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Electromagnetic Interference Simulation of a Cell Phone in an Aircraft System Using Domain Decomposition Method

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***Abstract*— Laboratorial experiments to investigate the behavior of numerous embedded avionics installations to onboard electromagnetic interference (EMI) are extremely complex and costly. Even if all electronic subsystems in an aircraft are validated under the electromagnetic compatibility (EMC) standards, the integration between them can create numerous points of potential hazards that affects the total electromagnetic behavior of the entire system, hazards that can be detected only when the first complete aircraft prototype is available, and whose resolution at this phase of the development process is very time consuming and expensive. Numerical techniques such as the finite element method (FEM) present a reliable solution to analyze EMI responses enabling additional analysis of any portable electronic device without impact the in-service aircraft schedules. FEM technique requires a considerable computational resource to solve large field problems, and in order to create a reliable model of an aircraft interior, a new procedure called domain decomposition method (DDM) was used taking advantage of parallel processing. In order to address the concern for cellular phone EMI to an aircraft monopole antenna and a wiring harness, a full numerical methodology was developed including actual diagnostic signals. The study presents complete results regarding EMI and communication channel analysis addressing the potential hazards of a cell phone in an aircraft's electronic system.**

Keywords- Domain Decomposition Method (DDM), Electromagnetic coupling, Electromagnetic Interference (EMI), Electromagnetic Compatibility (EMC), Finite Element Method (FEM), Electromagnetic radiation effects.

I. INTRODUCTION

Cell phones are commonly used today and are a particular example of a Passenger Electronic Device (PED) that pose problems for aircraft electronic systems due to the relatively high power of their RF emissions compared to other PEDs (such as a MP3 player or laptop computer). The majority of the electronic equipments which integrate the avionics system are located under the floor of the passenger compartment, which might not provide the necessary shielding to preserve the signal integrity (SI) of the electronic system. Numerous parts of the aircraft structure also interact with the electromagnetic environment, like the aluminum airframe, which can act as a shield, a resonant cavity, or a phased array, and can drastically affect the sensitivities of the avionics. Particular seats in the passenger cabin of an aircraft are very close to the avionics systems or communication channels. Cell phones and other PEDs are expected to cause interference when they are used by people sitting in those seats. The radiation from the devices can couple to the avionics system through the antennas, the wiring, or directly into the receivers. The following anomalies in avionics systems were observed at incident electric fields of 30 V/m (a level that can be generated by a cell phone operating at maximum power and located 30cm from the victim equipment or its wiring harness [1-4]): Compass froze or overshot actual magnetic bearing; Instability of analogue and digital indicators; Digital VOR (VHF Omnidirectional Ranging) navigation bearing display errors up to 5 degrees; VOR navigation To/From indicator reversal; VOR and ILS (Instrument Landing System, an aeronautical navigation aid using the VHF spectrum) course deviation indicator errors; Reduced sensitivity of the ILS Localizer receiver and background noise on audio outputs. Figure 1 display the electromagnetic spectrum used by the common avionics systems today. Most of the aircrafts flying today were projected when cell phones and PEDs were not as common as they are today, so EMI is a concerning if the devices are allowed to be used during the flights. In order to assist aerospace and avionics engineers to create robust designs on new projects, and also analyze the EMI effects of

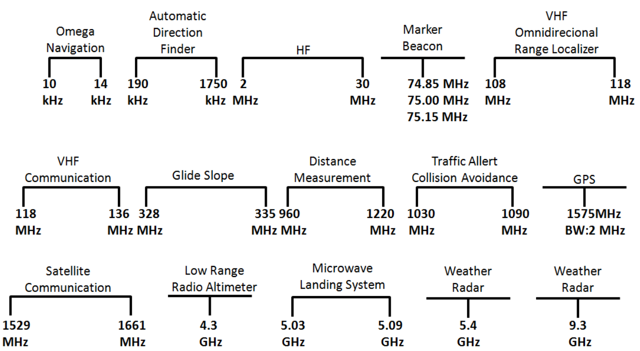

Fig. 1. Frequency bands used by aircraft communication and navigation systems. The electromagnetic spectrum goes from a few kilohertz up to several gigahertz. Radiation from portable electronic devices can occur almost anywhere in the spectrum below 2.4GHz

new PEDs on current aircrafts, we have developed a full numerical methodology using full wave methods and a circuit simulator. The wide application of finite element method does not restrict any geometry or material; nevertheless, for any radiation problem, an air box must be modeled around the radiation structure to enable the calculation of the electric fields and radiation patterns. The dimensions of this air box might sometimes increase the size of the model being evaluated, especially when considering the size of an aircraft and the complexity of the geometries. If the model is comprised of a large amount of elements the solving algorithm process can be very demanding and sometimes even impossible to implement [5]. To overcome this situation, the domain decomposition method was used. DDM is an attractive technique that split the entire domain into sub domains, which are in turn solved in different computers connected through a high speed network.

II. Numerical Methodology

A. Finite Element Model

In order to increase the accuracy of our analysis, details of the cell phone radiation source were modeled and a human head was placed inside of the aircraft. Figure 2a shows the details of the cell phone including all the parts that are usually omitted in a FEM analysis due to excessive computer effort required to solve the mode. Nevertheless, these details might affect the electric field distribution near this region. Figure 2b shows the entire model, where a monopole antenna is placed outside of the aircraft, a cell phone is positioned near the human head both placed at a variable distance d from the aircraft window. A wiring harness is first modeled as a victim in this analysis, and it is placed near the aircraft wall distant 80cm below the cell phone.

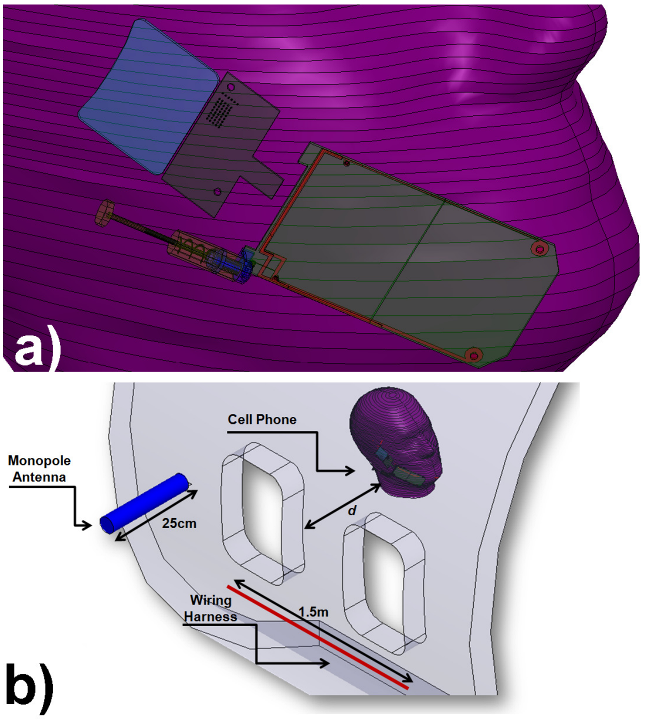

Fig. 2a. Cell phone modeled as a radiation source. The details of antennas, keyboard, glass and plastic case are shown. Fig. 2b. Detail of the entire model showing the monopole antenna, the cell phone and human head, the wiring harness and the aircraft external wall.

B. Domain Decomposition Method

DDM has emerged as a powerful and attractive technique due to its inherent parallelism which enables the use of distributed memory. DDM is based on a divide-and-conquer philosophy where instead of solving a large and complex problem directly; the original problem as defined by the mesh is partitioned into smaller and easier parts to solve sub meshes or sub-domains. In this approach it is critical to enforce continuity of electromagnetic fields at the interfaces between adjacent sub-domains through some suitable boundary conditions [5-11]. To address the basic idea of DDM, we solve a FEM matrix by decomposing the original problem into two domains:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \tag{1}$$

Where A_{ii}, x_i and b_i, i=1,2 are the matrix system, the solution vector and the right hand solution for domain i, respectively; and A_{12}, A_{21} are the coupling matrices between the two domains. To solve in parallel sub-domain problems, one popular domain decomposition algorithm is of Jacobi type:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} + \begin{bmatrix} 0 & A_{12} \\ A_{21} & 0 \end{bmatrix} \tag{2}$$

Using (2) and applying iteration, (1) can be solved as:

$$\begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}^{\eta} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} - \begin{bmatrix} 0 & A_{12} \\ A_{21} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}^{\eta-1} \tag{3}$$

Through some simple algebra, equation (3) leads to two coupled systems:

$$A_{11}x_1^{(\eta)} = b_1 - A_{12}x_2^{(\eta-1)} \qquad A_{22}x_2^{(\eta)} = b_2 - A_{21}x_1^{(\eta-1)} \tag{4}$$

By setting $x_1(0)=x_2(0)=0$, the initial guess $x_i(1)=A_{ii}^{-1}b_i$ is obtained from (4), and then the final solution can be found through iterative refinement by the coupling matrices A_{12} and A_{21}. The approach (3) is known as a stationary Jacobi solution of (1) which unfortunately converges rather slowly [5]. A more advanced approach is to apply a preconditioning on the matrix A, leading to equation 5. A preconditioner P of the matrix A is a matrix such that P^{-1} has a smaller condition number than matrix A. Preconditioners are useful when using an iterative method to solve a large, sparse linear system.

$$\begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}^{-1} \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}^{-1} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \quad (5)$$

This advanced Domain Decomposition Method technique maximizes the use of all hardware resources because it can also balance the memory for each sub-domain, so every computer connected to the network can be used. We have performed the analysis with 4 sub-domains using a maximum of 7.65 GB of RAM memory per sub-domain.

C. *Electromagnetic Analysis*

The cell phone is first excited with a sinusoidal source of 250mW and frequency of 850MHz, which is the central frequency for the first band of Global System for Mobile Communication (GSM) frequency. The external monopole antenna is assumed to be terminated (50 Ω impedance match network) since the source excitation does not change the scattering (*S* parameter) matrix. Ansoft HFSS was used to solve the FEM matrix for all elements of our model. After the matrix solution, one can instantaneously change the phase and magnitude of the source signal leading to a very fast process to calculate the electromagnetic field anywhere in the model. The cross sectional electric field distribution is shown in figure 3. It is clearly visible that the radiation generated by the cell phone leaks through the aircraft window and interferes with the external monopole antenna. The inset graphic shows the cell phone radiation pattern, where it is possible to observe that the human head also affects the radiation directivity.

In order to investigate the coupling between the cell phone and the external monopole antenna, a parametric analysis was performed and the distance *d* which denotes the distance between the cell phone and the aircraft wall was varied from 0mm to 130mm. Parametric analysis can also take advantage of parallel computing and each variation of *d* can be solved in separated computers in order to reduce the

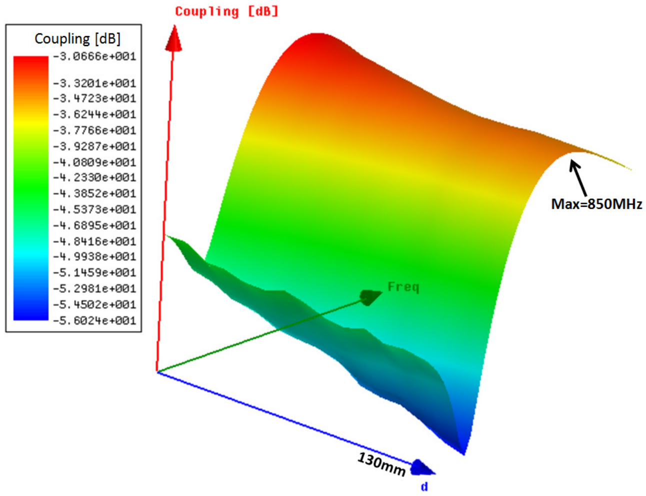

Fig. 4. Response surface plot showing the coupling in dB between the monopole antenna and the cell phone as a function of the distance *d* and the frequency. Maximum calculated frequency is 1GHz.

analysis time. A frequency sweep analysis was also used to evaluate the antenna coupling for a bandwidth of 1GHz. As expected, figure 4 shows that the coupling between both antennas ($S_{cellphone,monopole}$) linearly decreases (with a ratio of 1.4dB/mm approximately) as the cell phone is placed away from the external wall. The cell phone antenna was designed to resonate at 850MHz (minimum reflection coefficient $S_{cellphone,cellphone}$ @850MHz), so in this frequency the cell phone radiates its maximum power and the coupling achieves its maximum value.

D. *Integrating Circuit into Electromagnetic Analysis*

Ansoft Designer was used to create the electronic schematic responsible for supplying all the signals to the electromagnetic model and to evaluate the entire system in terms of signal integrity (SI). Figure 5 shows the complete schematic, detailing the electromagnetic model comprised of six ports (wiring harness I/O, cell phone input and three reference grounds) , a 300MHz clock source with 5V of magnitude to represent the signal being transmitted by the

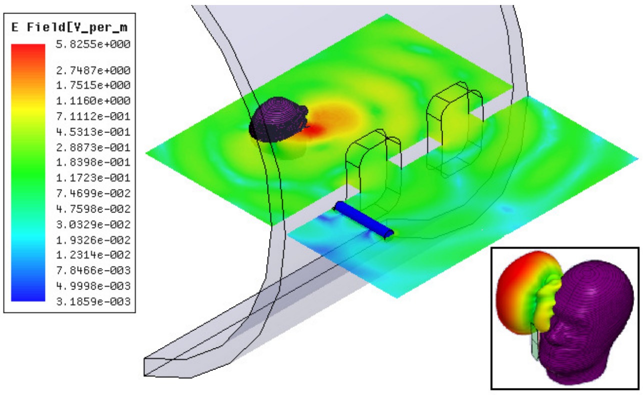

Fig. 3. Plot of the electric field distribution due to cell phone radiation. The inset plot shows the cell phone radiation pattern.

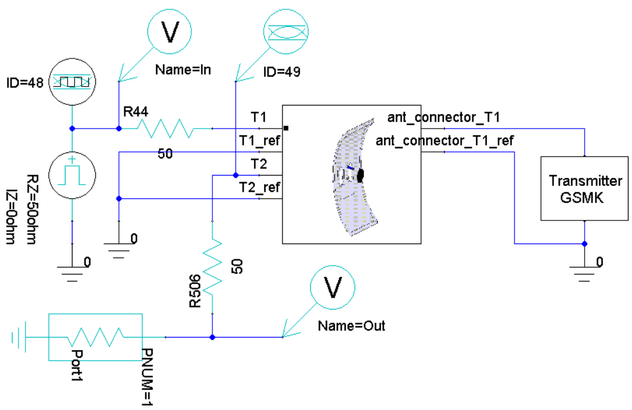

Fig. 5. Electrical schematic used to create excitation signal and evaluate the electromagnetic model through voltage probes and signal integrity tools.

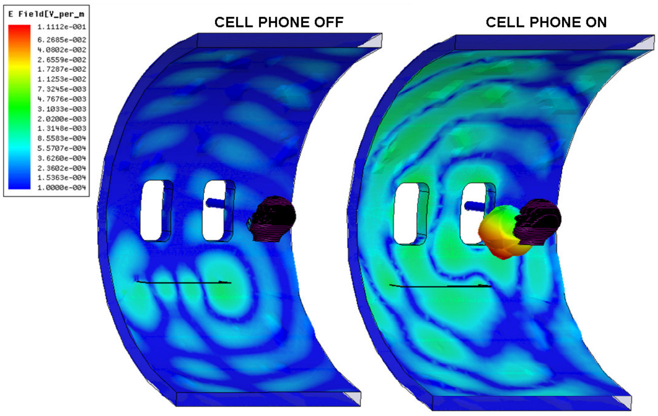

Fig. 6. Electric field distribution on the aircraft wall due to the wiring harness excitation and the cell phone radiation by actual signals.

wiring harness and an eye source and probe to simulate a statistical SI analysis. GSM technology uses Gaussian-filtered Minimum-Shift Keying (GMSK) modulation, so a complete transmitter was developed and inserted into the schematic as a macro component to feed the cell phone. All the signal information is then inserted into the electromagnetic model, so the actual far field patterns and electric field distribution can be calculated. The interference caused by the cell phone radiation into the wiring harness signal can also be evaluated in terms of signal integrity.

As observed in the left plot of figure 6, when the cell phone is turned off, the electric field distribution on the wall is due to the clock signal being transmitted in the wiring harness. The source of radiation is concentrated in the terminals of the wiring harness connected to the ground (both ends). When the cellular is turned on, the wiring harness electric field is somewhat overlapped by the cell phone radiation. The electric field plot on the aircraft wall now follows the cell phone radiation pattern behavior (right plot in figure 6). The electromagnetic interference caused by the cell phone radiation in the wiring harness is analyzed in terms of scattering parameter (*S* parameters) [12-19]. The magnitude and phase of the signals in the electromagnetic model are dynamically linked to the circuit simulator and the interference of the cell phone radiation in the wiring harness signal can be calculated on the fly. In the case of the circuit simulator generates a frequency carrier or harmonic that was not previously calculated by the electromagnetic model, the circuit simulator invokes the electromagnetic simulator and the *S* parameters are generated automatically for the missing frequencies.

Figure 7 shows the 300MHz clock signal with a magnitude of 5V measured at the wiring harness' input and output terminals. By comparing both graphics it is possible to observe the attenuation on the clock level due to the wiring harness insertion loss and the 20ns transitory time required to achieve a steady state. The EMI in the clock signal due to the cell phone radiation changes the amplitude and frequency content of the original signal. These interferences can lead to an interpretation error at the receiver, where the logic level of the digital bits can be shifted. Statistical signal integrity tools are employed in order to investigate the integrity of the wiring harness as a communication channel. Eye diagrams are useful tools to help answer one of the fundamental questions of signal integrity: if we transmit a

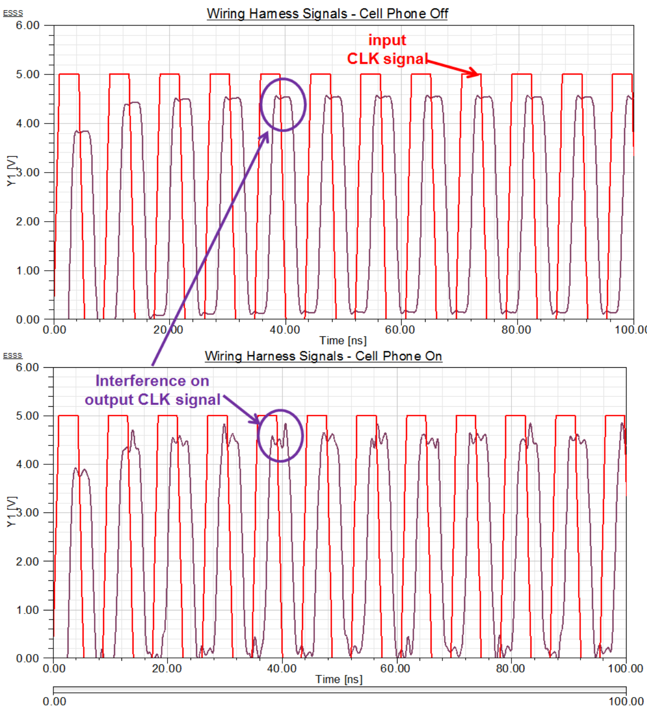

Fig. 7. Voltage signal measured on both ends of the wiring harness for two cases: cell phone on and off. Red and purple lines represent the input and output clock respectively.

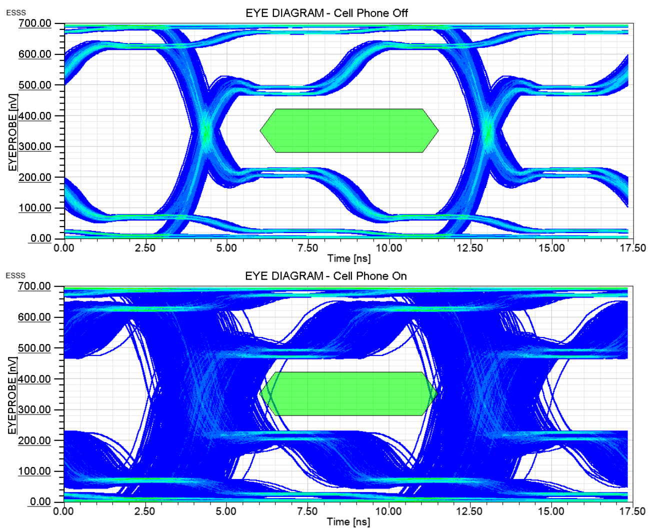

Fig. 8. Eye diagram analysis of the signal being transmitted by the wiring harness for the cases of cell phone on and off.

sequence of ones and zeros into a channel, separated in time by a specified unit interval (UI), what are the chances of correctly detecting the sequence of bits at the far ends? In a traditional eye diagram, copies of the waveform generated at the far end of the channel by transient analysis are overlaid at a spacing of one unit interval. For certain types of channels, the resultant diagram resembles an eye, hence the name. The required width of the eye depends on the bit error rate (BER) due to timing variations such as jitter and variations in setup and hold times. The required height of the eye depends on the noise margin. Slicing through the eye at the midpoint of the amplitude displays the BER as a “bathtub” curve. Comparison between the eye diagrams (for the two cases: cell phone on and off) shows the principal cause of bit errors, the intersymbol interference (ISI). When the response of the channel to a transition takes more than a UI to settle, the effects of previous bits affect the waveform for the current bit. The green mask displayed in the middle of the eye in figure 8 is a mask that guarantees that there is no ISI in the channel. When the cell phone is on, it is possible to observe a closed eye signals overlapping the mask, indicating that ISI will occur in this case of UI equal to 3.33ns. When the cell phone is off the simulated BER is 1.10^{-10}, and when the cell phone is turned on, the BER drops to 3.10^{-8} indicating that the cell phone radiation increases the bit detection error probability by 2 decimal orders.

III. CONCLUSION

We have reported a detailed investigation of the electromagnetic interference that cell phones can address to avionics communication and navigation systems. It was shown a methodology that combines the finite element method, domain decomposition technique and numerical computational and statistic tools that enables design engineers to proactively reduce EMI issues on aircraft systems, and thus increasing the safety of flights. A dynamic link between electromagnetic and circuit simulation allows a complete analysis, with actual signals that are used by avionics systems, leading to very accurate results, no matter the complexity and size of the geometries being evaluated. The cell phone electromagnetic coupling in a monopole antenna placed outside the aircraft was investigated. It was found that the distance between the cell phone and the aircraft wall affects the coupling between antennas, which achieve its maximum value at the cell phone frequency of 850MHz. The interference of the cell phone in a wiring harness carrying a digital signal was also evaluated. The changes on the magnitude and frequency content of the signal were graphically shown and the wiring harness is analyzed as a communication channel. Through the use of statistical tools, it is possible to verify that the cell phone radiation reduces the signal integrity, leading to an increasing in the bit detection error probability by 2 decimal orders. The numerical methodology presented herein can be employed to predict any intrasystem interactions, optimizing test time, reducing costs and above all increasing the safety of flights.

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