POWER LINE DATA BUS (PLUS)

Stephen Dominiak[1], Jürgen Wassner[2], Sven Gastel[3], Jürgen Späh[3]

[1]plc-tec AG
Panoramastrasse 5, 5607 Hägglingen, Switzerland

[2] Lucerne University of Applied Sciences and Arts
Technikumstrasse 21, 6048 Horw, Switzerland

[3]Diehl Aerospace
Alte Nussdorfer Strasse 23, 88662 Überlingen, Germany

stephen.dominiak@plc-tec.ch

Abstract

Aircraft wiring contributes significantly to the weight and complexity of the overall aircraft. A means is required in order to reduce the overall amount of wiring in the aircraft. For that goal, an innovative solution is the use of the Power Line Communications (PLC) technology as a data bus. The Lucerne University of Applied Sciences and Arts (HSLU) has developed a PLC technology dedicated for aeronautics applications providing high reliability, low latency and deterministic behaviour. The HSLU PLC solution (Power Line data bUS - PLUS) not only targets a communications protocol which can meet the necessary functional and performance requirements, but also provides design assurance. Diehl Aerospace, PLUS technology provider plc-tec AG and research partner HSLU are cooperating in order to apply the cumulative PLC R&D results from the last 12 years into the development of PLC-enabled aircraft systems based on PLUS. This paper will describe the challenges of using the PLC technology in an aircraft, present an overview of the PLUS technology and show how PLUS overcomes these challenges. An overview of previous verification and validation testing from different R&D projects and aircraft applications is also provided.

1 INTRODUCTION

Recent trends such as the more electric aircraft and health monitoring have led to growing communications demands in avionics systems. Realizing these communications demands with traditional avionics data buses has led to a large increase in the aircraft wiring. In turn the aircraft wiring contributes significantly to the weight and complexity of the overall aircraft. Today's aircraft will typically contain between 200 and 500 km of cables. On the A380, there are more than 100,000 wires constituting 470 km and weighing 5,700kg along with 40,300 connectors [1]. Not included in these figures are the harness-to-structure mounting material such as hooks and cable ties (ca. 30% additional weight). Today's traditional avionics systems consist of separate power and data networks with data networks accounting for about 40% of the overall electrical wiring in an aircraft [2]. Less wiring will therefore lead to lower costs, less emissions and less maintenance. As jet fuel on average accounts for about 33% of airlines' operating costs [3], a reduction in weight will lead to a significant savings over time. According to Colin Sirett, Head of Research at Airbus UK: "Each kilogram cut means a savings of roughly $1 million in costs over the lifetime of an aircraft…" [4]. A means is therefore required in order to support the growing communication demand of avionics systems while reducing the overall amount of wiring in the aircraft. Wireless communications and Power Line Communications (PLC) provide two potential solutions. The authors view these technologies as complimentary as all potential solutions will need to be considered in order to obtain the overall goal of wiring reduction. The focus of this paper is on the PLC approach.

2 POWER LINE COMMUNICATIONS

PLC is a wired communication technology that uses the aircraft Power Distribution Network (PDN) for data transmission by superimposing a modulated high frequency carrier signal over the standard power signal. The PLC signal is modulated completely independent of the underlying power signal, i.e. PLC will function over any DC, AC or even non-energized systems. PLC combines the advantages of wireline communications with the use of an existing (non-dedicated) wiring network. The specific advantage of PLC technology comes from the fact that it has been specifically designed for communications over wiring channels that have not been designed for high-speed data communications. This mainly involves a multi-carrier transmission scheme in the form of Orthogonal Frequency Division Multiplexing (OFDM) which optimizes spectral efficiency in the presence of a frequency selective channel. Other important features provided by PLC are strong Forward Error Correction (FEC) techniques to combat impulsive noise. It is these robust protocols that allow relatively high data rates to be achieved over wiring networks not normally supporting data communications such as can be found in aircraft PDNs. Similar to wireless communications, the term PLC refers to a broad range of diverse communication protocols. Furthermore, as is also the case for wireless communications, certain protocols may be better suited for avionics applications and one should be careful in drawing conclusions based on the analysis of commercial protocols developed for the consumer electronics market.

3 CHALLENGES FOR PLC IN AN AIRCRAFT

Transmitting data over the aircraft PDN does not come without its challenges. The following main factors differentiate the wiring of the PDN from the wiring typically found in data networks:

- The PDN wiring is unshielded.
- The PDN will usually either consist of a single-wire with return over the aircraft chassis or several wires routed in parallel for differential or 3-phase systems.
- The PDN topology is often tree-like and contains a number of branches or other points at which impedance discontinuities will occur.
- The impedance of loads attached to the PDN is optimized for the maximum power transfer of the power signal and is rather arbitrary for higher frequencies.
- Power conversion and other active power elements within loads will generate static and transient (impulsive) noise which will be conducted or coupled onto the PDN.

- Several power lines will exist in a common harness bundle and the lack of a shield or twisting of the power cables means that the potential isolation from external effects which may be electro-magnetically coupled onto the power line is reduced.

The aircraft PDN communications channel will therefore exhibit relatively high transmission signal attenuation and frequency selectivity. Figure 1 shows typical PLC communications channels which have been measured within the EU FP7 TAUPE project at different locations on a test bench of the Airbus A380 Cabin Lighting System. The highly frequency selective attenuation with a few deep "notches" is apparent. It is also apparent that the mean attenuation increases versus frequency which is mainly due to the skin effect and dielectric losses from the insulating material.

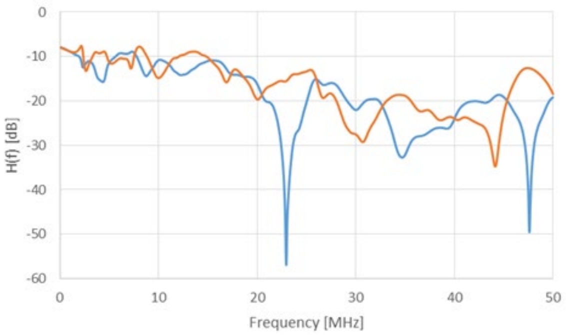

Figure 1 – Example PLC Channel Transfer Function

It is a common misconception that PLC cannot communicate given these channel characteristics. On the contrary the PLC protocols have been optimized for over 20 years now to provide reliable communications under these harsh channel conditions. Where traditional data bus protocols would fail, PLC is still able to provide reliable communications. The fact that the PLC signal propagates over a fixed wiring network means that the channel will exhibit a certain amount of determinism. This is especially true within the aircraft in which the PDN specification is well documented. In fact, time-varying behaviour in an installed avionics PLC system would only result from the time-varying impedances of loads or switching within the network. Proper filter and coupler design can provide a solution which reduces the influence of application device impedance changes on the PLC channel, thereby providing less time-varying behaviour. Currently wireless communication is also being considered alongside PLC as an avionics communications technology since it provides many of the same advantages. However, the dynamic propagation environment of a wireless signal poses a significant challenge for the use of the technology in safety-critical applications due to the highly random and time-varying nature of the wireless channel. The determinism provided by PLC is considered to be one of the main advantages for the use of PLC over wireless technology.

The Electromagnetic Compatibility (EMC) of PLC is recognized as one of the main potential showstoppers in the use of PLC in the aircraft. A PLC system must be designed and installed such that operation of that PLC system will not adversely affect or be adversely affected by the operation of the aircraft function supported by the PLC system (intra-system EMC) or the simultaneous operation of any other equipment or systems on the aircraft (inter-system EMC). The challenges of EMC are nothing new for the PLC technology as they exist in other application scenarios. Unfortunately, the use of in-home PLC is not strictly governed meaning that not all commercial solutions perform well in terms of EMC. For this reason, previous PLC feasibility studies including EMC testing based on commercial technology must be considered with caution. Fortunately, for avionics systems EMC is strictly regulated at both the aircraft and the unit/device level within Federal Aviation Regulation Part 25 and RTCA DO-160/EUROCAE ED-14 documents. On the one hand, restrictions will be placed on PLC in terms of the high-frequency emissions and susceptibility. However, on the other hand, the EMC of other devices within the aircraft are also regulated and the EMC behaviour of these devices is known. It is this regulated environment that will help to provide deterministic behaviour for PLC.

4 AVIONICS PLC

PLC is widely used for consumer in-home use as a wired alternative to IEEE 802.11 Wireless Local Area Networks or for scenarios where indoor wireless coverage is not possible (e.g. through multiple walls). Commercial Off the Shelf (COTS) PLC solutions are available targeting this consumer market. The application of COTS PLC solutions has been previously evaluated in the EU FP7 TAUPE project [5]. Within the TAUPE project no principle showstoppers regarding the use of the technology for avionics applications were identified and a COTS PLC technology was successfully demonstrated for the Cabin Lighting System (CLS) achieving a Technology Readiness Level (TRL) of 4. However, the use of COTS IP must take into consideration the specific needs of avionics systems related to the harsh environment, certification issues, fault tolerance and long lifetime [6]. Meeting these needs requires support from the technology suppliers as a "black-box" certification of a new technology is unrealistic. Unfortunately, the limited number of technology suppliers combined with the relatively small aeronautics market segment (compared to the consumer market) resulted in a general lack of support for continuing the development of a COTS PLC solution towards a higher TRL.

Based on the need for a PLC technology to support the requirements of safety-critical, real-time applications not only in avionics, but also in other niche market areas, the development of the Power Line data bUS (PLUS) was started at the Lucerne University of Applied Sciences and Arts (HSLU) in 2012. From the very beginning, PLUS was developed targeting Mission-and-Time Critical (MTC) applications such as avionics applications. The design of PLUS not only targets a communications protocol which meets the necessary functional and performance requirements, but also provides design assurance as is required for safety-critical applications. The first step in this design process was to obtain a thorough understanding of the applicable requirements related to the certification of an avionics data bus. The following list shows some of these areas and an overview of the relevant design criteria is shown in Figure 2:

- Regulatory guidelines for the design and certification of an avionics data bus, (e.g. FAA Advisory Circle 20-156, FAA Report AR-09/24 "Data Network Evaluation Criteria Handbook" or ARINC 428 "Considerations for Avionics Network Design").
- EMC regulations at both the aircraft (EUROCAE ED-248) and device level (RTCA DO-160).
- Design Assurance Guidelines for both hardware (RTCA DO-254), software (RTCA DO-178) and model-based design (RTCA DO-331).
- Advanced error detection techniques for maximizing data integrity (e.g. FAA AC 00-66 - Selection of Cyclic Redundancy Code and Checksum Algorithms to Ensure Critical Data Integrity).
- Avionics systems at different Design Assurance Levels (DAL) and their requirements on a data bus.
- Electrical Wiring Interconnect System (EWIS) regulations (e.g. FAA AC 25.1701).
- Additional aircraft manufacture requirements such as Airbus Directives (ABD).
- Design of existing avionics data buses (e.g. AFDX, CAN, ARINC 629, ARINC 429, MIL-STD-1533).

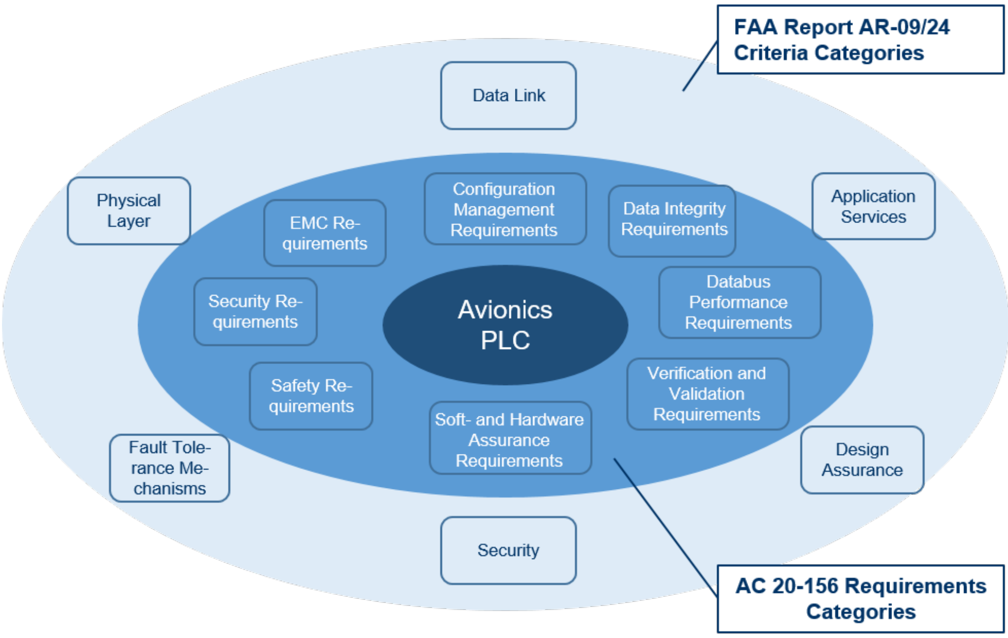

Figure 2 – PLC Certification Categories

There are a number of performance requirements that an avionics data bus must fulfil. In general, these can be summarized by the five categories shown in Figure 3. The main metric for determining the performance of any communications system is the Signal to Noise Ratio (SNR) at the receiver. The communications channel capacity (rate at which information is reliably transmitted over a communications channel) is a direct function of the SNR. The available channel capacity is the main resource for determining if these performance requirements can be met. The question then becomes how best to use the available channel capacity in order to meet the application requirements which results in a multi-objective optimization problem. Optimizing one of these performance goals may lead to a negative influence on the other goals. For example, increasing the transmission power will improve the throughput and/or reliability, however it will reduce the EMC. Another example is using re-transmissions to improve reliability, which will reduce the effective throughput and increases latency.

Figure 3 provides a visual representation of this design trade-off. It also captures another area of communications system design, namely the deterministic quality of the performance. As previously mentioned, the SNR may be time-variant. This inherently leads to the fact that the performance may also being time-variant. In some application areas it is acceptable if, for example, the throughput reduces to almost zero for a brief time as long as it is very high in the average. For avionics applications this is not the case as the performance will be measured based on the "worst-case." Achieving deterministic communications system behaviour for all cases requires proper design consideration.

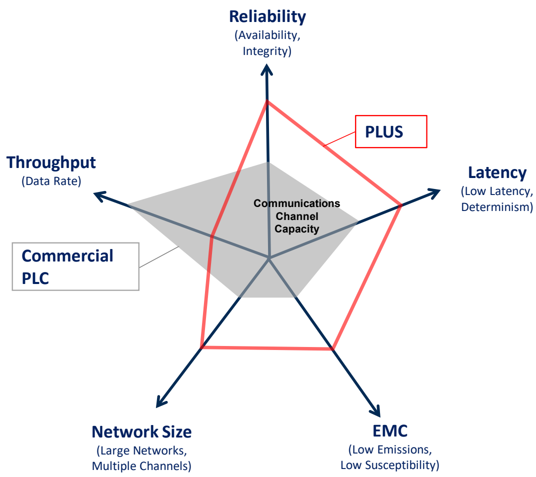

Figure 3 - PLUS Design Trade-off

The grey area represents the commercial PLC technology. The design of that technology attempts to maximize throughput which comes at the cost of the other performance metrics. In addition, the technology is largely non-deterministic meaning that in the best case the throughput may be very high (e.g. several hundreds of Mbps). However, in the worst case the throughput will be very low or even zero. The technology is highly adaptable which inherently leads to dynamic behaviour. The spontaneous performance at any point in time can vary within the grey area in this figure. PLUS follows a different design approach. More weight is placed on maximizing reliability, reducing latency and achieving EMC compliance. Adhering to aircraft EMC regulations has been a central design criterion for the PLUS PLC technology since the very beginning. This is based on over 12 years' experience of the key PLUS design team in performing EMC analysis and measurements with the PLC technology based on a detailed understanding of the underlying EMC regulations. Network sizes in the aircraft are also much larger than in-home networks which only support a few modems. Achieving these optimization goals will inherently lead to an overall reduction in the achievable throughput. The solution will also provide deterministic behaviour. This is shown in Figure 3 by the fact that the achievable performance area (red band) is much narrower than the grey area for the commercial technology.

5 POWER LINE DATA BUS (PLUS) PROTOCOL

The Power Line data bUS (PLUS) protocol has been developed specifically for use as an avionics data bus for safety-critical systems. The specification for PLUS is shown in Table 1. PLUS has been designed around the use of existing and proven standards including IEEE 1901 for the physical layer and ARINC-629 for the bus arbitration. The following lists some of the differentiating factors of the PLUS protocol compared to other commercial PLC solutions:

- Bus arbitration is based on a deterministic protocol with no single point-of-failure.
- Synchronization for signal decoding (due to asynchronous clocks) is done in a distributed manner, i.e. no central bus/clock master is required.
- Connections are stateless so that the protocol behaviour remains static and provides more determinism.
- Zero network setup time after hardware start-up.
- No network management traffic.
- Optimized support for the transmission of short messages (<20 bytes).
- Error detection is based on optimized techniques from the avionics industry which allows PLUS to achieve extremely low probability of undetected error (Pud)[1].
- Support for segregation of multiple PLC networks through a Frequency Division Multiplexing (FDM) feature.
- Multiple services can be multiplexed onto a single PLC bus while still providing deterministic behaviour.
- Optimizations have been made to improve susceptibility especially to impulsive and strong narrowband interference

[1] It can be shown through analysis that a Pud less than 10^{-13} can be achieved even under extreme channel conditions which could lead to high frame errors (low availability).

The PLUS protocol defines layer 1 and layer 2 according to the OSI network model. This is further segmented into 5 sub-layers as shown in Figure 4:

1. Physical Layer
   - OFDM based physical layer
   - Based on international IEEE 1901 OFDM standard
2. PHY Convergence Layer
   - Adaptation of MAC frames to physical blocks
3. Media Access Control (MAC) Layer
   - Monitoring of the bus state
   - Scheduling of the transmission on the bus (core algorithm based on ARINC-629)
4. Logical Link Control (LLC)
   - Flow control and multiplexing
5. Data Services
   - Adaptation of one protocol to PLUS (gateway functionality)

Figure 4 – PLUS Protocol Architecture

Table 1 – PLUS Specification

PLUS Specification					
Physical Layer Signal	Multi-channel Orthogonal Frequency Division Multiplexing (OFDM) with 2048-point FFT				
Modulation	BPSK, QPSK, 8-QAM, 16-QAM				
Frequency Range	2 - 42 MHz				
Channel Modes	Mode A	Mode B	Mode C	Mode D	Mode E
Channel Bandwidth	40 MHz	30 MHz	20 MHz	10 MHz	5 MHz
Sub-carrier Spacing	24.414 kHz	16.276 kHz	12.207 kHz	6.104 kHz	3.052 kHz
OFDM Symbol Duration	40.96 µs	61.44 µs	81.92 µs	163.84 µs	327.68 µs
Physical Data Rates	20 Mbps – 142 Mbps	14 Mbps – 104 Mbps	10 Mbps – 71 Mbps	5 Mbps – 35 Mbps	2.5 Mbps – 17 Mbps
Forward Error Correction	Convolutional Turbo Coding with code rates 1/2, 16/21 and 16/18				
Error Detection	Multi-level Cyclic Redundancy Check (CRC) CRC-40, CRC-32, CRC-8				
Bus arbitration	ARINC-629 Basic Protocol with bus quiet time optimization				
Network Architecture	Peer-to-peer without central clock master				
Network Setup/Management	- Zero network setup time - No network management traffic				
Data services	- Gateway functionality for CAN bus, Ethernet / IP - Multiplexing of multiple data services supported				
Supported power distribution networks	28VDC, 115VAC, 230VAC, 270VDC				

All communications systems must make optimum use of the available channel resources. Resources may be shared in the dimensions of frequency, time or space. In order to maximize the benefits provided by a PLC solution, it would be necessary to operate several PLC systems concurrently in a single aircraft. However, extending the use of PLC to several systems within the aircraft is not so straightforward. This is due to the fact that the power line wiring within the aircraft is unshielded and wiring from several systems are co-located within large wiring harnesses within the aircraft. The crosstalk of the high-frequency PLC signal between the co-located wires between different systems within these harnesses must be considered. PLUS mitigates this issue by providing a hybrid resource allocation solution in which communication resources can be allocated in frequency and time. Following an innovative frequency division multiplexing scheme multiple co-located PLUS networks can be configured to operate on different orthogonal frequency channels, as shown in Figure 5. This allows for the operation of multiple segregated PLC systems. Each PLUS modem within a single network will then share the communications resources according to the PLUS MAC layer. A robust and deterministic protocol for the MAC has been developed for PLUS based on the Basic Protocol (BP) algorithm from ARINC-629. The channel access concept is based on Carrier Sense Multiple Access (CSMA). However, the protocol is NOT similar to the CSMA/Collision Avoidance (CSMA/CA) from many wireless systems in which a random time after the previous transmission is selected in order to “avoid” collisions. With CSMA/CA the probability of collision can only be minimized in which different nodes may choose different times to start their transmissions and the earliest node will win contention, however due to the random nature of the protocol no deterministic upper bound on the channel access time can be defined. With a non-zero probability collisions will still occur if two or more nodes choose the same back-off time. The CSMA protocol used by ARINC 629 is better described as a CSMA/Collision Prevention (CSMA/CP) protocol. With CSMA/CP the back-off time is statically defined for each node such that collisions will not occur during normal operation. The advantage is that a deterministic upper bound on channel access latency can be achieved at the cost of requiring a static configuration.

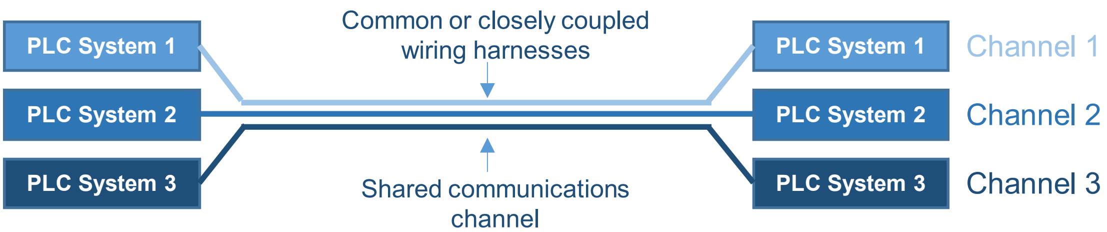

Figure 5 - PLUS Frequency Division Multiplexing

The PLUS protocol has targeted a flexible design which can be adapted to a number of different application scenarios. PLUS is configurable through various parameters. Similar to other avionics data buses a system design is required in order to correctly specify those parameters. The system design will lead to a particular network configuration which is optimized for the requirements of that system. With this configuration PLUS will provide deterministic behaviour and performance. It is important to note that no a-priori information about communications channel conditions are required for configuring a PLUS network. Table 2 shows the resulting performance for the PLUS technology for different application scenarios. The purpose of this table is to provide a number of examples of the performance that can be achieved by PLUS for some selected scenarios. Of course, not all scenarios are listed here, but the table should provide a general idea about the performance of PLUS.

Table 2 - Application Configuration and Performance Examples

Channel Bandwidth	Maximum Number of Orthogonal Channels	Modems per Channel	Transmission Robustness	Maximum Message Size	Maximum Latency	Physical Layer Data Rate	Application Layer Data Rate *per Modem*
40 MHz	1	200	High	30 bytes	33.7 ms	33.8 Mbps	7.1 kbps
40 MHz	1	10	High	30 bytes	1.7 ms	33.8 Mbps	141.8 kbps
40 MHz	1	50	Medium	375 bytes	10.9 ms	77.3 Mbps	275.0 kbps
40 MHz	1	50	Low	1518 bytes	14.0 ms	103.1 Mbps	864.4 kbps
20 MHz	2	75	High	30 bytes	19.9 ms	16.9 Mbps	12.1 kbps
10 MHz	3	75	High	30 bytes	34.5 ms	8.5 Mbps	7.0 kbps
5 MHz	7	75	High	30 bytes	63.6 ms	4.2 Mbps	3.8 kbps

6 PLC VERIFICATION AND VALIDATION

Much work has already been performed in the development of an avionics PLC solution. This includes previous work with COTS technology as well as recent work with the PLUS technology. The PLUS protocol has been realized on a series of different hardware prototypes. These hardware prototypes have been used for functional/performance verification and validation testing in a laboratory environment on top of different aircraft systems as well as EMC testing. These results are summarized in Table 3 and Table 4. A detailed presentation of these results is out of the scope of this paper; however no showstoppers have been identified for the further development of the PLC technology for aeronautics applications. The PLUS technology is currently assessed at a TRL of 5.

Table 3 – PLC Verification and Validation Summary

Project	Aircraft System	Scope
EC FP6 ECAB 2006-2009	In-flight Entertainment	- Initial feasibility study of PLC in an aircraft - COTS PLC solution from DS2 successfully demonstrated on IFE with 5 Mbps per seat
EC FP7 TAUPE 2008-2012	Cabin Lighting System (CLS) Cabin Communication System (CCS)	- COTS PLC solution from DS2 successfully demonstrated for CLS and CCS (28VDC, 115VAC, coupling to multiple lines) - Verification and validation demonstrated TRL 4 - Detailed analysis on architectures, weight savings, safety, security, EMC identified no showstoppers for PLC
EC ASHLEY 2013-2017	Ventilation Control System (VCS)	- First demonstration for PLUS technology as part of a larger IMA2G concept - Control of ventilation fans from Nord Micro (115VAC/230VAC, up to 1.5kW) realized transparently over PLC
LuFO[2] SESAM 2014-2017	Cabin Management System	- Small form factor modem prototypes developed for the cabin management system - PLUS technology successfully demonstrated at Hamburg's Center of Applied Aeronautical Research (ZAL)
LuFO NETKAB 2017-2019	General Cabin Systems	- PLUS technology is being analyzed in different representative power distribution structures including 270VDC - Certification aspects of the technology are also being evaluated

[2] German Aeronautical Research Program (LuFO)

Table 4 – Previous PLC EMC Measurement Campaigns

Date	Scope	PLC Technology
June 2008	Initial PLC EMC feasibility measurements at Ascom (Schweiz) AG within the EU FP6 ECAB project - Conducted and radiated emissions (non-DO-160)	COTS Technology
May 2011	Measurements performed at NLR Marknesse within EU FP7 TAUPE project - RTCA DO-160 sections 16-22 - Bifilar architecture	COTS Technology
Nov. 2014	Measurements performed at NLR Marknesse with TAUPE PLC prototypes - Conducted/radiated emissions according to DO-160 section 21 - Crosstalk measurements (different wiring types/separation distance)	COTS Technology
March 2016	Measurements performed at Diehl Aerospace (DAs) Ueberlingen within the EU ASHLEY project - RTCA DO-160 sections 19, 20, 21 - Differential and single-wire architectures	PLUS
May 2016	Measurements performed at Airbus Group Innovations (AGI) Toulouse within the EU ASHLEY project - RTCA DO-160 sections 20 and 21 - Influence of variable wire separation and impulsive noise investigated	PLUS
July 2017	Measurements performed by Airbus Hamburg within the LuFo SESAM project - Conducted emissions measurements performed directly on the demonstrator wiring harness	PLUS

7 SUMMARY

The Lucerne University of Applied Sciences and Arts (HSLU) and the HSLU spinoff plc-tec AG have developed a Power Line Communication (PLC) technology, the Power Line data bUS (PLUS), which specifically targets mission-and-time critical applications in aircraft, trains, Smart Grids, etc. An overview of the PLUS protocol as well as previous verification and validation testing from different R&D projects and aircraft applications has been provided. For aeronautics applications Diehl Aviation, plc-tec AG and HSLU have entered into an exclusive cooperation for the further development, certification and industrialization of PLUS. This agreement opens the door for Diehl Aviation to use the PLUS technology for the transmission of data over power distribution networks to be integrated into their aerospace products. This also enables customers and partners of Diehl Aviation to utilize the benefits of PLC Avionics for their own products and solutions. The PLUS technology has reached a TRL of 5 and work now continues towards achieving higher TRLs.

8 REFERENCES

[1] Pichavant, C, Schwark, U, “WRC-15 Agenda Item 1.17 - Industry’s Motivation.” EC – CEPT Workshop on WRC-15, December, 2013.

[2] Schroeter, T & Schulz, D, “The Electrical Aircraft Network–Benefits and Drawbacks of Modifications.” IEEE Transactions on Aerospace and Electronic Systems Vol. 49, no. 1 January 2013.

[3] Tyler, T, “IATA Annual Review 2014.” 70th Annual General Meeting, June 2014.

[4] BBC News, “Carbon fiber planes: Lighter and stronger by design” [Online]. Available: http://www.bbc.com/news/business-25833264

[5] Dominiak, Stephen, et al. "The application of commercial power line communications technology for avionics systems." Digital Avionics Systems Conference (DASC), 2012 IEEE/AIAA 31st. IEEE, 2012.

[6] Forsberg, Håkan, et al. "Next generation COTS-commercial IP blocks in avionics." Digital Avionics Systems Conference, 2004. DASC 04. The 23rd. Vol. 2. IEEE, 2004.