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Aircraft PLC Channels Characterization: Initial Discussion

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***Abstract*— This paper presents a characterization of aircraft power line channels limited in the frequency band 1.7-100 MHz. Analyses of frequency response magnitude, additive noise, and channel capacity are described. Two measurement configurations of power lines are considered in order to better understand the aircraft electric power network channel. The harness analyzed belongs to a flight test prototype aircraft Embraer Legacy 450 equipped to perform flight tests. Results show that for a transmission power of -50 dBm/Hz, the upper and lower channel capacities are around 1000 and 900 Mbps, respectively.**

***Keywords*— Channel characterization, sounding, power line communication, aircraft.**

I. INTRODUCTION

Power line communication (PLC) systems and its applications have been widely studied by academic and business communities with the main focus on in-home (residential and commercial buildings). However, recently, the PLC technology has began to be investigated in the context of transportation systems such as: ships, trains, vehicles, spacecraft, and aircraft [1].

Regarding aircrafts, we point out that approximately 15% of its weight is due to cables dedicated to condition monitoring and control, in-flight entertainment and cabin management [2]. Furthermore, there is a tendency of "more electric" aircraft since the pneumatic source energy will be replaced by the electrical ones [3]. Consequently, an increase of complexity, weight and volume of electrical system is expected [4]. In this scenario, the use of wire harness for both data communication and power delivery comes up as an interesting solution. In fact, the use of PLC technology has a great potential of cost-cutting in aircraft applications [4].

Nevertheless, as well known, electric power grids were not design for data communication. They are a harsh medium, in which the PLC signal suffers significant attenuation with distance and frequency increase, impedance mismatching, and high power impulsive noise presence. Also, topology diversity and unpredictable connection/disconnection of devices becomes electric power grids hard to characterize. For this reason, there are several contributions focused on the measurement and the characterization of in-home and outdoor electric power grids. However, the discussed results do not reflect the reality of wire harness in aircraft once the geometrical characteristics and tree-shaped topologies of cable bundles are completely different [1].

In order to contribute with a better understanding about the aircraft power network characteristics for data communication, a measurement campaign was performed at a flight test executive aircraft, specifically on the harness that deliveries energy for instrumentation equipment of flight tests. In this work, two measurement configurations of power lines were adopted: CF $\#1$, which represents the current topology of the aircraft harness, and CF $\#2$, that is an alternative configuration we are interested in evaluate in this work. Considering the frequency band $1.7-100$ MHz, analyses of frequency response magnitude, additive noise, and channel capacity are taken into account. It is important to emphasize that the measures refer to a flight test executive aircraft equipped with instrumentation devices, which is a novel application for PLC technology. The results show that CF $\#2$ is a better scenario for data communication than CF $\#1$ is. Additionally, the collected data reveals upper and lower channel capacities around 1000 and 900 Mbps, respectively, for the frequency band $1.7-100$ MHz.

This paper is organized as follows: Section II describes the two measurement configurations of power lines and the measurement setup adopted; Section III presents the measurement campaign; Section IV shows the numerical results; and finally, Section V presents the conclusions.

II. MEASUREMENT CONFIGURATIONS AND SETUP

To obtained estimates of channel frequency response (CFR) and additive noise from aircrafts's 28 Vdc power lines, two measurement configurations of power lines, named CF $\#1$ and CF $\#2$, were considered.

Fig. 1 shows the measurement configuration one (CF $\#1$), in which two loads (data acquisition system (DAS) and switcher) are connected to 28 Vdc harness through different wire harnesses (around 9m of length). So that, there is no clear physical connection between these two devices. However, in CF $\#2$ (Fig. 2), from a point of view of electric power grid, the instrumentation equipments of the flight test aircraft are physically interconnected, since there is one direct and defined physical path between them. In both measurement configuration, the grounds are connected in aircraft's chassis - common-mode (CM). Besides, there are two derivations to terminals A and B, where the measurement devices are connected.

It is import to highlight that CF $\#1$ represents the employment of the PLC technology over the power lines that

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supplies the instrumentation equipment in flight test aircraft. On the other hand, CF #2 is an option, *a priori*, interesting for using PLC technology, once it allows the data traffic through power lines that physically connect two devices. In this context, we intend to characterize the media data by using either CF $\#1$ or CF $\#2$, and after we assess the throughput demands of the instrumentation equipments we can determine, in a quantitative way, which of those configurations is the best one to be considered in aircraft.

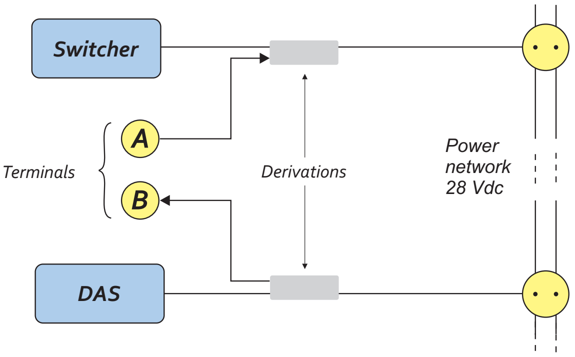

Fig. 1: Illustration of the measurement configuration CF $\#1$.

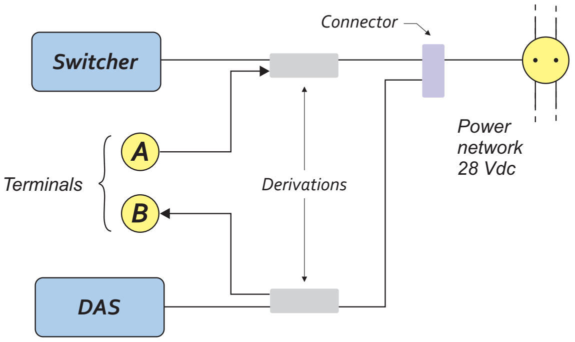

Fig. 2: Illustration of the measurement configuration CF $\#2$.

A. *Channel Frequency Response*

To obtain the CFRs of power lines in the aircraft, we decided to adopted the measurement method based on sounding that is described in [9]. The advantage of this method is that we can have one CFR every 23.04 μs. As illustrated by Fig. 3, the measurement setup is connected on the terminals A and B (see Fig. 1 and Fig. 2) and is made up by three main components:

- Signal generator: Board installed in a rugged computer. A pre-designed sounding sequence is loaded into it and converted into an analog signal, which is submitted to the power cable under analysis;
- Capacitive coupler: Circuit used to connect both signal generator and data digitalizer to the power network. It has as function, basically, to block the voltage signal direct current from the power cable;
- Data digitalizer: Board installed in a rugged computer. Its function is to convert the analog signal into a digital signal. It is responsible to receive the sounding sequence submitted to the power cable to be analyzed later.

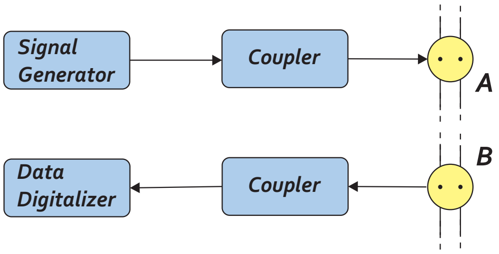

Fig. 3: Sounding-based method setup for PLC measurement.

As illustrated in Fig. 3, the sounding sequence is coupled in a power cable through the signal generator and collected by the data digitalizer. With the discrete-time version of both transmitted and received signals, the channel-estimation methodology described in [9] is performed, encompassing the following stages: (i) input-output timing synchronization; (ii) initial channel estimation, (iii) sampling-frequency offset correction; (iv) channel estimation enhancement, which mitigates the noise effects. The parameters used in the channel estimation setup are summarized in Table I. The sounding sequence is composed by orthogonal frequency-division multiplexing (OFDM) symbols [10].

TABLE I: Configuration for the PLC channels estimation.

Description	Value
Sampling frequency	$f_s = 200$ MHz
Number of sub-carriers	$N = 2048$
Modulation	BPSK
Cyclic prefix length	$L_{cp} = 512$
Frequency resolution	$\Delta_f = 48.83$ kHz
Symbol duration	23.04 μs
Length of the sequence $y_j[n]$	$L_j = 9216$
Number of samples used to compute $\mathbf{m}_t$	$K_d = 8$
Number of shift in vector $\mathbf{m}_t$ calculus	$R = 128$

B. *Additive Noise*

The measurements of additive noise were performed using the data digitalizer and the coupler (see Fig. 3). There was no sounding sequence injected in the aircraft power line, i.e. the signal generator was turned off.

III. MEASUREMENT CAMPAIGN

A measurement campaign was performed in a flight test prototype aircraft Embraer Legacy 450, that was appropriate equipped to realize flight tests. As a precaution, the measurement campaign was carried out with the aircraft powered by an external power supply. During the measurements all instruments and equipments used in flight tests were powered on.

We collected $3,422$ estimates of CFR for CF $\#1$ and $3,446$ estimates of CFR for CF $\#2$. Regarding additive noise, three measures with 32×10^6 samples from each terminal was obtained, totaling 6 measures for each measurement configuration.

IV. NUMERICAL RESULTS

A. *Channel Frequency Response*

Fig. 4 and Fig. 5 depict the aircraft PLC channel magnitude response, considering the frequency band $1.7 - 100$ MHz for CF #1 and CF #2, respectively. One can see the maximum, minimum and mean values of the channel magnitude response. In Fig. 4, the minimum values of magnitude attenuation are between 19.31 and 44.32 dB, whereas the maximum attenuation is higher than 100 dB. The mean values of magnitude attenuation are between 21.26 and 55.45 dB.

The channel magnitude function presents a smooth decrease as the frequency increases, as it is shown in Fig. 5. The minimum attenuation is between 10.09 and 30.43 dB, whereas the maximum attenuation can reach 85.19 dB. The mean values of the magnitude attenuation are between 10.46 and 39.86 dB. Comparing Fig. 4 and Fig. 5, the CF #2 comes up as the best choice for data communication.

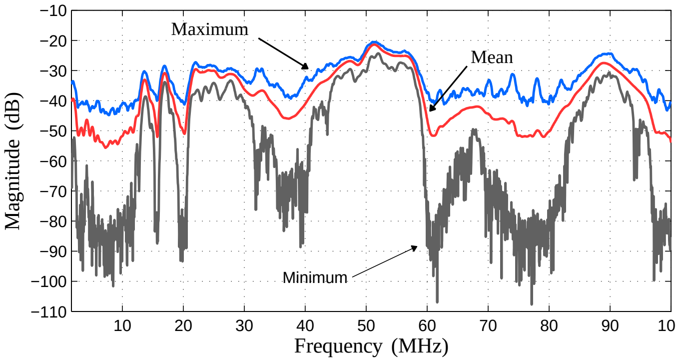

Fig. 4: Aircraft PLC channel magnitude response for CF #1.

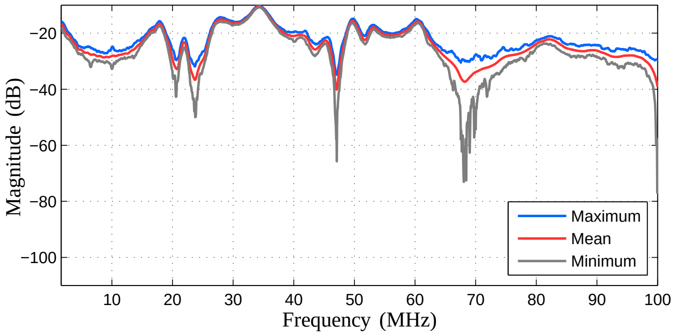

Fig. 5: Aircraft PLC channel magnitude response for CF #2.

B. *Additive Noise*

Fig. 6 and Fig. 7 depict the current spectral density (CSD) of the additive noise measured in the power lines of instrumentation equipment for aircraft flight tests through CF #1 and CF #2, respectively. CSD was chose rather than power spectral density (PSD) because the aeronautic standard RTCA/DO-160G [6] gives the upper limit (20 dBμA/kHz) of the signal in terms of CM current flowing through all wires. Also, the frequency band $1.7 - 100$ MHz was adopted for this analysis.

In Fig. 6, the CSD vary from around -7.5 dBμA/kHz (-110.5 dBm/Hz, impedance of 50 Ω) up to 23 dBμA/kHz (-80 dBm/Hz, impedance of 50 Ω). Fig. 7 shows a similar behavior, however, the mean CSD presents a slight higher oscillation than the mean CSD found in CF #1.

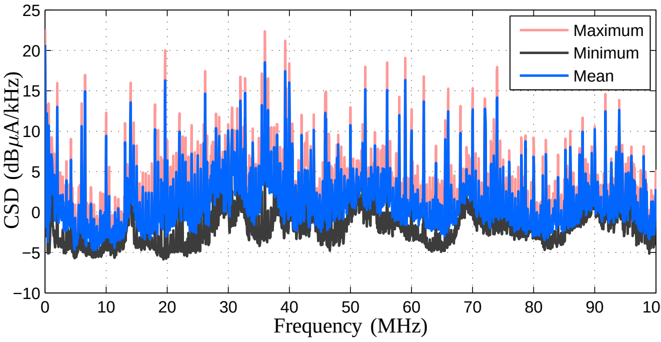

Fig. 6: Estimate noise: CSD in the measured aircraft PLC channel for CF #1.

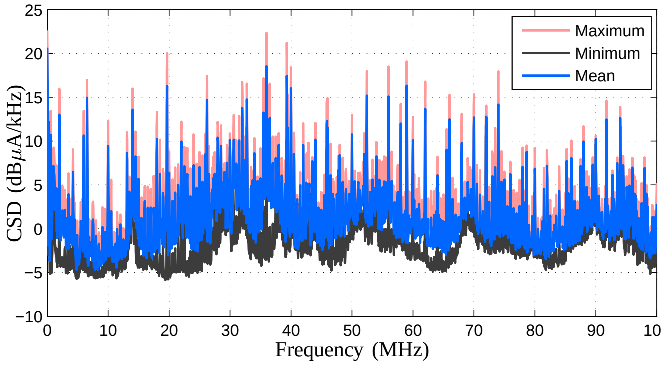

Fig. 7: Estimate noise: CSD in the measured aircraft PLC channel for CF #2.

C. *Channel Capacity*

Upper, lower and mean capacities for FB1 ($1.7 - 30$ MHz), FB2 ($1.7 - 50$ MHz), and FB3 ($1.7 - 100$ MHz) bands are depicted in Fig. 8 and Fig. 9 for CF #1 and CF #2, respectively. As explained previously, the channel capacity is presented in terms of CSD instead of PSD. The CSD of the transmitted signal is ranging from 13 dBμA/kHz (-90 dBm/Hz, impedance of 50 Ω) up to 53 dBμA/kHz (-50 dBm/Hz, impedance of 50 Ω). The theoretical capacity was computed with the additive noise and the CFRs obtained from the measurement campaign performed in the flight test prototype aircraft.

In Fig. 8, the upper capacity is around 540 Mbps for the frequency band FB3, whereas the capacity is nearly 150 Mbps for the frequency band FB1. However, in compliance with the aeronautic standard RTCA/DO-160 [6], the upper bound of CSD that the transmitter can emit is 20 dBμA/kHz, which limits the capacity in 4 and 20 Mbps for FB1 and FB3 bands, respectively.

Regarding CF #2 (Fig. 9), there is a minimal difference between upper, mean, and lower capacities. Furthermore, for the frequency band FB3, the upper capacity can reach around 1000 Mbps, whereas for the frequency band FB1 the capacity is around 320 Mbps. However, when limits of aeronautic standard RTCA/DO-160 are considered, the upper capacities only reach 38 and 100 Mbps for FB1 and FB3, respectively.

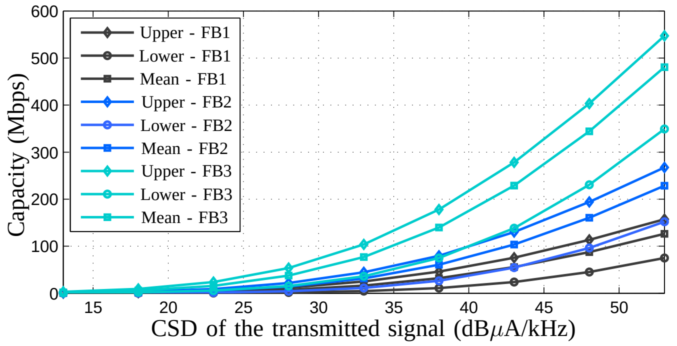

Fig. 8: Channel capacity of the measured aircraft PLC channels considering CF #1.

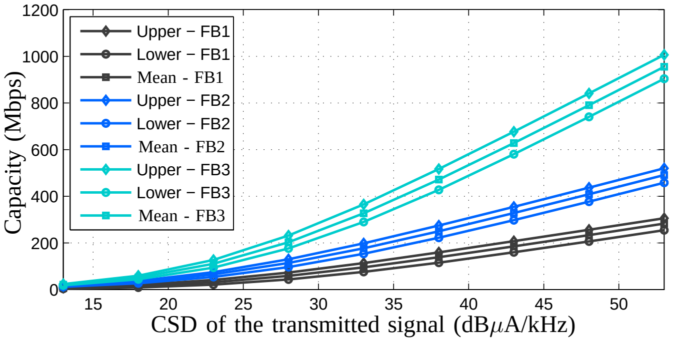

Fig. 9: Channel capacity of the measured aircraft PLC channels considering CF #2.

Comparing the upper capacity of aircraft PLC channels for CF #2 with the upper capacity obtained from Brazilian in-home PLC channels (1550 Mbps) [5], a difference of 550 Mbps is observed. However, due to the limit of CM current flowing imposed by aeronautic standard RTCA/DO-160, this difference increases to 1450 Mbps.

Nevertheless, as supposed in [3], if a changing in aeronautic standard is adopted in the future, where the upper bound of CM current would increase to 40 dBμA/kHz, then the maximum capacities for frequency band FB3 considering CF #1 and CF #2 would increase to 230 and 600 Mbps, respectively.

V. CONCLUSIONS

This paper presented a characterization of aircraft PLC channels over power lines of the flight test executive aircraft Legacy 450. The raw data were collected by considering two measurement configurations of power lines. Analysis of frequency response magnitude, additive noise, and channel capacity were presented.

The results indicated that measurement configuration of power lines where the instrumentation equipments (loads) are physically connected (CF #2) is a better scenario for data communication than the one in which the loads are connected to the instrumentation equipment harness through different power lines (CF #1). Also, the analyses showed that, when transmission power is -50 dBm/Hz, CF #2 presents the upper and the lower capacities around 1000 and 900 Mbps, respectively, for the frequency band $1.7 - 100$ MHz.

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