) results in an average selection diversity gain of 1.90 dB (i.e., closer to predict). Our conclusion is that the wide-body aircraft's environment is more severe than the Rayleigh assumption and thus diversity techniques result in improvements greater than predicted by (1). We reinforce this conclusion in §III.D when considering gains using channel diversity.

B. Position selection diversity

Fig. 5 illustrates the effectiveness of spatial selection diversity in mitigating small scale fading effects in the narrow-body airframe. These measurements compare vertically oriented PSG antennas that are spatially separated by 6.0 cm. This distance is ~5λ/4 and was chosen as representative width for a wireless sensor node. Five records were analyzed as discussed in § III.A resulting in an average selection diversity gain of 1.76 dB.

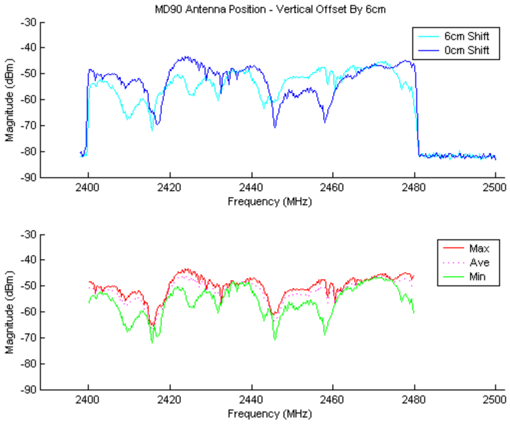

Figure 5. Position diversity data

C. Azimuth rotation selection diversity

The final orientation comparison considered the PSG having its antenna in the horizontal orientation and then rotating 90º in azimuth. A representative plot is shown in Fig. 6. Two wide-body records were analyzed, again across the band of interest, resulting in an average gain of 2.06 dB when employing selection diversity. Again, the selection diversity gains for the wide-body aircraft are greater than predicted by (1).

D. Channel selection diversity

Given the somewhat larger than expected gains using selection diversity between M=2 channels for the wide-body aircraft, we now investigate benefits of increasing the number of available channels (i.e., *M*). Using the data presented in Fig. 2 (wide-body) and Fig. 3 (narrow-body), we divide the band of interest into 16 channels (as per the IEEE 802.15.4 specification). Considering the average selection diversity gain of all permutations in which *M* channels can be configured out of 16 possible total, results in the data given in Fig. 7. Clearly, the diversity gain opportunities are significantly higher for the wide-body case as opposed to the narrow-body case. Note, however, that with the diversity gain comes the added complexity of frequency coordination and degradation in spectral efficiency.

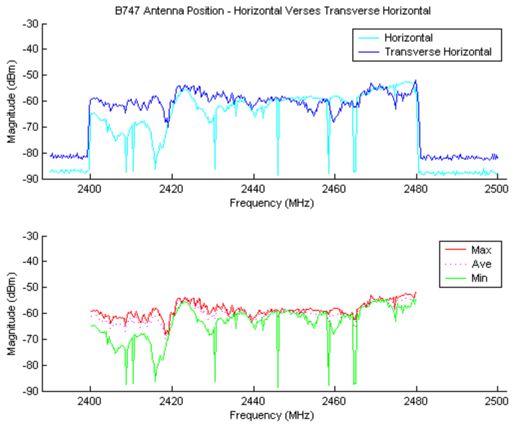

Figure 6. Rotational diversity data

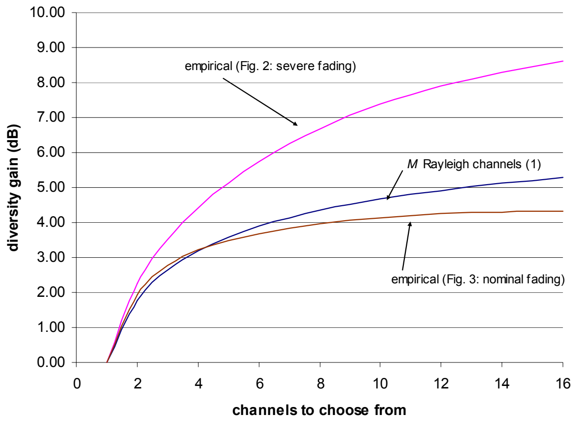

Figure 7. Frequency diversity gains

IV. CONCLUSIONS

In this paper, we have presented results of an initial investigation in which we characterize the multipath environment within airframes. The work considered only the 2.4 GHz ISM band, but this band is of special interest to WSN that may employ the IEEE 802.15.4 standard or possibly the IEEE 802.11b/g standard. Results indicate, as expected, that wireless systems operating in an airframe (essentially a metal cavity) are highly susceptible to multipath. Note that our results are for airframes alone and do not consider effects passengers may have. Our results consistently show the wide-body aircraft to be a more severe multipath environment as opposed to the narrow-body aircraft. At the same time, selection diversity gains for this severe multipath environment may exceed those predicted by *M*-independent, Rayleigh channel analysis.

This latter result emphasizes the point that the airframe environment is not typical of, say, cellular or even in-building WLAN systems. As such, the authors hope this work motivates other researchers to consider characterizing environments appropriate for other WSN applications, for very little analysis of this type has been done to date.

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