Path Loss from a Personal Electronic Device Inside an Aircraft Cabin to an Exterior Fuselage-Mounted Antenna

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1. Introduction

In this paper we consider the problem of how to determine path loss from a personal electronic device (PED) radiating in the cabin of a large passenger aircraft to the terminals of a “victim” antenna mounted on the fuselage. The ability to perform such calculations quickly and accurately is important in the analysis of electromagnetic compatibility (EMC) between PEDs and aircraft navigation and communications systems. Solutions for this problem using full-wave integral equation methods or ray tracing methods is awkward due to the large dimensions of the fuselage relative to the wavelengths of interest (as small as 6 mm) and the fact that the cabin consists of a complex collection of objects including people and seats. Prior investigations have mostly bypassed this problem by focussing on the path loss measured from the point at which power leaves the fuselage to the victim antenna. However, lossy materials within the cabin play an important role in determining the overall path loss. Therefore, it is desirable that any new analysis technique yield reasonable estimates in the presence of interior features, but at the same time should not require detailed information about the specific geometries or constitutive parameters of the media. Section 2 of this paper presents our solution to this problem, which involves a combination of techniques including microwave cavity theory for the interior part of the problem and the Uniform Geometrical Theory of Diffraction (UTD) for the exterior part of the problem. In Section 3, we demonstrate the effectiveness of the technique by comparison to measurements of various aircraft at the L1 (1575.42 MHz) frequency of the U.S. Global Positioning System (GPS).

2. Methodology

Our solution consists of three steps. In the first step, we estimate the power which escapes the cabin through windows. For this, we use the method of Hill et al. (1994) [1], viewing the aircraft cabin as a reverberant microwave cavity in which only four loss mechanisms are possible: (1) loss due to escape from the cavity, (2) loss due to absorption by lossy media, (3) loss due to finite wall conductivity, and (4) loss due to intercept by other antennas. We assume that the loss due to mechanisms (3) and (4) is insignificant compared to the first two mechanisms, and we further assume that transmission through windows is the dominant contribution to (1). Under these assumptions, the ratio of power escaping the cabin (through windows) to total power transmit is \( L_w \approx Q_2/(Q_2 + Q_3) \) where \( Q_2 \) and \( Q_3 \) are “quality factors” associated with absorption and escape loss, respectively, obtained from expressions in [1]. These terms depend only on frequency; the total volume of the cabin; the total number and equivalent radius of windows; and \( < \sigma_a > \), the
mean absorption cross-section for all lossy media in the cabin. We estimate \( <\sigma_a> \) as \( N_p <\sigma_{ap}> + N_s <\sigma_{as}> \), where \( N_p \) is the number of people in the cabin, \( <\sigma_{ap}> \approx 0.4 \text{ m}^2 \) is the mean absorption cross section of a person, \( N_s \) is the number of seats, and \( <\sigma_{as}> \approx 0.04 \text{ m}^2 \) is the mean absorption cross section of a seat [2]. We assume that the power escaping from each window is equal, independently of the location of the transmitter within the cabin. This assumption is justified based on the copious scattering that occurs within the cabin. The power per window is then \( P_w = P_T L_w / N_w \) where \( P_T \) is the total power transmit by the PED.

Next, we model each radiating window as a pair of orthogonally-polarized electrically-short magnetic current moments oriented tangentially to a perfectly conducting right circular cylinder representing the fuselage exterior. The magnitude of these current moments is readily found to be \( \sqrt{6\pi\eta P_w/k^2} \), where \( \eta \) is the impedance of free space and \( k \) is the free space wavenumber. This assumes that the power is equally divided across both polarizations, again justified due to the copious scattering within the cabin. The electric field due to any one current moment at any other point on the fuselage can be found using the UTD convex surface “creeping wave” formulation given in [3]. Assuming the associated geodesic ray paths are unobstructed by wings and other discontinuities, the total field at any given point on the fuselage is obtained simply by repeating this procedure for each current moment and summing the results, yielding the total electric field \( \mathbf{E}' \). Thus, this method works without modification for antenna mounted along the top (dorsal) region of the fuselage but requires modification (i.e., additional UTD diffraction calculations to account for scattering from discontinuities) for antennas at most other locations on the aircraft. The power received by the victim antenna is \( P_R = |\mathbf{E}' \cdot \mathbf{l}_e|^2/(8\pi R_A) \) where \( R_A \) is the radiation resistance and \( \mathbf{l}_e \) is the vector effective length of the victim antenna.

Finally, we recognize that the current moments used in the above procedure are expected to have essentially random phase, again due to the copious scattering within the cabin. To account for this, the preceding steps are repeated many times in Monte Carlo fashion, varying the phases from trial to trial in order to determine the statistical distribution of path loss. However, the \textit{minimum} path loss (worst case from an EMC perspective) is obtained by assuming that the contributions from each current moment arrive in-phase and thus add constructively.

3. Example of Analysis for a GPS L1 Antenna

In this section we apply our method to the calculation of path loss from a PED in the cabin to a dorsal-mounted antenna operating at the L1 frequency (1575.42 MHz) of GPS. The aircraft considered are listed in Table 1, along with the relevant dimensions. For all aircraft we assume windows with effective radius 14 cm and which are evenly spaced along the length of the cabin, which we assume to be \( 0.8 L_f \). The volume of the cabin is then roughly estimated as \( V = (0.8 L_f) (\pi a^2) \frac{1}{2} \).

First let us consider the part of the path loss associated with propagation from a window, along the surface of the fuselage, to the GPS antenna. Measurements of this mechanism for a Boeing 737 aircraft by Jafri, Ely, and Vahala in 2005 [4] provide a convenient source of data for comparison to predictions using our method.
In their experiments, they measured the path loss for a linearly-polarized transmit antenna located in a window, repeating the measurement for both vertical and horizontal transmit polarizations in each of the 33 windows on one side of the aircraft. We modeled their measurements assuming zero passenger load, and assuming that one-half of the total power radiated by the transmit antenna propagates into the aircraft and is lost. The results are shown in Figure 1. Both measurements and simulation indicate that the dominant contribution for windows close to the GPS antenna (which is above Window No. 9) is vertical polarization, whereas the dominant contribution is horizontal polarization for windows further away. The results are quite satisfactory except for the significant difference between measurement and simulation for vertical polarization when the source is in a window close to the GPS antenna. This difference remains to be explained.

Figure 2 shows the results when the full method is used to determine minimum path loss for a PED completely inside the cabin to the GPS antenna, compared to measurements reported in a variety of sources reported in [5]. Note that we have shown the comparison between measurement and simulation for two cases; in one case assuming in the simulation that the aircraft was empty during the stated measurements, and in the second case assuming 50% passenger load for simulation. The actual situation in reported measurements is typically not clear: Whereas the measurements typically do not involve passengers, in many cases they seem to have involved significant numbers of workers in the cabin, or may have involved open doors or other conditions which would produce similar effects. Agreement within an order of magnitude seems to exist between simulation and measurement in most cases, although clearly with high variance and some outliers. Because of the difficulty and possibility for inconsistency in test procedures, it is difficult to know in each case whether it is measurement or simulation which is closer to “true”. Nevertheless, the simulation approach proposed here appears to be a promising start to the development of the desired models for EMC analysis.

References


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Table 1: Boeing and Airbus aircraft considered in this study.

Figure 1: Comparison of simulated and measured “interference path loss” (IPL) for vertical (V) and horizontal (H) polarizations of a transmit antenna placed in the indicated window of a B737 (see text).

Figure 2: Comparison of simulated and measured minimum “interference path loss” (IPL) for a variety of aircraft. Circles ("o") correspond to simulations assuming empty conditions, where as the “×” correspond to 50% passenger load.