Enabling Wireless Communication in Aircraft Using Multiple Antenna System

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Introduction

Sensor technology is advancing to provide the robust, miniaturized sensors needed for aircraft prognostics health management (PHM). Aircraft maintainers would like to add numerous pressure, temperature, vibration, fuel quantity, moisture/chemical sensors, but a major challenge of retrofitting old aircraft with them is how to collect the data. . Wireless data transfer in aircraft has been identified as a 'transformative' technology for aviation. The industry is pursuing wireless prospects, but so far all are limited by the extreme multipath channels in aircraft. Spread spectrum communication is extremely limited in aircraft because of the multipath channels[1], and [2] found problems with ultrawideband interfering with aircraft radios, even when operated at approved, 'safe' levels. This paper explores multiple input multiple output (MIMO) communication in aircraft because of its high capacity in rich multipath environments. In addition to the multipath that raises MIMO capacity, the aircraft channel is also rich in noise, interference, and channel correlation that decreases its capacity. This paper presents a complete channel model for MIMO in aircraft that includes the effects of noise, interference and channel correlation. The capacity obtained from this detailed system model is used as a metric for antenna selection and system evaluation.

MIMO Noise and Interference Model

MIMO systems have traditionally been analyzed from an information theory signal processing perspective [3] or a network level perspective [4]. Landon [5] has enhanced the network model to include the effects of efficiency, polarization agility, antenna directivity, spatial correlation, and normalization. This paper further expands this model to include the effects of Gaussian, EMI, thermal, impulsive and non-Gaussian noise and co-channel interference which are common in an aircraft system. The capacity for a MIMO system with L interferers and N_i impinging signals for N_t transmit and N_r receive antennas is given as:

$$C_E = E\{\log_2 | I + M_R E_{cdr} H_{DP} E_{cdt} Q (M_R E_{cdr} H_{DP} E_{cdt})^H R^{-1} \frac{1}{N} |\} \tag{1}$$

$$R = \sum_{j=1}^{L-1} M_R E_{cdr} H_{DP} E_{cdt,j} Q_j (M_R E_{cdr} H_{DP} E_{cdt,j})^H \tag{2}$$

$$N = \sigma^2 I + N_{mc,t} + N_{mc,r} + f_n(N) + N_{aircraft\_system} \tag{3}$$

where R is the co-channel interference and N is the noise in the system. N includes the Gaussian noise, thermal noise (at the transmitter and the receiver), non-Gaussian noise,

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and the aircraft system noise in that order. A detailed analysis of this can be found in [6]. This model forms the basis for analyzing MIMO system in aircraft.

Correlated and Uncorrelated Aircraft Channel Models

Another major factor in the MIMO capacity is the aircraft channel – its multipath component, loss and delay spread. This has been modeled using four different channel models: Clarke's, hyper-Rayleigh, IEEE TGn and an advanced ray-tracing model. The Clarke's model [5] works on the principle of waves impinging on the receiver and the angle of arrivals (AOAs) and angle of departures (AODs). It also includes the channel and the gain pattern correlation. Frolik's hyper-Rayleigh model [7] is based on the concept of two-waves with diffuse power (TWDP) and is used to predict the extreme multipath measured in vehicles. The IEEE TGn model [8] calculates a loss factor from the RMS delay spread profile. The ray-tracing model [9] is currently being adapted and expanded for aircraft channel modeling. This model will be discussed in detail at the conference.

The detailed MIMO model, including noise and channel models in (1) was used to analyze the effects of correlation, interference and noise on the system capacity. Figure 1 shows the capacity for a 2 X 2 MIMO system in a hyper-Rayleigh channel with and without interference. The transmitter and receiver are separated by a distance of 0.5 wavelengths and the antennas are self matched half wave dipoles. The IEEE TGn model (D) has about a 1-2 bit/sec/Hz lower capacity as compared to the hyper-Rayleigh model and Clarke's model when the transmitter and receiver are separated by about 3 m at 2.45 GHz (24.5 wavelengths). Figure 1 shows the capacity for a range of hyper-Raleigh K values obtained from SISO measurements performed in various aircraft locations and indoor and outdoor environments. For K values less than 0 dB the capacity remains almost the same for all channels. Figure 1 also shows how the number of transmitters increases the co-channel interference power and thus reduces the capacity. Designing a system with a specific minimum detectable power limits the number of transmitters and the spacing between them. Both environmental and gain pattern correlation affect the performance of the MIMO system.

Figure 2 shows MIMO capacity for both channel correlation and the gain pattern correlation using the capacity model obtained in (1) for a 2 X 2 MIMO system with dipole antennas at various spacing. The transmit power is 20 dB and Clarke's model is used for modeling the channel. The top curve "C full sim" of figure 2 uses (1) assuming AWGN noise and four interferers at -10 dB. It uses 30 impinging rays, and signals from the j^{th} transmitter are idealized by assigning a uniformly distributed phase φ_j without modeling a gain pattern or position. This achieves a higher capacity as compared to the channel correlation and the gain pattern correlation at smaller spacing and almost constant capacity at larger spacing. If we had ideal, uncoupled, omni-directional antennas, we could claim that the correlation matrix, R_s, is purely a function of the environment. Assuming that two such antennas receive Rayleigh-distributed power with uniformly distributed phases and arrival angles, we can use Jake's model and compute the channel correlation matrix using $R_{s,ij} = J_0(2\pi \, |d_i - d_j| / \lambda)$, where J_0 is the 0^{th}-order Bessel function and d_i represents the location or displacement of the i^{th} receive antenna. The "$R_s = J_0$" prediction curve deviates from the "C full sim" reference curve in important ways: (a) it dips at a greater antenna separation (0.4 λ), (b) it decays to zero, and (c) it dips away from its peak level both from 0.4 λ to 0.7 λ and again above 0.8 λ. This means that the model including only the correlation of the antennas is overly simplified and does not provide an accurate prediction which would require more than just correlation. Still, a major improvement is visible in the "Rs = R_{gp} x J" curve of figure 2, when R_s is modeled as consisting both of environmental correlation, J_0, and gain-pattern correlation, R_{gp}. The correlation matrices, J_0 and R_{gp}, are combined by element-wise matrix multiplication, $R_s = J_0 \times R_{gp}$. Computations based on either J_0 or R_{gp} alone predict excessive capacity losses at separations near 0.6 λ and above 0.8 λ. When combined as $R = J \times R_{gp}$, these artifacts disappear. We can also observe that for a system with interference and noise none of the simplified models give a perfect match to the "C full sim". In the absence of noise and interference the $R = J \times R_{gp}$ gave a better estimate to "C full sim". It was also observed that for a correlated system the signal starts dominating at an SNR of about 40 dB and the noise correlation can be ignored which was not the case when correlation was ignored.

Antenna Design Tradeoff

A global search algorithm using capacity as the metric was used for analyzing various dipoles, patches, polarization agile patches and PIFA antennas. The antennas have been optimized based on their size, separation, material, orientation, polarization agility, etc. The hyper-Rayleigh channel and the IEEE TGn channel have been compared. To reduce the processing time, we ran a local search algorithm before performing the global search. The capacity for various antenna combinations for an 8cm x 3cm sensor at 2.45 GHz is shown in figure 3. The polarization agile PIFAs and polarization agile patches perform better than the dipoles and normal patches. The normal patches have a size limitation which prevents us from using more than two patches on the device. The shrunken patch design (using higher dielectric material) allowed 6-8 patches to be placed on the sensor. The PIFA antennas also had a size advantage, because more PIFAs than patches can fit in the sensor area. From figure 3 we can also conclude that the polarization agile PIFAs have higher gains. These results are for a specific channel example and will vary with the type of channel and gain pattern correlation associated with the specific system.

Conclusion

This paper develops and applies a complete channel model for MIMO in aircraft that includes the effects of noise, interference and channel correlation. Clarke's, hyper-Rayleigh, IEEE TGn and an advanced ray-tracing model were used to predict the channel effects. Gaussian noise, thermal noise (at the transmitter and the receiver), non-Gaussian noise, and the aircraft system noise were included as well. It was observed that the IEEE TGn model (D) has about a 1-2 bit/sec/Hz lower capacity as compared to the hyper-Rayleigh model and Clarke's model when the transmitter and receiver are in the far field. The reduction in capacity from co-channel interference and correlation are quantified. Polarization agile PIFA and patch antennas were found to give higher capacity than the dipoles or regular patches for both correlated and un-correlated channels. This was due, in part, to the fact that more of these antennas could be placed on a small (8cm x 3cm) sensor surface.

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Figure 1: MIMO performance in hyper-Rayleigh and indoor channels with transmit power of 20 dB and 4 co-channel interferers with an INR of -10 dB each.

Figure 2: Capacity estimates based purely on a reference capacity and a de-correlation correction term, $\log_2|R_s|$ varied simplified models of R_s. Assuming that this correlation is defined by the gain pattern correlation, R_{gp}, or the environment correlation alone, J_0, is clearly a worse model than using the element-wise product of the two, $R_{gp} \times J_0$

Figure 3: Capacity for various antenna combinations. The polarization agile PIFAs and patches provide the best capacity for an aircraft sensor of 8cm x 3 cm dimension.