Effect of Human Presence on UWB Radiowave Propagation within the Passenger Cabin of a Midsize Airliner

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Abstract—We have characterized the effect of human presence on path gain and time dispersion over ultrawideband (UWB) channels within the passenger cabin of a typical midsize airliner. We measured a few hundred channel frequency responses over the range 3.1 – 6.1 GHz between various locations within a Boeing 737-200 aircraft, with and without volunteers occupying the passenger seats. The links were deployed in a point-to-multipoint configuration with the transmitting antenna along the centre-line of the forward part of the cabin at either the ceiling or headrest level and the receiving antenna at the headrest or armrest level at selected locations throughout the rest of the cabin. As the density of occupancy increased from empty to full, path gain dropped by no more than a few dB on the ceiling-to-headrest paths but dropped by up to 10 dB on the ceiling-to-armrest and headrest-to-armrest paths. The gain reduction reached its maximum at the mid-point of the cabin and decreased thereafter. In all cases, increasing the density of occupancy caused the distance dependence of the rms delay spread to decrease greatly, the decay rate of the scattered components in the power delay profile (PDP) to almost double and the number of significant paths to drop by almost half. The results suggest that human presence substantially affects both path gain and time dispersion within the aircraft and should therefore be considered when assessing the performance of in-cabin wireless systems.

I. INTRODUCTION

HUMAN presence in the vicinity of a short-range, low-power wireless link often leads to shadowing and scattering that affect both the path gain and time dispersion experienced by the link [1],[2]. Concern for the effect of human presence on short-range wireless links has motivated both measurement- and simulation-based studies of: (1) the depth and duration of shadow fading due to pedestrians moving in the vicinity of such links [3]-[5], (2) the effect of human presence on wireless personal area networks (WPANs), i.e., where one end of the link is located either close to or on a person [6]-[9], and (3) the effect of human presence on wireless body area networks (WBANs), i.e., where both ends of the link are located either close to or on a person [10]-[12].

In recent years, airlines and aircraft manufacturers have expressed much interest in deploying short-range wireless links within the passenger cabins of airliners in order to: (1) permit deployment of in-flight entertainment (IFE) and network access services and (2) facilitate operations and maintenance through deployment of sensor networks [13]-[17]. Although various wireless technologies have been considered and evaluated, ultrawideband (UWB) wireless technology that operates within the frequency band between 3.1 and 10.6 GHz have attracted particular interest for future systems because it: (1) can support very high data rates (up to 480 Mbps) over short distances, (2) occupies a particularly small footprint, radiates little RF energy, and consumes little power, and (3) can support precise positioning capabilities.

With its cylindrical structure, its confined volume, the regular layout of its seating, and its high density of occupancy, an airliner passenger cabin is fundamentally different from the residential, commercial and industrial indoor environments considered previously by UWB researchers [18],[19]. The confined volume and high density of occupancy suggest that human presence will affect the performance of wireless systems in aircraft passenger cabins more than it will in other environments. Two previous studies presented characterizations of the UWB wireless channel within aircraft passenger cabins [20],[21], but disclosed only limited information concerning the effect of human presence on UWB wireless propagation in such environments. In other previous work, assessments of the excess pathloss introduced by human presence and internal components in passenger cabins were presented based upon: (1) narrowband measurements collected using CDMA handsets onboard a Boeing MD-90 with up to 17 passengers in the cabin [22] and (2) simulations of the effect of passengers and internal components on electromagnetic field strength inside Boeing B747, B767 and B777 aircraft passenger cabins [23]. Other previous work has yielded estimates of the manner in which the presence of windows, people and furnishings affect the field statistics and...
spoil the Q-factor of an enclosed space that functions as a multimode cavity [25]. However, designers require a more complete description of the effect of human presence on propagation in aircraft passenger cabins that account for the different types of paths within such environments and which are based upon larger data sets. A very recent study, conducted about the same time, as ours, considered the effect of human presence on UWB propagation within a large wide-body aircraft [26]. Here, we present the results of a complementary study conducted within a smaller narrow-body aircraft.

After completing a pair of rigorous research ethics reviews and recruiting almost 100 volunteers to occupy passenger seats, we collected a few hundred UWB channel frequency responses (CFRs) over the frequency range of 3.1-6.1 GHz in a point-to-multipoint configuration within the passenger cabin of a Boeing 737-200 aircraft. We mounted the transmitting antenna at either the cabin ceiling or headrest level along the centerline of the forward part of the cabin and collected channel frequency response data with the receiving antenna mounted at headrest or armrest level at selected locations throughout the cabin with three degrees of occupancy: empty, partially filled and completely filled. We processed the result to determine the manner in which human presence affects the distance and frequency dependence of path gain, the form of the channel impulse response, the distance and frequency dependence of rms delay spread, and the number of significant multipath components (MPCs) arriving at the receiving antenna and the frequency-dependent three-dimensional radiation pattern of each antenna [28].

We recruited volunteers to occupy passenger seats during the measurement session. In order to meet RF emission limits imposed upon us by the Research Ethics Boards at the University of British Columbia and the British Columbia Institute of Technology, we set the transmit power to 5 dBm. We set the intermediate frequency bandwidth of the VNA to 3 kHz which reduced the resulting displayed average noise level (DANL) to -107.2 dBm. The minimum sweep time was automatically set to 2 seconds. As configured, the channel sounder can resolve channel impulse responses (CIRs) with an SNR ≥ 25 dB at transmitter-receiver separation distances of up to 15 m assuming a distance exponent of 2.2, based on the worst case observed in our previous work [20], and average transmit and receive antenna gains of 0 dBi over all angles and directions.

During data collection, the VNA was configured to sweep from 3.1 to 6.1 GHz over 2560 frequency points. The frequency sampling interval of 1.1718 MHz corresponds to a maximum unambiguous delay of 853 ns or a maximum observable distance of 256 m. The frequency span of 3 GHz gives us a temporal resolution of 333 ps or a spatial resolution of 100 mm.

B. Channel Sounder Calibration

Before measurement data can be collected, the channel sounder must be calibrated so that systematic variations in the amplitude and phase of the measured frequency response due to factors other than the propagation channel can be removed. The process involves two steps. The first step is to use the VNA’s built-in calibration routines, which are based upon a standard 12-term error model, to compensate for amplitude and phase distortions up to the point where the cables attach to the transmitting and receiving antennas. Care must be taken to ensure that the distortions for which the error correction model is compensating do not change appreciably during the measurement session. The second step is to use the VNA’s built-in calibration routines, which are based upon a 12-term error model, to compensate for amplitude and phase distortions up to the point where the cables attach to the transmitting and receiving antennas. Care must be taken to ensure that the distortions for which the error correction model is compensating do not change appreciably during the measurement session. The second step is to use the VNA’s built-in calibration routines, which are based upon a 12-term error model, to compensate for amplitude and phase distortions up to the point where the cables attach to the transmitting and receiving antennas. Care must be taken to ensure that the distortions for which the error correction model is compensating do not change appreciably during the measurement session.

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Implementing the required measurement setup within the confines of the aircraft passenger cabin would be problematic, however.

The antenna calibration problem is simplified considerably if we can assume that the environment is rich with scatterers so that the physical MPCs arrive from all possible directions and each resolvable MPC includes many physical MPCs. Because the directivity of any antenna averaged over all directions is unity for all frequencies, the measured CFR will be independent of the radiation patterns of the transmitting and receiving antennas. In such cases, after appropriate account has been taken for the return loss of the antennas and the amplitude of any line-of-sight (LOS) components, the measured CFR will be equivalent to the propagation channel response. The dense single cluster form of the CIRs that we observed within that environment suggests that the density of scatterers within the cabin is very high. Moreover, previous work in conventional indoor environments has shown that the AoA distribution in the vertical plane broadens considerably as the size of the enclosed space becomes smaller [29]. Accordingly, it is not unreasonable to assume that the scattering is sufficiently broad that the effective gain of the transmitting and receiving antennas over all directions and frequencies is unity. Thus, while our results strictly characterize the radio channel, it seems likely that the measured channel is a useful approximation to the propagation channel.

C. Data Collection

We collected the CFR measurements within the passenger cabin of a Boeing 737-200 aircraft. The cabin, which can seat 130 passengers, is 3.54 m in width, 2.2 m in height and 21 m in length of which 18 m actually includes passenger seating. So that we could assess the effect of human presence on RF propagation aboard the passenger cabin, we collected measurement data with three levels of occupancy: empty, partially full and completely full. When the cabin was partially full, volunteer passengers sat in every seat from row 4 through 19. When the cabin was full, volunteer passengers sat in every seat from row 4 through 19. During data collection, all of the passengers were asked to engage in quiet activities such as talking or reading while seated rather than standing in the aisle or moving about the aircraft. Before we collected production data, we verified that we could exploit the bilateral and translational symmetry inherent in the cabin layout to dramatically reduce the number of measurements needed to characterize propagation within the aircraft.

We mounted the transmitting antenna along the centerline of the cabin at row 2 at either ceiling or headrest height, as appropriate, in the manner of an access point. We considered three different path types: ceiling-to-headrest (C-to-H), ceiling-to-armrest (C-to-A) and headrest-to-armrest (H-to-A). For both the C-to-H and C-to-A path types, we mounted the transmitting antenna at the ceiling level and used a custom-designed mount to place the receiving antenna at the headrest or armrest level of passenger seats in a reproducible manner on the port side of the aircraft from rows 4 to 19. For the C-to-H path type, the receiving antenna was placed on alternating aisle, middle and window seats, while for the C-to-A path type, the receiving antenna was placed only on alternating middle and window seats. For the H-to-A path type, we mounted the transmitting antenna at the headrest level and placed the receiving antenna at the armrest level of alternating middle seats on the port side of the aircraft from rows 4 to 18.

The two different receiving antenna mounting positions not only represent typical use cases such as using a cell phone (at headrest level) or a laptop (at armrest level) but also represent both LOS (at the headrest) and NLOS (at the armrest) channels. A cross-section view of the cabin that shows the various antenna mounting positions is given in Fig. 1. A plan view of the cabin is shown in Fig. 2.

D. Measurement Database

During the development phase, we considered three transmitter locations at rows 2, 11 and 16 and over 50 receiver locations in the empty passenger cabin. For selected paths, we took multiple sweeps to verify the static nature of the channel and the reproducibility of our measurements. This yielded over 200 CFRs in the development phase. During the production phase, we used only one transmitter location and collected data only on the port side of the aircraft. For each of the three levels of occupancy, i.e., empty, partially filled and completely filled, we collected CFRs at 24 and 16 different receiver locations along the port side of the aircraft for the C-to-H and C-to-A path types, respectively. For the empty and full aircraft cases, we also collected CFRs at 8 selected receiver locations for the H-to-A path type. This yielded 152 CFRs in the production phase. In total, we collected over 360 CFRs.
III. EFFECT OF HUMAN PRESENCE ON PATH GAIN IN THE AIRCRAFT ENVIRONMENT

The manner in which path gain decreases with distance determines the maximum range that can be achieved by a wireless link. For UWB-based wireless systems, path gain is an especially important consideration given the relatively low power levels that such systems are permitted to radiate. Within the passenger cabin, path gain decreases with increasing transmitter-receiver separation due to the combined effects of spatial spreading and obstruction by cabin fixtures, seating and passengers. Assessing the effect of human presence on path gain within the aircraft environment allows system designers to more accurately predict the coverage and reliability of UWB-based point-to-multipoint wireless systems deployed within such environments.

We modeled the path gain within the passenger cabin environment as follows. First, we divided the 3.1-6.1 GHz frequency range into two band groups \( b = \{1, 2\} \), each of which is 1.5 GHz wide. Over each band group, we verified that the envelope of the frequency response was effectively flat. We obtained the distance-dependent path gain \( G_p(d) \) by taking the average of the magnitude of the measured complex CFRs, \( H(f_i, d) \), across each band group, yielding

\[
G_p(d) = \frac{1}{M} \sum_{i=0}^{M-1} |H(f_i, d)|^2.
\]

where \( d \) is the transmitter-receiver separation distance, \( M \) is the number of frequency steps in each band group, and \( f_i \) is the \( i \)th frequency step. At each location, we estimated the path gain when the cabin was empty, and then estimated the reduction in path gain, \( \Delta G_p \), when the cabin was partially and fully occupied. The configuration of the transmitting and receiving antennas and their antenna patterns remained constant as the level of occupancy increased. Thus, any variation in antenna gain due to changes in the path geometry

![Fig. 2. Locations of the transmitting antenna (►), receiving antenna (● = transmitting antenna at ceiling, O = transmitting antenna at headrest level) and volunteers (…) within (a) the empty, (b) the partially filled and (c) the completely filled Boeing 737-200 aircraft.](image)
with distance would have cancelled out when the difference in the estimated path gains was calculated.

In Fig. 3, the reduction in path gain, $\Delta G_p$, observed in band group 1 is presented as a function of distance, $d$, for different path types and, within each plot, for different levels of occupancy. Although we had anticipated that the reduction in path gain would generally increase with distance over the length of the cabin, the actual relationship was more complicated. Initially, path gain decreases as the distance between the transmitter and receiver increases. Beyond the mid-point in the cabin (a distance of between 7 and 9 meters), however, the trend reverses. The time dispersion results presented in the next section do not reveal a similar breakpoint at the mid-point of the cabin so it seems likely that AoA effects are responsible. Although our measurement data are insufficient to reveal such effects, ray tracing simulations similar to those described in [23] and [24] may provide additional insight and be a useful next step.

In all cases and both band groups, we found that the reduction in path gain associated with human presence was well-approximated by a quadratic expression in distance of the form

$$\Delta G_p(d) = \Delta G_{p0} + Ad + Bd^2 + X_\sigma. \quad (2)$$

where $\Delta G_{p0}$, $A$ and $B$ are constants and $X_\sigma$ is a zero-mean Gaussian random variable with a standard deviation of $\sigma$ that accounts for location variability. In each case, we determined the constants $\Delta G_{p0}$, $A$ and $B$ by applying regression analysis to the measured data. We estimated $\sigma$ by subtracting the quadratic regression line from the measured values of $\Delta G_p$ and fitting the results to a Gaussian distribution. The values of the parameters in each case are presented in Table I. In the C-to-H configuration, the maximum decrease in mean path gain due to human presence is relatively low (no more than a few dB), as one might expect given that the C-to-H paths are relatively unobstructed by human presence. In the C-to-A and H-to-A configurations, the maximum decrease in mean path gain is much greater (up to 10 dB), as one might expect given that the C-to-A and C-to-H paths are much more obstructed by passengers.

IV. EFFECT OF HUMAN PRESENCE ON TIME DISPERSION IN THE AIRCRAFT ENVIRONMENT

Our first step in characterizing time dispersion within the cabin was to convert the CFRs that we measured into CIRs. Following [27], we truncated the CFRs into band groups and zero-padded them to restore the original length and thus preserve the temporal resolution. If $f_{u,b}$ and $f_{l,b}$ are the upper and lower frequency boundaries of band group $b$, respectively, then the complex CFR for band group $b$ is given by

Fig. 3. Reduction in path gain with respect to distance for band group 1 for (a) ceiling-to-headrest, (b) ceiling-to-armrest, and (c) headrest-to-armrest configurations.
Following the approach described in [31], we applied a Kaiser window with $\beta = 7$ to the CFR in order to suppress dispersion of energy between delay bins. We then applied an inverse Fourier transform (IFT) directly to the complex baseband of the CFR to yield a CIR. We expressed the result in the form of a power delay profile (PDP),

$$H_b(f,d) = \begin{cases} H(f,d), & \text{if } f_{b,1} \leq f \leq f_{b,0}, \\ 0, & \text{otherwise.} \end{cases}$$

(3)

where $a_k$ are the amplitudes (expressed in units of power) of MPCs at different delays $\tau_k$.

Measured PDPs typical of the C-to-A configuration under empty, partially filled and completely filled conditions in the aircraft are given in Fig. 4. It is immediately apparent that the passenger cabin is rich with scatterers leading to a high density of MPCs in the PDPs. For LOS channels, we define the start of the PDP as the first MPC that arrives within 10 dB of, and 10 ns, before the peak MPC. For NLOS channels, we define the start of the PDP as the first MPC that arrives within 10 dB of, and 50 ns, before the peak MPC. We remove the propagation delay by setting the start time of the first arriving MPC to zero. These criteria are based upon those adopted by IEEE 802.15.4a and used in [32].

Using regression techniques, we estimated the decay time constants, $\tau_0$, i.e., the reciprocal of the slope of the scattered components in the PDPs, for various path types, degrees of occupancy and band groups. The values are given in Table II. As the density of occupancy increased from empty to half full, the decay rate of the scattered components in the PDP almost doubled. Further increases in the density of occupancy had little effect, however.
A. Delay Spread

The normalized first-order moment of a PDP gives the mean excess delay,
\[
\tau_{\text{mean}} = \frac{\sum_k P_{b,h}(\tau_k)\tau_k}{\sum_k P_{b,h}(\tau_k)},
\]
while the square root of the second central moment of a PDP gives the rms delay spread,
\[
\tau_{\text{rms}} = \sqrt{\frac{\sum_k P_{b,h}(\tau_k)\tau_k^2}{\sum_k P_{b,h}(\tau_k)}},
\]
where
\[
\sum_k P_{b,h}(\tau_k)\tau_k^2 = \sum_k P_{b,h}(\tau_k),
\]
Before we estimated the rms delay spread, we removed all MPCs with amplitudes that are more than 25 dB below the peak scattered component.

In Fig. 5, we show how rms delay spread depends upon the transmitter-receiver separation distance \(d\) for the three different path types (C-to-H, C-to-A, H-to-A) in band group 2. We model the distance dependence as
\[
\tau_{\text{rms}} = \tau_i + 10\gamma \log_{10} d + X_{\sigma_i},
\]
where \(\tau_i\) is the mean rms delay spread at \(d = 1\) m, \(\gamma\) is the distance exponent, and \(X_{\sigma_i}\) is a zero-mean Gaussian random variable with a standard deviation of \(\sigma_i\) that accounts for location variability. The values of these parameters for various path types, degrees of occupancy and both band groups are given in Table II. In all cases where the aircraft was empty, the rms delay spread increased rapidly with distance while increasing the density of occupancy to half-full generally caused \(\gamma\) to decrease by a factor of nearly four. Increasing the density of occupancy caused little further reduction in \(\gamma\). The decrease in \(\gamma\) is likely the result of energy in the scattered components being blocked or attenuated as the number of passengers aboard the aircraft increase.

The rms delay spread generally decreases with increasing center frequency, which is likely a consequence of the corresponding increase in attenuation and diffraction losses with frequency. Although increasing from band group 1 to 2 for the C-to-H path type causes the rms delay spread to drop by 15 - 20\%, doing so for the C-to-A and H-to-A path types results in little if any reduction. The mean excess delay and rms delay spread that we observed for the C-to-H and C-to-A cases for band group 2 as a function of threshold levels of 5, 10, 15 and 20 dB below the strongest MPC are summarized in Table III and Table IV, respectively. When assessing the performance of practical systems, it may be more realistic to apply a dynamic noise threshold that accounts for the
diminishing signal-to-noise ratio and the tendency of weaker multipath components to drop below the noise floor at greater ranges.

B. Number of Significant Paths

We define a significant path as a resolvable MPC that exceeds a given threshold of 5, 10, 15 and 20 dB below the strongest MPC. In Table III and Table IV, respectively, we have summarized, as a function of the threshold level, the number of significant paths that we observed for the C-to-H and C-to-A cases and band group 2 and the percentage of energy that each set captures. We found that the PDPs associated with band group 2 have between 10 and 30% fewer significant paths at a given threshold than those associated with band group 1. Moreover, we found that the PDPs measured in a full aircraft have between 40 and 45% fewer significant paths at a given threshold than those measured in an empty aircraft. These results are consistent with our observation that the duration of the PDP shrinks with increased occupancy and increased carrier frequency.

V. CONCLUSIONS

Because the passenger cabin has a confined volume and may be densely occupied, human presence affects radiowave propagation within a midsized airliner more than in conventional indoor environments such as homes, offices and industrial sites. In order to assess the effect of human presence in such environments, we collected channel frequency response data over the range 3.1 to 6.1 GHz within the passenger cabin of a Boeing 737-200 aircraft.

Despite the essentially square layout and short extent of the widebody scenario considered in [26] compared to the long and narrow extent of the case considered here, the results obtained within the two environments showed remarkable consistency. In particular, increasing occupancy tended to increase path loss by a few dB and lower delay spread by a few tens of nanoseconds. Otherwise, the much different geometry of the two scenarios precludes meaningful detailed comparison.

Our investigation of path gain over point-to-multipoint links within the narrowbody cabin with the transmitting antenna in the front of the cabin reveals that: (1) the decrease in path gain that occurs as occupancy increases reaches a maximum near the mid-point of the cabin, decreases thereafter, and is well-approximated by a quadratic function, (2) the maximum decrease in path gain becomes more acute as: (a) the transmitting antenna drops from the ceiling to the headrest level and (b) as the receiving antenna drops from the headrest to armrest, (3) in the ceiling-to-headrest configuration, the maximum decrease in the mean path gain due to human presence is only a few dB; in the ceiling-to-armrest or headrest-to-armrest cases, the maximum decrease in the mean path gain is up to 10 dB. Although our measurement data are insufficient to reveal the physical cause of the distance-dependent behaviour, numerical simulations similar to those described in [23] and [24] may provide additional insight and might be a useful next step.
Our investigation of time dispersion within the narrowbody cabin reveals that: (1) the channel impulse response always presents a dense single cluster regardless of the level of occupancy, (2) the rms delay spread generally increases with distance when the aircraft is empty but is essentially uniform when the aircraft is partially or fully occupied, (3) both the rms delay spread and the number of significant paths reduces by up to half as the level of occupancy increases from empty.
to half occupied, and (4) increasing the level of occupancy from half to full has little additional effect.

In summary, our results: (1) suggest that human presence substantially affects radiowave propagation within an aircraft passenger cabin and should be considered when characterizing the performance of in-cabin wireless systems and (2) will be helpful to those wishing to validate the results of software simulations of in-cabin wireless propagation. Further measurements in different aircraft will be required to assess how seatbacks that incorporate in-flight entertainment units contribute to excess shadowing on ceiling-to-armrest and headrest-to-armrest links.

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REFERENCES


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