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POWER LINE COMMUNICATION APPLIED TO FLIGHT TEST INSTRUMENTATION

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Abstract

This paper investigates the usefulness of the power line communication (PLC) technology for assisting the data communication demands related to flight test aircraft. In this way, statistical analyses of the average channel attenuation, the coherence bandwidth, the root mean squared delay spread, and the ergodic achievable rate of the electric power grids used by flight test aircraft are discussed. Also, a PLC modem prototype designed to operate in flight test aircraft is presented. Numerical results show that PLC systems in a peer-to-peer configuration can reach up to 306.33 Mbps, free of packet losses.

1 Introduction

Power line communication (PLC) applications have been widely studied for indoor (residential and commercial buildings) and outdoor electric power grids [1, 2]. Recently, PLC systems applied to in-vehicle environment, such as cars, ships, trains, spacecrafts, and aircraft have attracted interesting more interested due to the feasibility of PLC systems to fulfill several data communication demands and constraints in these environment (i.e., ubiquitousness, redundancy, weigthing reduction and cabling installation cost).

One the other hand, it is well-established that electric power grids were not specified and designed for data communication purposes. In fact, in such media the transmitted signals can suffer significant attenuation due to the distance and frequency increases, the impedance mismatchings and be considerable corrupted due to the presence of high impulsive noises. Aiming to study this harsh data communication environment, there are several contributions focusing on the measurement and the characterization of in-home and outdoor electric power grids [3, 4] and reference therein. However, these studies do not addresses the aircraft electric power network, in which the geometrical characteristics and tree-shaped topologies of cable bundles and the design of electric circuits are completely different from in-home and outdoor electric power grids [5].

In order to verify the viability of PLC in aircraft some studies have characterized the aircraft power network. [6–9]. Relevant is to mention that the measurements of fourteen PLC channels and the characterization of their channel frequency responses (CFRs) magnitude on a test bench of a cabin lighting system (CLS) cell were addressed in [8]. Also, [6] discussed about the coherence bandwidth and the delay spread (DS).

Based on the fact that limited research results about PLC systems for aircraft are found in the literature, this paper focuses on the measurement and statistical characterization of the aircraft power network that delivers energy to flight test instrumentation equipment. In addition, it discussed the prototype of a PLC modem, which was designed based on the *a priori* measurement and characterization of electric power network for flight test intrumentation. In this way, the main contributions of our work are summarized as follows:

- A measurement campaign performed at a business jet test prototype, specifically on the power network that deliveries energy for instrumentation equipment of flight tests covering the frequency band $1.7-86$ MHz.
- Statistical analyses of the average channel attenuation (ACA), the coherence bandwidth (CB), the root mean squared delay spread (RMS-DS), and the ergodic achievable data rate.
- A presentation of a prototype of PLC modem that is capable of reaching up to 306.33 Mbps, free of packet losses, at the level of transport layer by using the user datagram protocol (UDP) protocol.

This paper is organized as follows: Section 2 discusses the measurement campaign carried out at the business jet test prototype; Section 3 presents the PLC modem prototype; Section 4 shows the numerical results; and Section 5 states some concluding remarks.

2 Measurement campaign

A measurement campaign was carried out at the flight test business jet in order to characterize the 28 Vdc electric power network that deliveries power to instrumentation equipment. To do so, we adopted the measurement configuration shown in Fig. 1. In that configuration, loads or PLC modems are connected to the 28 Vdc electric power network through the same cable. It is a new proposal of aircraft power network aiming to improve the data communication since it can alleviated the multipath effects [10, 11].

Aiming to obtain the CFR estimates and measure additive noises, the measurement setup was constituted based on the top-down approach. Such approach allows us to characterize the aircraft electric power network without knowledge of the aircraft electric circuits (i.e., block box).

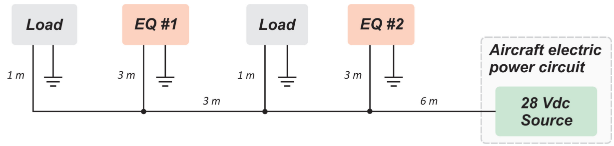

Fig. 1 The block diagram of the measurement configuration.

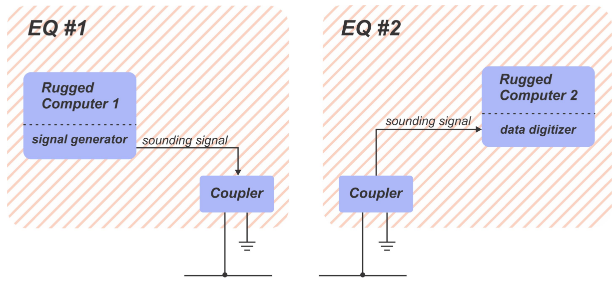

Fig. 2 The block diagram of the sounding-based measurement setup.

The sounding method used for estimating the CFRs is detailed in [12].

The measurement configuration is constituted by two main parts, named EQ #1 and EQ #2 (see Figs. 1 and 2). Essentially, EQ #1 is made up by a rugged computer with a signal generator board installed and a capacitive coupler, while EQ #2 is constituted by a rugged computer with a data digitizer board installed and a capacity coupler.

To obtain CFR estimates, EQ #1 injects the sounding signal into the aircraft electric power network and EQ #2 collects it. This injected signal covers the frequency band $1.7-100$ MHz. With the transmitted and received discrete-time signals provided by EQ #1 and EQ #2, the chosen estimation method [12] is applied. Further details about the measurement configuration can be found in [10, 11].

Aiming to collect the additive noise samples, only EQ #2 is used. The additive noise was recorded at the points of connection of both EQ #1 and EQ #2, see Fig. 1. In the measurement campaign, we collected a total of 3,446 CFR estimates and three measures of additive noise, which is composed of 32×10^6 samples.

3 PLC modem prototype

the prototype of the PLC modem is based on modifications of a PLC modem, which is available in the market, designed for in-home environments. The introduced modification refers to allow it to operate over a 28 Vdc electric power network of flight test aircraft and mitigate additive noise coming from the electric circuits of the aircraft. To do so, their power input and filter, which consists of two inductors and one capacitor, were removed. Also, its input integrated circuit (AC/DC converter) was removed since it will receive 28 Vdc and a power source was added in order to convert 28 Vdc to 3.3 Vdc.

For the PLC modem prototype and instrumentation equipment proper work in the flight test aircraft, interferences between them need to be avoided. To do so, a lowpass filter with cutoff frequency of 73 kHz was used. Basically, it blocks the existing additive noise over the 28 Vdc electric power network and prevents any interference yielded by the PLC modem impairs the instrumentation equipment of the aircraft. The filter was designed to block the signal with frequency content up to 68 MHz once this is the operational frequency band of the prototype of the PLC modem.

Fig. 3 shows how the components of this prototype are laid out inside the equipment. The connectors used for powering purpose and providing data communication. In addition, the Ethernet interface of the propotype is accessed through the RJ-45 connector. The ON/OFF button allows to control only the internal operation of the PLC modem prototype, which can be manually switched on and off at any time by the user. It is important to emphasize that the push button does not interfere with electric energy traveling through the PLC modem and does not emit pairing signals or data traffic over the Vdc electric power grid. Finally, the push button is responsible for pairing two PLC modem prototypes, i.e., to establish the data communication between both of them.

Fig. 4 shows the perspective view of the interior of the PLC modem prototype made in a com-

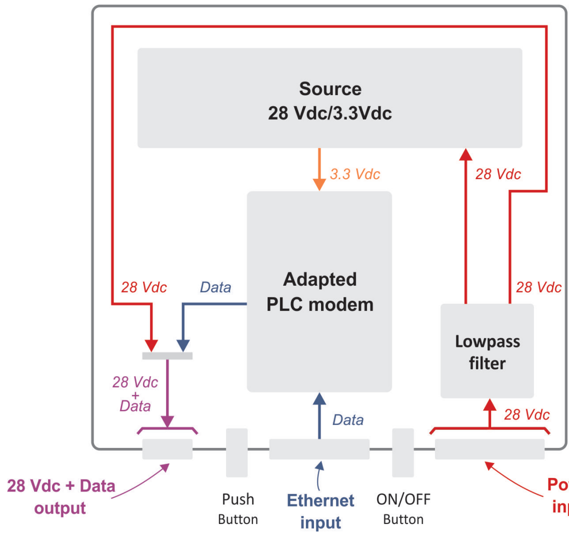

Fig. 3 The layout of the components of the PLC modem prototype.

mercial 3D software, whereas Fig. 5 shows a picture of PLC modem prototype. Its case is made of an aluminum base and a carbon steel wrapping coated with an electrostatic paint in black color. The aluminum base allows a possible grounding by attaching the PLC modem prototype to metallic parts of the aircraft. The carbon steel wrapping is responsible for shielding the PLC modem prototype and for the user/data communication interface. Is important to emphasize that this kind of shielding makes the modem PLC prototype less vulnerable to noise emissions, which is the main source of interference to adjacent equipment because it can satisfactorily block external noises.

Finally, but not the least the electrical specifications of the PLC modem prototype are listed in Table 1. Note that it was designed to properly work in 28 Vdc electric power network with low current consumption and to deliver power to loads or devices connected to its output.

4 Numerical Results

In this section, we present some numerical results regarding the characterization of the measured aircraft PLC channels. To this end, we consider three frequency bands: $1 - 30$ MHz (FB1), to comply with European regulations for broad-

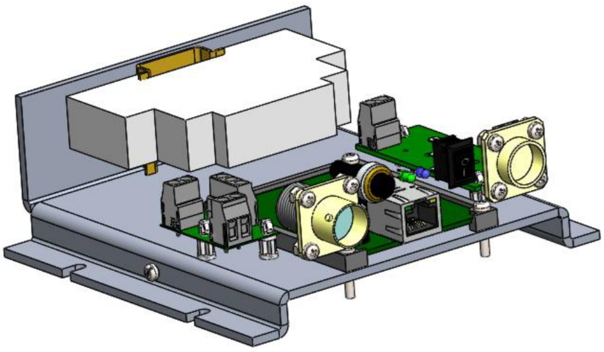

Fig. 4 The perspective view of the interior part of the PLC modem prototype.

Fig. 5 The prototype of the PLC modem.

Table 1 Electrical characteristics of the PLC modem prototype.

Description	Value
Minimum power supply voltage	12 V
Maximum power supply voltage	30 V
Average input current in 28 Vdc	115 mA
Dissipated power in 28 Vdc	3.64 W
Load input current	10 A
Operational temperature	0°C to 40°C
Storage temperature	-25°C to 70°C

band PLC; $1-50$ MHz (FB2), to comply with Brazilian Telecommunication Authority regarding broadband PLC, and $1-86$ MHz (FB3), in agreement with ITU-T Rec. G.9964. In addition, the throughput analysis of the PLC modem prototype are discussed.

4.1 Aircraft PLC channels

In order to support the design of PLC systems, values of ACA, CB, RMS-DS, and ergodic achievable rate must be obtaind from PLC channels, which are measured in the electric circuits of the flight test instrumentation aircraft. In this way, Table 2 lists the ACA values for the aircraft PLC channels. Note that the mean values of ACA are equal to 24.42, 22.54, and 23.65 dB for FB1, FB2, and FB3, respectively. Also, the minimum values are 24.01, 22.20, and 23.31 dB while the maximum values are 25.30, 22.95, and 24.04 dB for FB1, FB2, and FB3, respectively.

Table 2 ACA for FB1, FB2, and FB3 frequency bands.

Average Channel Attenuation (dB)			
	Maximum	Mean	Minimum
FB1	25.30	24.42	24.01
FB2	22.95	22.54	22.20
FB3	24.02	23.65	23.31

The maximum, mean, and minimum values of CB for the correlation level 0.9 are summarized in Tab. 3. One can note that the minimum values of CB are equal to 0.49, 0.78, and 1.07 MHz for FB1, FB2, and FB3, respectively. These information indicates the frequency selectivity level of the measured PLC channels and informs the maximum frequency bandwidth without intersymbol interference.

Table 3 PLC channel coherence bandwidth for FB1, FB2, and FB3 frequency bands.

Coherence bandwidth (MHz)			
	Maximum	Mean	Minimum
FB1	0.83	0.63	0.49
FB2	1.17	0.98	0.78
FB3	1.22	1.14	1.07

Table 4 shows the maximum, mean, and minimum values of RMS-DS. Note that the maximum values of RMS-DS are equal to 0.14, 0.09, and 0.07 μs for FB1, FB2, and FB3, respectively. Those information indicate how dispersive the PLC channel is. It is used to determine the guard interval duration (cyclic prefix length) in a multi-carrier scheme (e.g., orthogonal frequency-division multiplexing (OFDM)) and the time duration between successive symbol transmission that allow to minimize the inter-symbol interference.

Table 4 PLC channel RMS-DS for FB1, FB2, and FB3.

RMS-DS (μs)			
	Maximum	Mean	Minimum
FB1	0.14	0.11	0.09
FB2	0.09	0.08	0.06
FB3	0.07	0.06	0.06

The ergodic achievable data rates (C_{erg}) for FB1, FB2, and FB3 are shown in Fig. 6. The ergodic achievable rate is presented in terms of current spectral density (CSD) instead of power spectral density (PSD) since the aeronautical standard RTCA/DO-160G [13] gives the upper limits of the signal in terms of common-mode current flowing on all cables. The CSD of the transmitted signal ranges from 13 dBμA/kHz (-90 dBm/Hz for impedance of 50 Ω) up to 53 dBμA/kHz (-50 dBm/Hz for impedance of 50 Ω). The C_{erg} was computed with the additive noise and the CFRs obtained from the measurement campaign. One can see that the ergodic achievable rates can reach 838.4, 542.7, and 336.9 Mbps for FB3, FB2, and FB1, respectively.

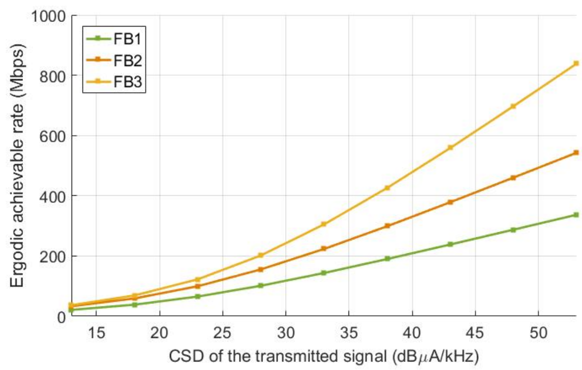

Fig. 6 Ergodic capacity of the aircraft PLC channels.

4.2 Throughput Analysis

Aiming to quantify the performance of the modem PLC prototype, throughput analyses at the transport level by using the UDP protocol were carried out at the laboratory facility. To do so, the configuration showed by the block diagram in Fig. 7 is taken into account. In this configuration, the PLC modems A and B are connected pear-to-pear (P2P) so that they emulate the traffic model of the aircraft data acquisition system. The data flow is generated and analyzed by the equipment Spirent SPT-3U considering the time interval of ten million Ethernet frames. The transmission of packets is continuous.

Fig. 8 shows the maximum throughput with zero packet loss measured for frame lengths ranging between 64 and 1024 Bytes. Note that for the frame length equal to 64 Bytes, the throughput is 50 Mbps and increases until 306.33 Mbps for the frame length equal to 448 Bytes. For frame

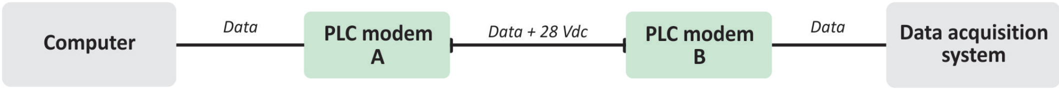

Fig. 7 Block diagram of CF #2.

lengths longer than 448 Bytes the throughput is almost the same.

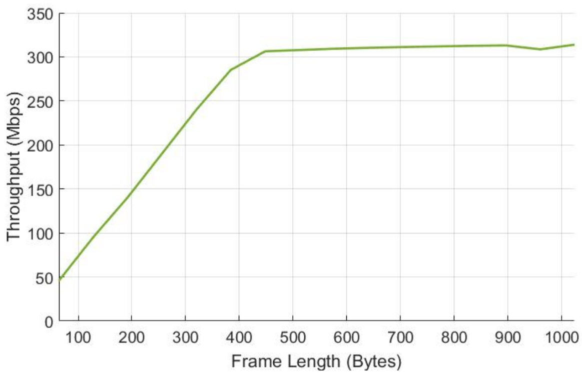

Fig. 8 Throughput Performance of the PLC modem prototype.

5 Conclusion

In this paper, we have presented an statistical characterization of the 28 Vdc electric power network that deliveries energy to instrumentation equipment of the business jet test prototype. Then ACA, CB, RMS-DS, and ergodic achievable rate parameters have been evaluated and discussed. Also, we have presented the PLC modem prototype developed to operate in flight test aircraft. In order to verify its performance, throughput analysis at the transport level layer have been provided.

The numerical results has shown an ergodic achievable rate of 838.4, 542.7, and 336.9 Mbps for the frequency bands FB3, FB2, and FB1, respectively. Also, they has shown that the PLC modem prototype in a P2P configuration can reach throughput equal to 306.33 Mbps, free of packet losses, by using the UDP protocol at the transport layer level. Those results indicate that the PLC system can be interesting solution of data communication for flight test instrumentation in aircrafts.

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