THE APPLICATION OF COMMERCIAL POWER LINE COMMUNICATIONS TECHNOLOGY FOR AVIONICS SYSTEMS

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Abstract

Using the Power Distribution Network (PDN) concurrently as a data bus with Power Line Communications (PLC) technology provides an interesting solution for reducing the complexity, weight and volume of electrical systems in commercial aircraft. The European Union project TAUPE has recently completed an investigation on the use of PLC in commercial aircraft. A Technology Readiness Level (TRL) of four was reached and significant weight and complexity savings were demonstrated. Extensive functional and performance tests have been performed for two cabin reference applications in a representative demonstrator. The measurements were performed with commercial off-the-shelf (COTS) PLC equipment based on a state-of-the-art industry standard. A detailed analysis of the results showed a number of deficiencies in applying COTS technology, which has been developed primarily for consumer in-home multimedia distribution, to avionics systems. This paper will provide an analysis of the deficiencies identified during testing as well as present a set of guidelines to aid the way forward for further development towards reaching a higher TRL with PLC which has become well established in the consumer market, but has yet to reach its full potential for avionics applications.

Introduction

Replacing hydraulic and pneumatic systems with electric systems according to the More Electric Aircraft approach can provide higher efficiency. However, this also leads to a significant increase in the complexity, weight and volume of electrical systems in commercial aircraft which has the potential to offset any efficiency gains. A significant part of this increase is related to data communications. In order to mitigate this increase, advanced concepts such as Integrated Modular Avionics (IMA) coupled with the Avionics Full-Duplex Switched Ethernet (AFDX) data bus have been introduced. Nevertheless, these concepts alone are not sufficient and there is still a need to decrease this complexity while providing increased flexibility. While the well-established AFDX communications bus has served the purpose of the backbone data network in newer generation aircraft, there is still a need for advances in ancillary subsystem buses or for other cases in which lower-capacity backbone buses may be required [1]. There is also a potential need to provide increased reliability through redundant data channels without increasing the weight and complexity. For these purposes using the Power Distribution Network (PDN) concurrently as a data bus with Power Line Communications (PLC) technology provides an interesting solution. The use of PLC not only provides savings by eliminating the data distribution network, but also can provide higher data rates compared to existing bus technologies such as ARINC 429, MIL-STD-1553 or CAN.

The European Union (EU) funded TAUPE (Transmission in Aircraft on Unique Path wirEs) project has recently completed an investigation on the use of PLC in commercial aircraft [2]. Development in the project has focused on two reference applications: the Cabin Lighting System (CLS) for cabin illumination and the Cabin Communication System (CCS) for passenger related services. The Airbus A380 served as a reference aircraft for wiring and system architecture. An integrated architecture has been defined with a PLC network providing a single data bus for these two systems. The project was able to successfully demonstrate an achieved Technology Readiness Level (TRL) of four, a weight savings of over 100 kg per aircraft and an almost 40% reduction in the required amount of cabling for the combined CLS/CCS. Next to the validation of these high level goals, extensive environmental, functional and performance testing has been performed.

Economic factors are partially driving the use of Commercial Off-the-Shelf (COTS) technology in order to provide reduced costs, faster development times and simplified maintenance. For this reason as well as to provide a sufficient basis for achieving a TRL of 4, the TAUPE project focused on the use of COTS PLC technology. A number of PLC-enabled avionics equipment prototypes for both 28VDC and 115VAC variable frequency power networks were developed using COTS chipsets based on the OPERA industry standard. These prototypes were integrated into a cabin system demonstrator along with actual aircraft equipment and representative wiring harnesses. Data delivery measurements in terms of achievable throughput, delay and jitter have been performed for the various traffic types on the integrated demonstrator. A detailed analysis of the results showed a number of deficiencies in the use of COTS PLC technology for avionics applications. This paper will provide an overview of the performance testing and results as well as describe the discovered deficiencies. While no showstoppers for the further development of an avionics PLC data bus have been identified, optimizations to the existing COTS technology are necessary. Therefore, a set of guidelines for the adaptation of COTS PLC standards to aid the way forward for further development towards reaching a higher TRL with this potentially interesting technology are also provided.

This paper is organized as follows: Section 2 provides a general overview of the PLC technology. This is followed in Section 3 by a description of the most common (broadband) PLC standards. Section 4 motivates this work by reviewing the potential of PLC as an avionics data bus. In Section 5 the test environment (demonstrator) is described and in Section 6 test results are presented. Section 7 presents an analysis of the test results and identified deficiencies. In Section 8 the potential steps towards achieving a deterministic PLC data bus are provided followed by concluding remarks in Section 9.

Introduction to PLC Technology

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 individual protocols. The common factor defining PLC protocols is that a data signal is transmitted over a wiring network which was not designed for high-speed communications. PLC technology is typically divided into two different categories depending upon the band used by the communications signal. Narrowband PLC uses the frequency band below 500 kHz and can provides maximum data rates up to 500 kbps, however practical and regulatory limitations lead to a more typical achievable data rate of several 10’s of kbps. Broadband PLC (BPL) operates in the frequency range from 2-30 MHz with the next generation technology also supporting transmission up to 80 MHz. BPL can provide maximum data rates of 200 Mbps (using the spectrum up to 30 MHz) or even 500 Mbps (using the spectrum up to 80 MHz). The higher supported data rates and lower noise levels in the frequencies above 2 MHz found on aircraft PDNs have led to focusing on using BPL as an avionics data bus.

The driving application for the development of BPL has been in the consumer market for last-mile or in-home Internet distribution. Therefore, BPL standards development has focused on providing a solution which is directly compatible to existing Ethernet/IP networks. Wall plug adapters providing a PLC interface connecting to the wall outlet and an Ethernet interface for the data connection have become the de-facto product solution. Owing to this, the majority of BPL solutions provide a network which is essentially a virtual switched network defining PLC specific physical (PHY) and Medium Access Control (MAC[1]) layers below an IEEE 802.3 convergence layer. For this reason BPL networks are sometimes referred to as *Ethernet over power lines*. This can provide a distinct advantage when interfacing to other Ethernet based bus technologies

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[1] This paper will follow the IEEE convention of referring to the Open Systems Interconnection (OSI) layer 2 as the MAC layer rather than the more conventional term of data link layer.

such as AFDX as the gateway interface between different bus technologies may cause performance degradation [3].

What really defines PLC as a technology is the robustness of the communication protocols to the harsh communication channel which exists in PDNs. This mainly involves a multi-carrier transmission scheme in the form of Orthogonal Frequency Division Multiplexing (OFDM) with bit-loading to optimize spectral efficiency in the presence of a frequency selective channel. Other important features provided by PLC are strong Forward Error Correction (FEC) techniques (e.g. turbo-convolution or low-density parity check codes) and advanced Automatic Repeat reQuest (ARQ) schemes (e.g. selective or hybrid ARQ) to combat impulsive noise. It is these robust protocols that allow high data rates to be achieved over wiring networks not normally supporting data communications such as can be found in aircraft PDNs.

On the other hand are protocols also belonging to PLC technology such as the logical network architecture or channel access scheduling which have been developed against a different set of design criteria. These protocols have been designed around the current market driver which is consumer in-home use where BPL is typically used as a wired alternative to IEEE 802.11 Wireless Local Area Networks (WLAN) or for scenarios where indoor wireless coverage is not possible (e.g. through multiple walls). In-home network sizes are relatively small and the traffic has more best-effort delivery constraints. Recently devolo AG one of the largest PLC modem manufacturers published data collected from 75,000 end user networks showing that over 86% of all the networks consist of four modems or less [4]. The major differences from consumer to aircraft applications are related to the larger number of nodes typically found in a PLC network combined with stricter traffic delivery requirements.

Commercial BPL Standards

At the beginning of the TAUPE project in 2008, the BPL standardization status was unclear with a number of competing solutions existing in the market based on industry (de-facto) standards or proprietary solutions. Since then, significant standardization activity has occurred. This section will provide a brief summary of the available standards. More detailed overviews of the most relevant standards can be found in [5][6][7].

The PLC technology used in the TAUPE project is based on a solution developed within the EU OPERA project [8]. This solution is commonly referred to as the OPERA standard even though it is technically an industry standard. While no technology selection process was carried out within the scope of the TAUPE project, OPERA did represent one of the most mature solutions for BPL at that time. The OPERA PHY layer is based upon OFDM providing 1536 subcarriers with different transmission modes supporting various channel bandwidths in the spectrum between 2-34 MHz. For the TAUPE project, a 28 MHz channel from 2-30 MHz was used. Two different bit-loading modes are supported: an adaptive mode in which the modulation scheme for each subcarrier is dynamically adapted between 2 – 10 bits/symbol (QPSK – 1024 QAM) based on real-time channel measurements and a robust mode known as HURTO (High performance Ultra Redundant Transmission mOde). In the HURTO mode, all OFDM carriers use the most robust constellation and data is mapped using an 8:1 redundancy which provides a raw data rate of approximately 4 Mbps. For adaptive bit-loading, a raw data rate of up to 205 Mbps or 150 Mbps at the application layer can be supported. It is important to note that the achievable data rate will not usually be the maximum data rate and is dependent upon the channel conditions.

The MAC layer follows a master/slave convention. A number of slave terminals transmit/receive traffic in a shared medium to/from a centralized station (master). While repeater nodes are also supported, they are typically not required for avionics applications due to the relatively small size of the PDN (see next section). The master is responsible for allocating all the resources within its cell. OPERA defines an Adaptive Dynamic Time Domain Multiple Access (ADTDMA) protocol for this purpose. Rather than assigning fixed resources (in time) equally to all nodes within the PLC cell, the master will periodically poll all slaves in order to determine their current offered traffic requirements. Based on this information, the master will then dynamically allocate the time slot resources to itself (downlink traffic) as well as all of the slaves with available data to transmit (uplink traffic). The slave which is currently granted channel access by the master is informed of that decision as well as the maximum channel access time through the passing of a virtual token. Upon completion of data transmission or expiration of the maximum channel access time, the token is returned to the master. If a slave has no available data, it may immediately return the token. The OPERA standard does not define the exact algorithm to be used by a master to determine the scheduling of all the PLC nodes with available data to send. This is left as a proprietary solution for vendor implementation. Details of the scheduling algorithm of the modem chipset supplier were not made available.

In addition to the OPERA standard, the HomePlug Alliance has also been largely responsible for driving the development of consumer BPL technology through the development of the HomePlug (HP) specifications [9]. The first specification, HP 1.0, was released in 2001 and supported a maximum data rate of 14 Mbps. In 2005, the HP AV specification was introduced which supported data rates of up to 200 Mbps and was a direct competitor to OPERA. Similar to OPERA, HP AV also uses an OFDM modulation, however with less subcarriers (1155) with a signal spectrum between 2 and 30 MHz. HP AV also supports adaptive bit-loading with up to 1024-QAM or a robust modulation mode (ROBO). ROBO mode uses QPSK on all subcarriers with redundant copies of the information across multiple subcarriers. It supports a maximum throughput of 4, 5 or 10 Mbps depending upon the desired amount of redundancy. HP AV uses CSMA as the basic channel access scheme, however a hybrid scheme providing contention and contention-free transmission with a central coordinator performing scheduling is also provided. Similar to OPERA, the scheduling algorithm for contention-free transmissions is not defined in the specification and left up to proprietary implementations. Recently, looking towards low-power applications, especially for smart grid, a derivative of the HP AV has been defined called HP Green PHY (HP GP). The main difference is that HP GP only supports the ROBO transmission mode from HP AV which leads to lower costs and power consumption. This allows HP GP to target the embedded market for applications in which high data rates are not required. The use of an underlying contention based MAC protocol however makes its use for real-time applications extremely challenging.

While OPERA and HP may be considered as industry standards, two new international standards have recently been approved. The first standard, IEEE P1901 was approved in September 2010. IEEE P1901 is an integration and extension of two formerly competing PLC technologies, namely the HP AV and HD-PLC (from Panasonic) specifications. IEEE P1901 is backwards compatible to devices based on those previous specifications. Unfortunately, as no joint agreement could be reached, IEEE P1901 defines an incompatible multi-protocol solution only providing a mechanism for fair coexistence. This would, however, be irrelevant for use in an aircraft in which a homogenous PLC technology would be used. The second standard is the ITU G.hn (G.9960/G.9961) standard which also provides an OFDM-based PHY layer, however provides a parameterized solution capable of operating on any in-home wiring such as phone lines, power lines as well as coaxial cable. The major new feature provided by both the IEEE and the ITU standard is the optional use of spectrum above 30 MHz allowing maximum data rates approaching 1 Gbps to be achieved. With the standardization process completed and commercial products now entering the market, it remains to be seen how these standards will establish themselves in the consumer market.

PLC as an Avionics Data Bus

Introducing PLC as an avionics data bus poses a number of principle challenges due to the harsh transmission channel and noise conditions on the complex aircraft PDN combined with the strict emissions limits defined by aeronautics EMC standards. The PLC channel will vary both in location along the wiring harness as well as with time due to impulsive noise or changes in the load impedance of application equipment. It is, therefore, critical to ensure that PLC can provide sufficient link performance under realistic channel conditions. Modeling and simulation work performed within the TAUPE project has shown that high raw link data rates are possible [10]. Also, of significant importance, is that PLC-enabled equipment could achieve conducted and radiated EMC emissions compliance according to fully compliant RTCA DO-

160 testing [11]. One particular challenge to achieving these results is posed by the unshielded single wire PDNs with current return over the aircraft chassis which are common for avionics systems. Similar to optimizations which are performed to the architecture of data networks, modifications of the PDN, such as the introduction of a bifilar wiring network, still allow high data rates and low emissions to be achieved [12]. This makes PLC's potential much more promising for integration into future avionics architectures rather than as a retrofit solution.

The attenuation of the PLC signal increases over distance, however the attenuation is not significant for power line cable lengths as found in the aircraft (typically less than 50 m). However, as the received signal will still be many orders of magnitude less than the transmitted signal, signal isolation is difficult to achieve and currently only half-duplex operation is supported in commercial technology. Similar to the indoor PLC channel, the attenuation of the PLC signal in an aircraft has been found to be dominated by frequency selective fading due to multipath. This also means that the use of repeaters within an aircraft is not required.

Additional challenges are introduced by avionics systems such as the cabin network due to the relatively large number of devices (several hundreds), hierarchical system architecture and wide variety of functions, i.e. data traffic types and bandwidth needs. There are additional industrial aspects (in addition to weight and complexity reduction) which must be considered such as providing a cost effective and flexible integration which can support variability in the aircraft cabin layout. Furthermore, the nature of the applications and the fact that many functions are safety related leads to real-time data delivery requirements.

The PDN for systems similar to the CLS/CCS in the cabin is a broadcast bus topology (multi drop) to which all application equipment are connected. A broadcast bus topology for the PDN provides significant weight savings and flexibility compared to a point-to-point (PTP) architecture. The PLC channel is thus a shared medium with only one node able to transmit at any time. However, for more safety critical systems a PTP-PDN may be more common due to its higher fault tolerance. For a data network with shielded or isolated cabling, a PTP topology would greatly reduce the requirement on channel access scheduling as the channel must only be shared by the nodes at either end of each cable. Nevertheless, for PLC, even with a physical PTP-PDN topology, sufficient isolation between individual links may be challenging to achieve due to the fact that power lines are unshielded and crosstalk may occur if power lines share a common bundle or power distribution box. If interference due to crosstalk would be high enough, this could still result in a shared channel even with a PTP wiring topology. This would, of course, be dependent upon the system architecture and requires further investigation. In any case, it becomes clear that proper coordination of the available communications resources is just as essential as achieving sufficient link capacity and reliability and is a crucial aspect for developing PLC as an avionics data bus.

The three main characteristics which differentiate avionics data buses from commercial communications technology are redundancy, fault tolerance and determinism in controlling the traffic. Achieving sufficient redundancy and fault-tolerance may require adaptations to the architecture of the PDN; however this is not a new concept as the distribution of power has always been important for safety critical systems. The use of PLC would just mean that data bus requirements must be integrated with PDN requirements which in some instances are relatively similar. On the other hand, fulfilling the requirements related to determinism and also certain aspects of fault tolerance requires proper communication protocol design. In order to better understand how a deterministic PLC bus may be designed, it is important to first provide a practical definition for determinism as this term is often misunderstood and sometimes incorrectly used. A deterministic data bus must be able to guarantee a maximum latency, jitter and packet loss. If no packet loss can be tolerated, this is referred to as a hard real-time data bus [13]. In [14] a set of MAC protocol constraints for a deterministic avionics data bus were defined and are summarized here:

1. Only one terminal may access the bus at any time.

2. Access rights must be distributed fairly and each terminal must be able to access the bus once per cycle.

3. A terminal holds the right to use the bus as long as it needs the bus, however the access time to the bus must be bounded.

However, another aspect which must be mentioned is that these criteria are guaranteed only under a specific set of design constraints. These design constraints can be a set of fault conditions, maximum number of nodes on the bus, maximum cable length, maximum offered traffic rate, etc. Therefore, based on a set of requirements defined by the end-to-end transport of application traffic, one must define a set of bounds with which the data bus technology is able to fulfill those requirements. While legacy data buses such as MIL-STD-1553, ARINC 429 or AFDX can be considered to be deterministic, they may break down (lose their determinism) when those bounds are exceeded.

In order for PLC to be introduced as an avionics bus, transmissions protocols must be able to provide robust and high speed communications in the presence of adverse channel conditions, compliance to environmental testing especially regarding strict emissions levels must be ensured, system architectures must be defined which provide suitable redundancy and fault-tolerance and channel access of the shared medium must be regulated in order to provide determinism under the necessary design requirements. Within the TAUPE project, the first two points have been successfully demonstrated and initial steps have been taken to define suitable architectures for PLC-enabled cabin systems. The rest of the paper will describe how commercial PLC technology has been able to provide significant performance in a representative avionics demonstrator, but has fallen short in providing a truly deterministic data bus.

PLC Demonstrator

During the TAUPE project an extensive Verification & Validation (V&V) campaign has been performed to verify the PLC technology against a set of over 350 system and unit level requirements including environmental, functional and performance testing. These requirements have been derived from the actual aircraft system and equipment requirements. Environmental testing included unit level power input, EMC susceptibility and EMC emissions tests according to RTCA DO-160. Results of the emissions testing have previously been published in [11]. A PLC demonstrator was developed for performing system level functional and performance testing. In order provide full testing capabilities, but still allow for transport between different locations a compact design for the demonstrator was selected (see Figure 1). It consisted of 41 PLC-enabled avionics devices and actual aircraft application equipment was used for both the CLS and CCS. For the CLS, 24 Hybrid Illumination Ballast Units (HIBU) containing a florescent light tube and LED strips were used. For the CCS, 16 Passenger Service Units (PSU) containing a speaker, passenger indication lights and reading lights were used. The HIBUs from the CLS operated on an 115VAC variable frequency network. The PSUs were on a 28VDC network with normal and emergency supply. Due to safety considerations, the PLC signal was only injected on the 28VDC normal network.

Figure 1: TAUPE PLC Demonstrator

In order to achieve maximum weight savings, an integrated approach was defined in which the PLC interface is integrated directly into the application equipment. However, this was not possible in the demonstrator due to space limitations in the application equipment. Therefore, a non-integrated approach was taken and separate PLC Terminal Unit (PTU) devices were developed for use in a 28VDC network (PTU-28) or 115VAC network (PTU-115). The only difference between the PTU-28 and PTU-115 was in the coupling unit and the power supply. The modems were otherwise the same in both devices. The 40 application equipment were connected over 5 individual power lines (2 – 28VDC and 3-115VAC) to a master PLC Head End Unit (PHEU) which was integrated into the Secondary Power Distribution Box (SPDB). The PHEU actually consisted of two redundant PLC modems with one modem functioning as a hot backup for increased reliability. Normally, all components of the CLS and CCS would be connected to a director (server) through the topline of the Cabin Intercommunication Data System (CIDS). In the PLC enabled architecture, the PHEU now connects to the top line with all data thereafter being transmitted over the PDN. In the demonstrator, the PHEU was connected to an application server which emulates the CLS/CCS functionality of the CIDS director.

All application equipment were part of the same logical data network with the 5 individual power lines being coupled to the PHEU through a power divider in the coupling unit. The wiring harness for the demonstrator was designed by Safran Engineering Services (Labinal) and verified with simulation and measurements to be representative of the actual CLS aircraft wiring harness [10]. The harness actually consists of two separate harnesses – a main harness which could be exchanged with different lengths and an equipment harness. The overall architecture for the demonstrator is shown in Figure 2.

COTS BPL modems based on chipset technology compliant to the OPERA standard provided by the Spanish company DS2 were used in the demonstrator[2]. These modems provide a PLC interface which is connected to the coupling unit and a standard 100 Mbps Ethernet interface. As previously mentioned, the OPERA standard supports raw data rates of up to 200 Mbps which will typically translates to roughly 150 Mbps of UDP throughput. Therefore, the maximum throughput for these modems was limited by the 100 Mbps provided by the Ethernet interface. The PSU already provided a direct Ethernet interface so the PLC modems could be directly attached to the PSU. The HIBU uses a serial data protocol so a protocol adapter unit was inserted between the PLC modem and the HIBU.

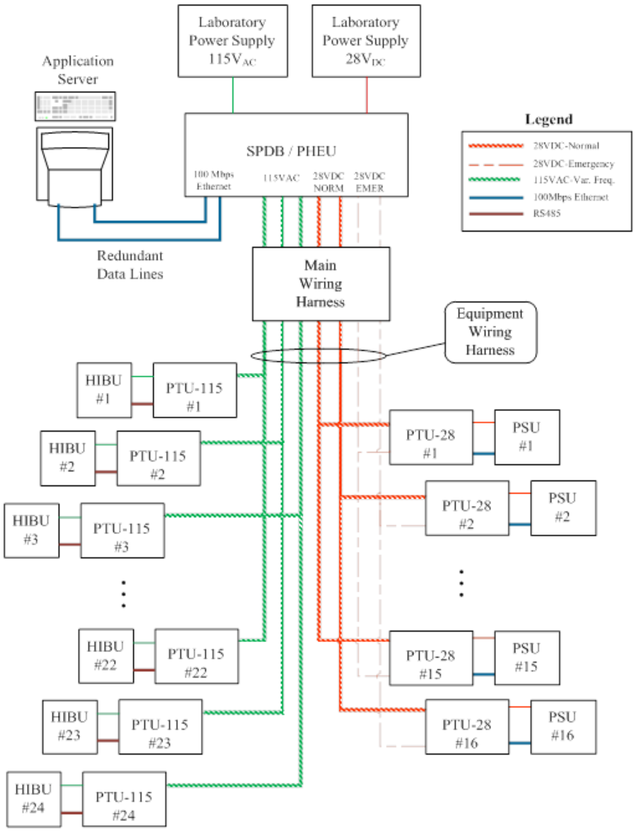

Figure 2: Demonstrator Architecture

For the CCS, application traffic consists of audio streams related to passenger announcements and cabin music, command messages for control of the passenger indicator and reading lights as well as passenger call functions. The majority of the traffic is downstream from the server to the PSUs except for acknowledgements or passenger calls. All traffic is sent with UDP frames. Downstream traffic is sent multicast with upstream traffic sent unicast. Requirements called for the PLC network to support 10 concurrent audio streams which results in a combined data rate of approximately 10 Mbps. Also in order to mitigate any echoes throughout the cabin, tight synchronization of the arrival of the audio streams is necessary resulting in strict requirements

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[2] All DS2 technology was acquired by Marvell in 2010

on latency and jitter. For the CLS, commands to control the HIBUs are sent in the downstream direction and after receiving a command, each HIBU must confirm the command by sending a status frame in the upstream direction. Again all traffic was sent with UDP frames. The commands to all HIBUs were sent as a single aggregated broadcast frame. Status frames were sent unicast. The requirement was for a single command frame and all status frames to be delivered within a 32 ms interval.

Functional and Performance Testing

Functional testing was performed for both the CLS and CCS in order to verify the normal operation of all control and monitoring functionality. For these tests, the equipment was connected as is shown in Figure 2. Tests included validating that a network connection is automatically formed after powering on the demonstrator, that each device as well as groups of devices could be controlled and that monitoring information is correctly received at the server side. No problems were observed during functional testing, however very long network setup times were noted after power-on or after a loss of power. The setup time was on the order of a few minutes when no application traffic was present in the network and as high as 10 minutes with a full traffic load during startup. This is, of course, much too high for avionics applications and will be explained further in the following section.

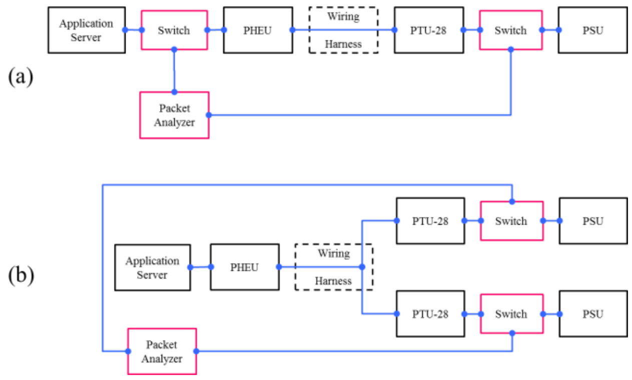

Figure 3: CCS Performance Measurement Test Setup

Performance testing for the CCS included data rate, latency and jitter tests and was performed by monitoring the network packet data using a hardware packet analyzer (Anritsu Data Quality Analyzer MD1230B). The first test was to measure the maximum data rate. This test was performed with additional switches added to the demonstrator setup allowing the packet analyzer to be integrated as shown in Figure 3a. The maximum data rate was then measured using unidirectional UDP traffic of different frame lengths in order to observe which frame length is more appropriate for the given scenario. This measurement was made between the server and PSUs at different locations along the wiring harness in both the forward (PHEU→PSU) and reverse (PSU→PHEU) directions. For all measurements reported here, the results of the forward and reverse measurements were similar and, therefore, only the forward measurement results are shown in this paper.

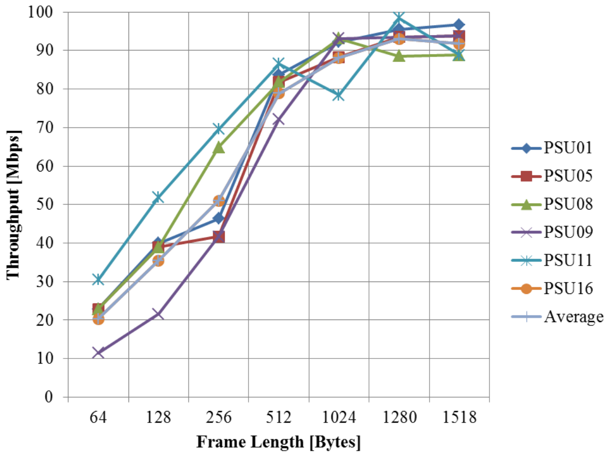

Figure 4: Measured Throughput versus Frame Length

The throughput measurement results are shown in Figure 4. The measured PSUs were selected based on their location in the wiring harness such that a wide distribution both in terms of overall power line length and number of branching points between the PHEU and PSUs is represented. The average of the measurements is also shown in the figure. As can be seen the achievable data rate is highly dependent upon the frame size. This is due to the fact that ARQ acknowledgements as well as channel access scheduling overheads are performed on a per frame basis leading to significant overhead for small frame sizes. As previously mentioned, details of the proprietary scheduling algorithm were not available, however it appears to be not well suited for small frame sizes as the throughput is reduced by about

450%. For audio streams in the CCS, the typical frame size is about 900 bytes so the available throughput is more than sufficient to support the required 10 Mbps. It is also apparent that the throughput is not highly dependent upon the position of the devices in the wiring harness especially for larger frame sizes.

The next step was to measure the frame loss, latency and Packet Delay Variation (PDV) with different frame sizes. The same setup procedure as the throughput tests was used. The offered throughput at the transmitter port of the packet analyzer was varied from about 4 Mbps up to 98 Mbps and for each offered throughput value; the arrival time of the frames was recorded at the receiver port. This test was repeated for each frame size and was carried out again at different locations in the wiring harness. This means that the frame transmission rate must be increased for smaller frame sizes in order to achieve equal offered throughput for the different frame sizes.

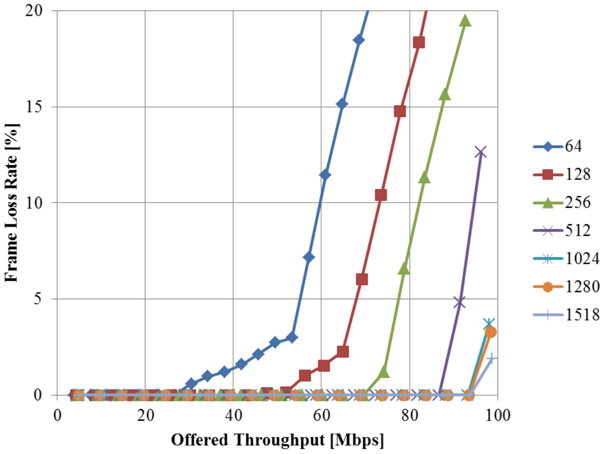

Figure 5: Measured Frame Loss versus Offered Throughput

The average frame loss for each offered throughput value and each frame size was calculated for all measurement points and is shown in Figure 5. Again, a high dependency upon frame size is visible. For frame sizes greater than 512 bytes, there is zero frame loss up to about 85 Mbps. For the target data rate of 10 Mbps, no frame loss was measured at any frame size. Latency and jitter was also measured together with frame loss. The average latency results are shown in Figure 6. The latency does not show any strong dependency on frame size. For data rates up to 70 Mbps it is generally between 1 and 3 ms (except for one anomalous measurement with a frame size of 512 bytes at 50 Mbps). As the offered throughput increases and the network becomes saturated, the latency increases. However, for the CLS and CCS applications, the measured values are well below the requirement of a maximum latency of 10 ms. PDV is defined to be the difference between the maximum and minimum latency measured over a certain time interval for a given data rate. PDV measurement results are not shown here due to space limitations, but it was found to be between 2 and 3 ms depending upon the node at which the measurement was taken for data rates below 50 Mbps.

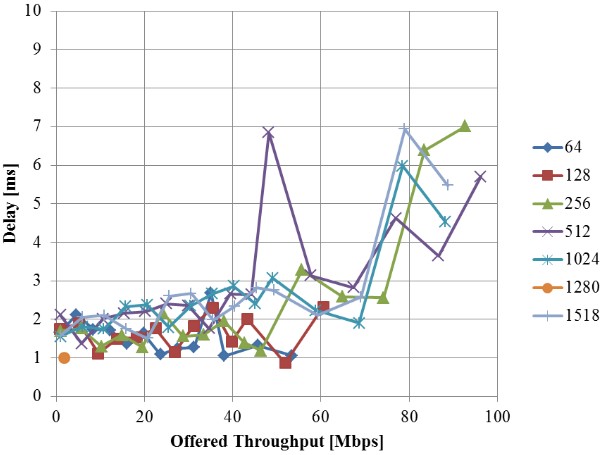

Figure 6: Measured Delay versus Offered Throughput

Finally, audio jitter was measured. Audio jitter is defined as the difference in absolute arrival times of a single audio stream at two different PSUs. In order to provide the worst case scenario, the two PSUs which had the furthest physical separation from each other on the wiring harness were measured. For this measurement, a 1 kHz audio tone was transmitted as a multicast UDP stream. Analog audio jitter was measured at the speaker output of two PSUs using an oscilloscope by comparing the time offset of the resulting sinusoidal signal. The difference was found to be approximately 2 ms. Digital audio jitter was measured by attaching the two ports of the packet analyzer to two PSUs as shown in Figure 3b and comparing the absolute arrival time of the frames from the audio stream sent by the server. The difference in absolute arrival times is shown for a number of frames measured over a time period of 100 seconds in Figure 7. From this figure, the method with which multicast traffic is sent by the PLC network becomes apparent. Assuming that a single frame is sent and received by each multicast group member, the differences in arrival times should be much less than what is observed. The distance between the two measurement points was only about 40 m which, in the worst case, would result in a difference in propagation delay of a few hundred nanoseconds. However, the figure shows that the difference in arrival time for a majority of the frames mainly alternates between two values around ±0.7 ms. This is due to the fact that multicast frames are sent as unicast copies which will be explained in detail in the next section. Unfortunately, both the analog and digital measurements have shown that the measured jitter is above the requirement of ±1 ms.

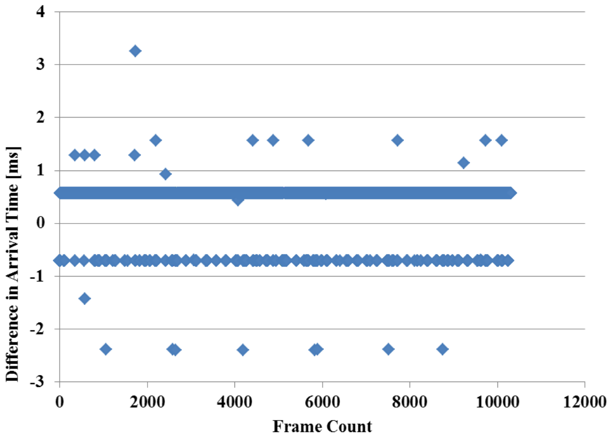

Figure 7: Measured Difference in Frame Arrival Times

For the CLS performance tests were made by monitoring the actual application traffic using a packet sniffer. Lighting commands were sent every 32 ms as a broadcast UDP frame. This broadcast frame was sent using the OPERA HURTO mode. The payload size of the command frame was 144 bytes. Each HIBU responded with a unicast UDP status frame with a payload size of 2 bytes. The broadcast command frames were observed to be delivered reliably to all HIBUs only if the CCS traffic was not present in the network. However, if the CCS audio streams were started, then several command frames began to be lost. After this observation a measurement of the maximum throughput using the HURTO mode was made and it was found to be only about 40 kbps without any additional traffic and only a few kbps when background traffic similar to the CCS audio was present. This is much less than the expected 4 Mbps provided by the HURTO mode even when any protocol overhead is taken into consideration. After further assessment of the DS2 implementation, it was found that the HURTO mode is not recommended for data traffic, but should rather be reserved for any PLC management frames. Therefore, it is believed that the scheduling algorithm severely limits the transport of broadcast data traffic.

A further analysis of the arrival of the status frames from the HIBU at the server showed that only about half of the frames could be delivered within the required 32 ms interval. Also, the order of arrival of the status frames was different in every round. This was the case even when only the CLS traffic was present on the network. Therefore, it seems to be that the scheduling algorithm is being adapted rather often even though highly deterministic traffic is present in the network. A few tests were then performed in order to observe the minimum overall time that would be required for all 24 HIBUs to deliver their status message to the server. It was found that it took about 60-70 ms meaning that each HIBU was occupying the channel for a little over 2.5 ms just to transmit 2 bytes of application data.

In conclusion, the results for the throughput, frame loss and latency performance measurements were very positive and showed PLC to be able to well exceed the necessary requirements. However, the results for jitter as well as measurements of the CLS traffic were less than optimal. They clearly show that certain deficiencies in the COTS technology exist which will be presented in more detail in the next section.

Deficiencies of COTS BPL Technology

Through the functional and performance testing, three principal deficiencies have been identified for the COTS BPL technology. The first deficiency is related to the network setup time. Network setup time can be defined as the time between when all PLC-enabled equipment is powered on until when all necessary connections have been established and application data traffic can be delivered. The BPL standards strive to support a plug and play architecture in which new modems are dynamically detected and integrated into the network through an access and authentication protocol. For the OPERA standard, this access protocol consists of a contention based polling scheme in which new nodes are sequentially admitted to the network. In this scheme the master will periodically send an access management frame to which new nodes in the network respond with an access reply frame. Any new nodes in the network will then compete to be the next to join the network through a random back-off timer based scheme. Should a collision occur during the current round (two or more nodes select the same time interval to transmit), then all nodes must wait until the next round to try again to join the network. This problem is further compounded by the fact that the transmission of access reply messages is also contending with any data traffic in the network leading to very high setup times if data is sent immediately after startup. For an avionics bus, this is unacceptable, however avionics networks do not need to support true plug and play connectivity. Therefore, the use of static configuration tables such as virtual link tables in an AFDX network could be considered which would mitigate this problem.

The second deficiency is related to the support of multicast and broadcast transmissions. As previously mentioned, this is critical for the CLS and CCS, however generally applies to most avionics control applications. The issue results from the use of an adaptive OFDM bit-loading in BPL systems. For unicast transport in which a single transmission channel exists, the channel can be measured and various bit-loading algorithms may be used in order to select the optimal modulation scheme for each subcarrier. However, for a broadcast or multicast transmission, multiple communications channels with varying quality will exist and the question then becomes what is the best method to select the bit-loading for this case. In the OPERA standard two different methods are supported:

- Robust transmission with a common modulation: A single frame is broadcast using the HURTO mode as described in the previous section. All protocol management and broadcast data traffic is sent using this method.
- Unicast conversion: Individual copies of the frame are sent unicast (sequentially) to all group members using the optimum bit-loading for each individual channel. This method is used for all multicast data traffic.

The first method increases the probability that a majority of the nodes can receive the transmission, however at the cost of a very low data rate which is only 2% of the maximum possible rate. This is similar to the method used for the popular IEEE 802.11 standard in which all multicast/broadcast traffic is sent at the basic rate of 1 Mbps. The second method may be able to provide a higher bandwidth if high quality channels are available, however can lead to a significant increase in delay and jitter when several nodes are part of a multicast group. It is, however, the second method which is extensively implemented in COTS BPL technology as it will usually provide better performance in in-home applications where the number of network nodes is relatively low. However, for the transport of passenger audio in the CCS in which 16 nodes where part of a multicast group, this introduced an unacceptable jitter.

The third deficiency concerns the MAC scheduling algorithm. The master must schedule the transmissions of its own data as well as that of all the slaves in the network in order to meet the necessary design goals in terms of fairness, delay and bandwidth. The OPERA standard uses a synchronized TDMA/TDD access scheme known as ADTDMA as described in the previous section. All transmissions are collision-free and the master node provides synchronization. The master will perform periodic polling of each slave in order to determine the requirements of its offered traffic and will dynamically schedule the transmissions accordingly. The adaptive nature of this protocol is optimal for networks in which the offered traffic by each node is aperiodic such as typical Internet traffic as it means that resources (time-slots) are not wasted on nodes that have no data to transmit. However, the overhead induced by the necessary polling is sub-optimal for periodic (deterministic) traffic especially traffic with a low payload size such as the CLS status messages. Even considering the significant overhead introduced by adding additional protocol headers, PHY block headers and FEC coding to the payload of CLS status messages, the time required to transmit a single CLS status frame will be on the order of tens of microseconds. However, each CLS occupied the channel for roughly 2.5 ms which shows a very inefficient scheduling.

It should be noted that BPL standards do not ignore network performance requirements and almost all of them offer Quality of Service (QoS) mechanisms for traffic prioritization. In the OPERA implementation, these mechanisms can be used to influence the scheduling algorithm used by the master. However, the implementation of QoS has been optimized for the type of data traffic typically found in Internet applications. The standard use case for QoS provisioning in such PLC networks is for the transport of Voice-over-IP or video streaming applications. While these applications have strict timing requirements compared to other Internet traffic, they are of an order different than the timing requirements specified for the CLS and CCS applications. For OPERA, the guaranteed minimum latency cannot be configured below 20 ms and even this value is only supported for smaller network sizes (<10 nodes). If larger network sizes are used a higher minimum latency parameter must be configured. This means that the minimal latency that the OPERA-based PLC system can guarantee is 20 ms. Note that this is not the minimum achievable latency as that is on the order of 1ms or less in the best case, but is only the minimum latency which QoS provisioning can guarantee. While these latencies may seem high for the target aircraft applications, they are more than suitable for the smaller network sizes and application traffic found in in-home PLC networks. In other words, the PLC technology based on the OPERA standard was tested within the TAUPE project outside of its design specification. That is, the QoS provisioning provided by COTS PLC can meet the deterministic bounds for consumer applications, but not the strict requirements of avionics systems. The TAUPE project has followed a top-down approach by taking the requirements of reference avionics applications and determining if the PLC technology as-is could achieve those requirements. This approach has shown that some deficiencies exist regarding network setup time, efficient support of multicast/broadcast data delivery and providing a deterministic channel access scheduling. These should not be considered as a showstopper for PLC as will be discussed in the next section.

Towards a Deterministic PLC Data Bus

In order to continue with the development of PLC technology for avionics systems, it will be necessary to realize a deterministic MAC protocol. Adaptation of existing standardized commercial technology may be difficult as the framework of the standard may not support true determinism. Also, as the available chipset implementations are partially based on proprietary algorithms which are not openly available, obtaining support from the chipset suppliers would be necessary. This may be difficult due to the comparatively small aeronautics market size. One potential alternative to undertaking the development of a completely new protocol would be to integrate an existing proven avionics MAC protocol on top of a PLC PHY layer. A number of proven data bus protocols do exist. While the proper functionality of some of these protocols may be dependent upon the underlying topology or PHY layer, other protocols are indeed more flexible. In fact, an interesting potential candidate is the Time Triggered Protocol (TTP) or its variant for safety critical systems TTP/C. TTP was originally developed by the University of Vienna and now further development is driven by TTTech as part of the Time Triggered Architecture (TTA) [15]. TTP is a fault-tolerant time-triggered protocol which uses TDMA as the underlying channel access scheme. Network nodes transmit in time slots which are pre-defined within a Message Description List (MEDL). An important aspect of TTP is achieving sufficient clock synchronization which is realized through a distributed Fault Tolerant Average (FTA) algorithm. The FTA algorithm requires a-priori knowledge of transmission times which are also included in the MEDL. Typically two redundant communication channels are used, however operation with only one channel is supported. The advantage of TTP in terms of PLC is that different topologies are supported (bus and star) and that the protocol is generally independent of the PHY layer. Further investigation would be required to determine if the time constrains and the time synchronization or the MAC protocol specified in the TTP Specification can be respected by an underlying PLC network.

While TTP or other protocols may be independent of the underlying PHY technology, there are certain characteristics of PLC which must be considered. These are related to the fact that the PDN provides an unreliable communications medium. As previously described, the PLC technology provides a number of mechanisms which are still able to provide robust communications under these conditions. However, the design of any MAC must take this into consideration. Similar considerations have been made regarding the use of a time-triggered protocol on top of CAN (TTCAN) [16]. One advantage that all BPL standards provide is the use of powerful error detection and correction techniques which will allow erroneous frames to be detected which is an important requirement for fault tolerance. For scenarios in which FEC alone may not be sufficient for reliable transmission, ARQ is typically used. A scheduling algorithm would need to allocate time for these retransmissions in all time slots which may be an inefficient use of the channel. Another option could be to enable frequency or time diversity which is supported through the robust communication modes which may make the use of ARQ unnecessary. Finally, as the PLC channel is a time-varying channel, adaptive bit-loading algorithms are essential in order to achieve the maximum throughput for each channel realization. These algorithms rely on a certain amount of feedback in order for the transmitter to measure the channel quality as well as for the transmitter to inform the receiver of the bit-loading scheme such that proper decoding is possible. These feedback messages would have to be periodically integrated into the scheduling scheme. Another option is to use a standardized protocol which uses a common modulation in place of adaptive bit-loading such as HP GP. While the throughput will not be as high, it may still be sufficient for many avionics applications.

Conclusion

The use of PLC for avionics applications has been investigated in the EU TAUPE project with positive results in terms of weight and complexity reduction of the aircraft wiring network. This paper has reported the results of functional and performance testing which has been made on a representative demonstrator based on COTS technology. Results have shown that a PLC-based data bus can provide bandwidth approaching 100 Mbps and relatively low latency times (<5 ms), however deficiencies have been found regarding network setup time, efficient support of multicast/broadcast data delivery and deterministic channel access scheduling. It is important to note that the deficiencies described in this paper are not inherent to PLC itself, but are rather specific to the implementation of consumer technology. There is a misconception that COTS solutions can be directly applied in the avionics environment. MAC for real-time avionics systems is especially challenging due to the explicit deterministic timing and reliability requirements. Therefore, one must be careful about drawing conclusions about the use of PLC based solely on these deficiencies. Interesting future work would be to further investigate the use of avionics MAC protocols on top of a PLC PHY layer. As for any other bus, PLC should provide determinism, fault tolerance and redundancy. However, if the system requirements lack the flexibility to adapt to the technology, a modular approach to system and network design may no longer be applicable. In order to achieve the maximum benefits provided by PLC, it may be necessary to rather follow an integrated approach to system and network design in which the characteristics of PLC are considered at an early stage.

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