WIRELESS PROPAGATION MODELLING INSIDE A BUSINESS JET

Keith Chetcuti, *Member IEEE*, Carl J. Debono, *Senior Member IEEE*,
Reuben A. Farrugia, *Student Member IEEE*, Serge Bruillot

Abstract: **Wireless communication on-board aircraft has recently received increased attention as passengers are demanding for seamless office-like communication environments during their flight. Aircraft manufacturers are also interested in this technology to reduce cable complexity and provide new in-flight services. Various technologies are being considered for this purpose, such as IEEE802.11a/b/g. A radio propagation map is necessary to determine the received signal strengths inside the environment and can be obtained either through accurate modelling or through a measurement campaign. A simulation model is more attractive as it can be used to identify ideal antenna locations that maximize coverage at the design stage. Since the business jet market necessitates customized cabin configurations for each customer this will avoid costly measurement campaigns.**

This work presents a novel simulation model which has been used to characterize propagation characteristics inside a Dassault Aviation business jet. The developed package is based on geometric optics (GO) and adopts ray tracing techniques. Simulation results were compared with actual measurements performed on-board the aircraft with a good correlation between the two. This study takes into account only a static channel whereby all passengers are seated.

Index Terms: **Ray-Tracing, Aircraft Communication, Electric Field Measurement, wireless modelling.**

I. INTRODUCTION

Over recent years, the use of personal wireless communication devices has increased considerably. A good portfolio of wireless services is offered in various countries, with mobile television and wireless internet at the top of the list. Such services require installations of transmitters and access points with the choice of the installation sites mainly depending on the area to be covered. The radio coverage pattern can be predicted either through an expensive but accurate measurement campaign or through the development of an electromagnetic propagation simulation software that estimates the signal power levels at each point. The latter solution is more attractive since it reduces design and deployment times and can easily be adapted to investigate different environment setups.

While wireless connectivity is consolidated on the ground, this service is still missing inside aircrafts during flight. This problem has recently been addressed by the European Commission as it prepared the legal framework for wireless connectivity inside aircrafts [1].

In order to determine the feasibility of deploying wireless services inside aircraft, a radio coverage map is essential. Various indoor models have been developed in the past [2], however, these cannot be directly exported to aircraft since the geometry inside an airframe is particular. A typical office building is composed of low density clutter and medium-to-large-sized rooms. Hence, although multipath characteristics do exist, the foremost limiting factor is the number of dividing walls, which cause severe attenuation. The geometry of the airframe is different; the space is limited, it has high density clutter, and the attenuation introduced by the fuselage is not considered as the propagation of interest occurs only within the fuselage itself. High density clutter results in a high number of multipath signals between the transmitter and receiver positions. Therefore, the propagation inside a cabin is mainly due to reflection, transmission and scattering effects.

In order to develop a realistic model, Dassault Aviation has provided a computer model that defines the geometry of one of their business jets and a model for a typical interior setup. The University of Malta has developed a propagation model which was overlaid on this model such that the necessary simulations to evaluate the expected performance of the wireless technologies considered could be performed. Dassault Aviation has also performed a measurement campaign to validate the propagation model.

The work presented here forms part of the integrated project E-enabled Cabin and Associated Logistics for Improved Passenger Services and Operational Efficiency (E-Cab) which is currently being carried out under the EU Sixth Framework Programme Thematic Priority Aeronautics and Space of the European Commission. E-Cab is a process-oriented research and technology project that integrates various electronically enabled end-to-end logistic chains. The aim is to develop the envisaged paperless information management system of the future, for improved passenger comfort, and crew convenience as well as airline and airport efficiency. On-board solutions should provide control over the means by which the passengers can access their connectivity, with options ranging from mobile phones, PDAs, laptop computers to new IFE interfaces [3].

This paper is organized as follows. Section II gives an overview of the Ray-Tracing technique and goes through the implementation of the propagation simulation package while Section III highlights the measurement campaign performed by Dassault Aviation aboard the business jet. Section IV provides a comparison between the simulation results and the measurements performed. Finally a conclusion is drawn in Section V.

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II. THE RAY-TRACING TECHNIQUE

The technique of ray-tracing comes from optics and is based on emanating a series of rays of light from a source and tracing these rays as they reflect off objects in a given scene [2]. This is analogous to the rays emitted from a transmitting antenna and therefore can be used to model radio propagation.

Ray tracing (RT) techniques are widely used to simulate fading characteristics experienced by a mobile system when either the transmitter or receiver is moved around a given environment [2]. The result obtained after applying the technique represents the received signal power as foreseen by the receiver.

The two most popular RT techniques are the method of images, and the shoot and bounce technique, sometimes referred to as brute-force attack. Both techniques are based on the theory of Geometric Optics (GO). The method of images has the limitation that it requires an environment composed of smooth, infinite, or semi-infinite perfect electrically-conducting surfaces arranged in a limited set of canonical geometries [4]. This is not the case inside an aircraft and therefore the shoot and bounce technique had to be used.

In order to use GO, the environment must satisfy the high-frequency approximation, i.e. the dimensions of the environment must be much larger than the wavelength of the operating frequency. The wavelengths for IEEE 802.11b/g and IEEE 802.11a are 12.5cm and 5.7cm respectively. These dimensions are much smaller than the dimensions of the environment inside a business jet and hence RT can be used successfully to estimate the propagation model inside the aircraft.

The transmit antenna is treated as a point source and a number of rays are launched at a predetermined power from this point. The power level along the path is calculated at each point. When a ray impinges upon a surface, the ray is reflected, transmitted, diffracted or scattered and will subsequently continue to travel in the new direction until it impinges upon another surface. If the power level falls below a predetermined threshold the trace is stopped. The outcome of the RT is a three-dimensional map of the power levels inside the cabin.

By definition a ray is associated to a local plane wave which can be represented by [5]:

$$\nabla^2\psi + k^2 n^2 \psi = 0 \qquad (1)$$

where ψ is the waveform function which governs the scalar wave propagation, n is the refraction index of the media and k is the wave number. A solution for ψ can be given as [5]:

$$\psi = Ae^{-jkS} \qquad (2)$$

The function A determines the amplitude of the wave while the function S determines the direction and phase. Using (1) and (2) we conclude that if

$$\frac{\nabla^2 A}{Ak^2} << n^2 \qquad (3)$$

a solution which is independent of frequency can be obtained and hence GO can be used.

The RT algorithm implemented is based on the procedure devised by [6]. Fig. 1 summarizes the main points of the flow of the developed simulation package.

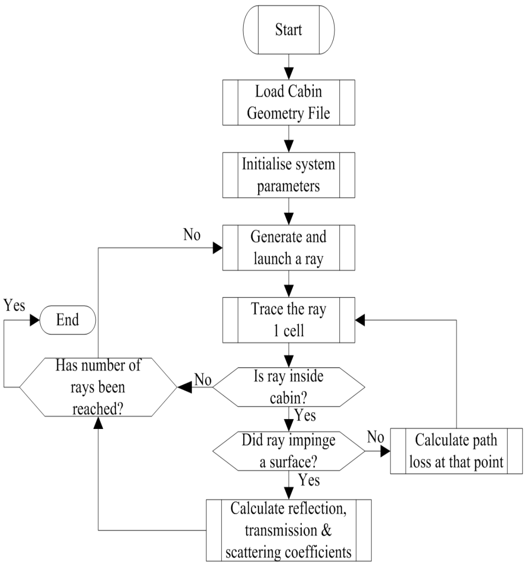

Fig. 1 – Ray-Tracing simulation flowchart

The geometry file used by the simulator represents a typical setup of a furnished Falcon business jet. The geometry file described the aircraft by a matrix of 514 x 114 x 114 cells with each cell containing an integer value; a cell with a value of 0 represents free space, while a cell containing a positive number refers to the material present in that position. Another file described the association between the material number, the material itself and the electric/magnetic characteristics of that same material. **Table 1** summarizes the main parameters for the materials used on-board the Falcon business jet used during the simulations.

Table 1 – Electric characteristics of materials used inside the cabin

Material	Electric Conductivity	Relative Permittivity
Aluminium	4E7	Inf
Leather	1E-2	1
Wood	1E-2	3

Taking into account the relatively small dimensions of the cabin space, a single access point scenario was considered, with the transmitting antenna located more or less in the centre of the cabin. The signal strength propagation map was determined by launching a number of rays (around 200000) from the transmitter having an equivalent isotropically radiated power (EIRP) of around 30dBm. The antenna was assumed to be omni-directional. At any particular cell inside the cabin, the signal strength was determined by summing the power levels of all the rays passing through that point. Each ray or component can add constructively or destructively. Therefore, the received signal is a distorted version of the transmitted signal.

The starting direction of each ray is determined using Monte Carlo techniques where two random numbers in the range 0 to 2π are generated representing the angles in spherical coordinates. Each generated ray is traced one cell size at a time. At each cell position, the program assesses whether the ray is still inside the aircraft. If it is found outside the aircraft, then the trace ends there and a new ray is generated and traced. If the ray is inside the aircraft, the propagation loss is calculated. The calculated power level is then compared to the predetermined threshold of -120dBm and if found above this value a check is performed to test whether the ray has encountered a surface. The -120dBm level is well below the minimum detectable signal for Wi-Fi, but due to the presence of multipath effects some margin was left to allow for the eventuality that the summed power level could be above the -100dBm limit defined in the standard [7]. The power strength at the receiver affects the signal-to-noise ratio thus limiting the maximum useable data rate for error free communication.

When a ray inside the cabin impinges on a surface it experiences reflection, refraction and diffraction. In order to simplify the model, obstacles were assumed to be made up of homogeneous material; hence diffraction effects were not considered. This implies that each surface can be described by its dielectric constant, magnetic permittivity and conductivity. If two media having different conductivity and permittivity are assumed to be separated by an infinite plane, equations relating the reflected electromagnetic wave to the incident wave as well as the properties of the media can be obtained [5].

Polarization effects are taken into account by splitting the electric field into a parallel component and a perpendicular component to the incident surface. The reflected and refracted rays can be estimated by taking the product of each component with the corresponding Fresnel's coefficient [8].

These Fresnel reflection coefficients account only for reflections from a smooth surface. The Rayleigh criterion [9] is used as a roughness test. The critical height (h_c), in metres, of surface protuberances is given by:

$$h_c = \frac{\lambda}{8\cos\theta_i} \tag{4}$$

where λ is the wavelength of the signal in metres, while θ_i is the angle of incidence of the ray in radians.

A surface is considered as rough when the protuberances exceed h_c. In this case the incident's ray energy will be diffused in angles other than the directed angle of reflection, reducing the energy of the main reflected ray [10]. For rough surfaces the reflection coefficients ($\Gamma_\perp$ and $\Gamma_\parallel$) are modified by a scattering loss factor ρ_s [10] and become:

$$\left(\Gamma_\perp\right)_{rough} = \rho_s \left(\Gamma_\perp\right)_{smooth} \tag{5}$$

$$\left(\Gamma_\parallel\right)_{rough} = \rho_s \left(\Gamma_\parallel\right)_{smooth} \tag{6}$$

The power received by the path of the k^{th} ray arriving at a single point is given by [5]:

$$P_k = P_T \left(\frac{\lambda}{4\pi r}\right)^2 G_T G_R \prod_i \rho_i \prod_j \tau_j \tag{7}$$

where P_T is the transmit power in Watts, G_T and G_R are the transmitter and receiver gains respectively, λ is the wavelength in meters, r is the total unfolded path length in meters, and ρ_i and τ_i are the reflection and refraction coefficients respectively.

Two simulation runs were executed, with the first to determine the propagation map at 2.4GHz and the other to obtain the map at 5.25GHz. The resulting radio coverage map for the IEEE802.11a scenario is shown in Fig.2.

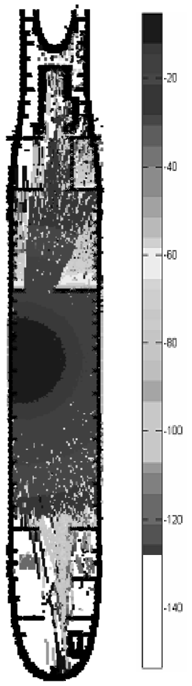

Fig. 2 – Radio coverage map at 5.25GHz

The resulting radio coverage maps for both frequency bands showed that within the cabin the signal levels were consistently above -50dBm, thus allowing for a fade margin of 50dB.

III. MEASUREMENT CAMPAIGN

Dassault Aviation carried out the measurement campaign on-board a Falcon business jet. This short to medium haul business jet has a maximum cabin height of 1.88m, a maximum cabin width of 2.34m, and a cabin length of 7.98m. This business jet is usually personalized to the client's requirements; with different interior designs, furniture layout and seating capacity. The personalization of the cabin affects the resulting propagation map as the different materials used for the interiors have different electric characteristics. Also the position and density of furniture and seats will alter the reflections, scattering effects and visibility between transmitter and receiver locations and will eventually change the multipath distribution within the cabin. Apart from different signal strength levels, the change in the layout also affects the time dispersion parameters which will reflect in the performance of the deployed wireless system.

A measurement campaign was carried out inside the cabin of the Falcon business jet in April 2008 in Paris. The measurements were performed on an aircraft having its interior layout similar to the provided model.

A frequency synthesizer transmitting a continuous signal was used as a transmitter, while a spectrum analyzer was used to record the received signal strength at different locations. A noise calibration procedure was performed on the spectrum analyzer, where it was verified that the spectrum analyser's noise floor was lower than the minimum detectable signal to be measured over all the frequencies of interest.

All data recording was carried out using an automatic acquisition procedure. No personnel was on board the jet during the acquisition. This ensured that the channel remained time-invariant for the duration of acquisition, as any perturbation would have affected the channel environment. A change in the channel could result in fast fading scenarios in which, depending on the frequency and on the number of people shadowing the signal, can reach depth of fades of 30dB [11]. The recorded value was the average of 5 readings. The recordings were taken at some time intervals to ensure that the measurement campaign was not influenced by external effects.

It is not feasible to perform the measurements for every single location within the cabin and aircraft itself. Therefore, five main locations were chosen and measurements were performed at those locations only. The choice of the locations ensured that the effect of doors, furniture, dividing walls and the length of the corridor were taken into account, thus providing a good benchmark. Fig. 3 shows a floor plan of the Falcon business jet highlighting the transmitter and receiver locations chosen for these measurements. The transmitter was located above window 8 on the right side of the cabin, which is the same position used in the simulation. Two of the receiver's locations, i.e. above windows 6 and 2 on the right side of the cabin, were within the cabin itself. The other three chosen locations: on the right side of the cockpit area, inside the back rest rooms and in the luggage bay at the back of the cabin, were obscured locations, hence there was no direct line-of-sight between the transmitter and receiver locations. Attenuation between transmitter and receiver locations depends upon their relative distances, losses due to absorption phenomena such as seats or carpets, and the attenuation due to doors or furniture.

The measurements were carried out in both the 2.4GHz and 5.25GHz band, such that the simulation results could be verified and model tuning applied if necessary.

In order to have a normalised value, the transfer function was computed by subtracting the gain of the antennas and the measured received strength from the transmitted power level. **Table 2** provides a summary of the results obtained from the measuring campaign inside the furnished cabin.

Table 2 – Measurement results performed on board the Falcon business jet

ZONE	**FREQUENCY**	
	2400MHz	**5200MHz**
Window 8 - Cockpit (dB)	37.6	37.89
Window 8 - Window 2 (dB)	26.53	28.00
Window 8 - Window 6 (dB)	22.29	31.00
Window 8 - Toilet (dB)	34.85	48.00
Window 8 - Luggage bay (dB)	54.65	56.97

The free space path loss (FSPL) is given by:

$$FSPL(dB) = 10\log\left(\left(\frac{4\pi d}{\lambda}\right)^2\right) \tag{8}$$

where d is the distance between transmitter and receiver and λ is the wavelength of the signal.

Equation (8) indicates a 6dB additional loss for every double distance covered by the ray at the frequency of operation. Considering the Window 8 to Window 2 scenario, if the propagation loss followed the free-space model, then the difference between the loss at 5200MHz and the loss at 2400MHz should have been of about 7dB. However, due to multipath effects, this is quite different from the measured difference of 1.5dB. Studies of the indoor channel [12] showed that for indoor propagation the drop-off rate of power level with distance is different than 2. An inverse exponent relationship with the distance is given by [12]:

$$P(dB) = P_0(dB) - (10n) * \log(d) \qquad (9)$$

where P_0 is the received power at a distance of 1m, d is the distance between transmitter and receiver and n is an environment dependent variable. For typical indoor buildings n is greater than 2 (2 represents FSPL) except for the corridor environment where n is smaller than 2 (in the range of 1.4 to 1.9). The cabin geometry is similar to the corridor environment; both are long and relatively narrow, a scenario similar to propagation within waveguides.

IV. COMPARISON OF RESULTS

The radio coverage map models the signal level at each cell location inside the aircraft. An algorithm was developed to extract the signal level and eventually the transfer function for the chosen locations. Table 3 summarizes the comparison between the measured values and the simulation results for the five chosen locations.

The values given by the simulation are the average values in the area being considered as they are more representative of the signal strengths within the area. The exact measured values exist in the model within the areas considered but are only at specific points which are frequency dependent.

A comparison of the measurement and simulation results for the receiver locations inside the cabin shows that the differences are less than 3.4dB, while the difference in results inside the cockpit has reached 4.4dB. The latter discrepancy is due to the fact that most rays would have reached the threshold in the model and would have been terminated. This means that the number of rays present in the cockpit is low reducing the accuracy of the model in this area. Such variances between the model and the measurements are within acceptable limits considering that electronic devices have different front-end sensitivity levels resulting in different received signal strengths. Therefore, the results are close enough to conclude that the simulation package developed is a true representation of all the main propagation phenomena occurring inside the aircraft.

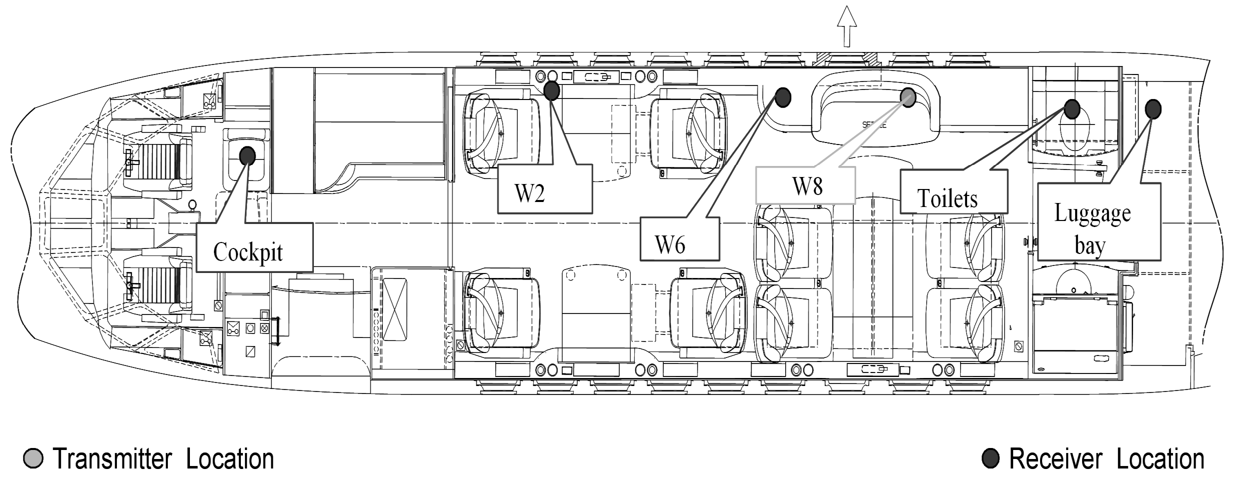

Fig. 3 –Business Jet Layout

Table 3 – Comparison between measurement and simulated results

ZONE	FREQUENCY					
	2.4GHz			5.25GHz		
	Measurement	**Simulation**	**Difference**	**Measurement**	**Simulation**	**Difference**
Window 8 - Cockpit (dB)	37.60	33.19	4.44	37.89	40.53	-2.64
Window 8 - Window 2 (dB)	26.53	28.35	-1.82	28.00	28.92	-0.92
Window 8 - Window 6 (dB)	22.29	22.57	-0.28	31.00	27.61	3.39
Window 8 – Rest rooms (dB)	34.85	38.25	-3.40	48.00	46.63	1.37
Window 8 - Luggage bay (dB)	54.65	53.45	1.20	56.97	60.02	-3.05

V. CONCLUSION

The paper presented the implementation and validation of a ray-tracing algorithm that simulates the propagation characteristics inside a Falcon business jet. The simulation results obtained were compared to the measurement results obtained from a measuring campaign conducted on a Falcon business jet. The differences reported are within a maximum variance of 4.5dB, clearly demonstrating the validity of the model developed.

Future work will seek to implement the human shadowing effect and the influence of passenger mobility on the received signal strength.

ACKNOWLEDGMENTS

This work forms a small part of the project E-Cab which is financially supported under the European Union 6th Framework Programme (FP6). The E-Cab consortium is made up of 30 partners from 13 countries across Europe. The authors are solely responsible for the contents of the paper which does not represent the opinion of the European Commission.

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BIOGRAPHY

Keith Chetcuti received his B.Eng.(Hons.) degree in Electrical Engineering from the University of Malta, Malta, in 2003. Between 2003 and 2008 he was employed as a Research Engineer within the R&D Department of Elber S.r.l. He was mainly responsible for the digital modulators and demodulators put on the market by the company. Since March 2008, he has been employed as a Research Engineer with the Department of Communications and Computer Engineering at the University of Malta, Malta. He is currently reading for a Ph.D. degree in Communications Engineering at the University of Malta, Malta. His research interests are modelling of communication systems, modelling and performance evaluation of multimedia transmission systems, and multimedia processing.

Carl James Debono received his B.Eng.(Hons.) degree in Electrical Engineering from the University of Malta, Malta, in 1997 and a Ph.D. degree in Electronics and Computer Engineering from the University of Pavia, Italy, in 2000. Between 1997 and 2001 he was employed as a Research Engineer in the area of Integrated Circuit Design with the Department of Microelectronics at the University of Malta. In 2000 he was also engaged as a Research Associate with Texas A&M University, Texas. In 2001 he was appointed Lecturer with the Department of Communications and Computer Engineering at the University of Malta and is now a Senior Lecturer. His research interests are in RF and microwave systems and applications, resilient multimedia transmission, and modelling of communication systems.

Reuben A. Farrugia received his first degree in Electrical Engineering from the University of Malta, Malta, in 2004 and is currently reading for a Ph.D. degree in Communications Engineering at the University of Malta. He has been employed as a Research Engineer with the Department of Communications and Computer Engineering at the University of Malta since 2004. In January 2008 he was appointed Assistant Lecturer with the same department. His research interests are resilient multimedia communication, error correction coding and modelling of wireless communication systems.

Serge Bruillot graduated from the French school ENSEM from where he received in 1983 an engineering degree in electronics. He also has a specialization degree in telecommunication received in 1984 at the French school ENST. He joined Dassault Aviation company in 1984. He is currently employed in the Research and Development directorate in charge of the development of mission and vehicle management systems. As senior expert in physical architecture for on-board information system, including networking and data processing, he has been involved in major military and commercial programs (such as Rafale fighter, Neuron UCAV or Falcon family business jets). He is also the technical point of contact for pre-program studies such as European Framework Program studies.