

Power Line Communications for Avionics Systems: Robustness Against Electromagnetic Compatibility

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Abstract—Electrification of numerous aircraft systems over the course of the past decades has caused a significant increase in weight and complexity of onboard power and data networks, and this trend is expected to continue on the road towards sustainable aviation. Hybrid data networks that combine conventional cabling with wireless technologies and power line communication have the potential to yield data networks with reduced weight. However, in doing so, safety should not be compromised. Therefore, this paper presents the results of a measurement campaign that was carried out to investigate the robustness of Power Line Communications with respect to Electromagnetic Compatibility. The tests include conducted susceptibility, as well as conducted and radiated emissions. Three different wiring configurations were tested, being a single wire and bifilar wire with structure as return, complemented by a wire pair with dedicated return wire. Overall, except for the single wire case, Power Line Communications performed well on all tests, with the bifilar wiring case slightly outperforming the wire pair case. Resonance phenomena observed in conducted emission results are explained by additional simulations.

Keywords—power line communication, electromagnetic compatibility, measurements, conducted emissions, radiated emissions, conducted susceptibility

I. INTRODUCTION

Beyond the everlasting race for more efficient aircraft, global warming has led to very stringent requirements on the developments of sustainable aviation. The European Union's Flightpath 2050 demands a 75% reduction in CO₂ and 90% reduction in NO_x emissions per passenger kilometre by the year 2050 [1]. More Electric Aircraft (MEA) developments have already yielded more efficient aircraft by replacing more and more on-board systems by electrical alternatives. This trend of electrification will continue in the upcoming years, implying more complexity and weight in the on-board power and data networks. The Horizon 2020 project ADENEAS (Advanced Data and power Electrical Network Architectures and Systems) has the objective to optimize the power and data network in terms of weight and complexity. Therefore, ADENEAS targets the development of enabling technologies for a safe, light, self-configuring, autonomous and modular power and data distribution network scalable to all aircraft sizes. A hybrid data network containing wireless technologies and Power Line Communications (PLC) as potential replacements for parts of conventional wiring is one of the enabling technologies under development.

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PLC utilizes the existing power distribution network in an aircraft for data transmission. PLC modems are attached to both ends of a transmission line, and the PLC signal is superimposed onto the original power signal. As a consequence, the data cable forming the original datalink has become obsolete and can be omitted. An analysis in the European Union FP7 TAUPE project has shown that PLC has the potential to decrease the number of wired links/connectors in avionics systems by 36% [4] [5], yielding decreased weight of the Electrical Wiring Interconnection System (EWIS). PLC at itself is not new, however to the aviation industry it is. One clear challenge for exploitation of PLC in the aviation industry is the stringent reliability constraints. To be compliant with those requirements, PLC needs to be robust with respect to electromagnetic compatibility (EMC).

The EMC of PLC is a critical factor for the introduction of the technology for avionics systems. However, relatively little work has been reported on EMC measurements with PLC. Results of PLC EMC emissions measurements for DC power lines in spacecraft were presented in [6]. Moreover, in [7] extensive EMC measurements were reported; however the measurements were made with a commercial-off-the-shelf (COTS) PLC technology and they only focused on a single wiring type (bifilar). [8] describes how COTS PLC technology is not suitable for avionics systems due to its lack of determinism and the difficulties in obtaining support for the necessary certification of the technology.

This paper discusses the results of an extensive EMC measurement campaign at NLR facilities, in which the EMC robustness of PLC has been investigated for three wiring types, including a single wire (SW) and bifilar wire, both with structure as return, as well as a wire pair with dedicated return wire. Conducted susceptibility (CS), conducted emission (CE) and radiated emission (RE) tests were performed and the performance of PLC over each of the wiring types for these tests will be discussed in this paper. In case of conducted emissions, a specific resonance around 40 MHz was observed, for which additional experiments combined with CST modelling were applied to come to a physical explanation. The measurements were made with the Power Line data bUS (PLUS) PLC technology which has been developed by the Lucerne University of Applied Science and Arts (HSLU) and plc-tec AG [9]. PLUS is one of the few PLC technologies that has specifically been developed for avionics systems.

The following section introduces PLC, after which Section III will discuss the EMC test set-up. Section IV will discuss

the test results, including the analysis of the conducted emissions resonance. Conclusions will be given in Section V.

II. POWER LINE COMMUNICATIONS

PLC utilizes the existing power distribution network to transmit data. PLC couplers superpose a modulated high-frequency carrier signal over an existing power signal on the corresponding power cable. The PLC signal is modulated independently of the underlying power signal, enabling the application to both alternating-current (AC) and direct-current (DC) power distribution.

In general, from existing aircraft wiring data, it is known that DC power is distributed over single wires with structure as return, while for AC power, wire pairs are used. Therefore, these two form the base for the use cases of PLC. Since single wire with ground return is known to be challenging in terms of EMC (ground loops tend to become large), an alternative approach for that wiring configuration is added as a third use case. This leads to the following wiring configurations to which the application of PLC is investigated:

1. Single wire with return via structure
2. Wire pair with dedicated return wire
3. Bifilar wire with return via structure

Fig. 1 schematically shows the application of PLC to each of the wiring configurations. The top figure shows the case of a single wire with ground return, for which a capacitive coupler is used. Both PLC and power signal travel in common-mode (CM) through the single wire to the load, and back via structure. The wire pair case is schematically very similar, except for that fact that the chassis ground is replaced by a dedicated return wire. The lower sketch in Fig. 1 shows the bifilar wiring case, which is designed as an alternative to the single wire case. Here, the single wire is replaced by two wires (with smaller diameters), where the power signal still flows in CM to the load through these two wires and back via structure. However, the main difference is that the PLC signal is coupled differentially onto the two wires. This wiring configuration is realized by making use of an inductive coupler. These wiring configurations are analyzed with respect to EMC robustness in the next sections.

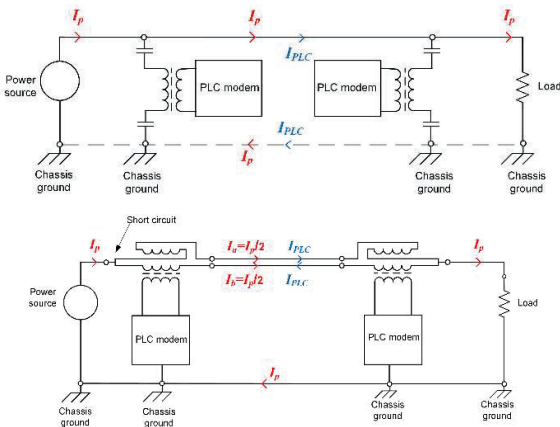


Fig. 1. Schematic representation of application of PLC in two wiring configurations: (top) single wire with return via structure and capacitive coupler, and (bottom) bifilar wire with return for power signal via structure and inductive coupler. The wire pair case is similar to single wire, where chassis ground is replaced by a dedicated return wire.

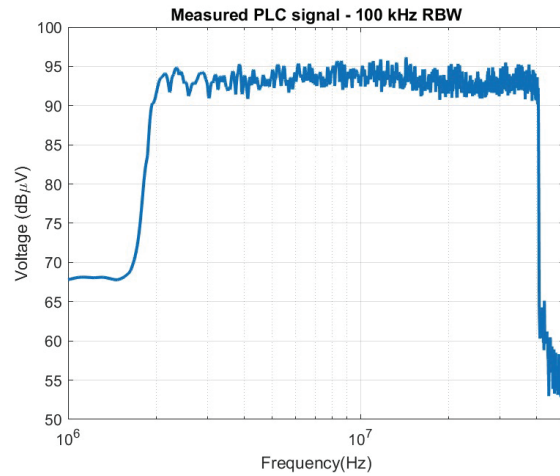


Fig. 2. Measured PLC signal spectrum at 100 kHz resolution bandwidth.

The PLUS PLC technology is specifically designed for applications in mission- and time-critical systems such as aircraft. PLUS provides deterministic low-latency communication in peer-to-peer networks without a single-point-of-failure. PLUS combines a broadband PLC physical (PHY) layer according to IEEE 1901 with the avionics-proven bus access protocol ARINC 629. PLUS uses a multi-channel orthogonal frequency division multiplexing (OFDM) with a 2048-point FFT together with Forward Error Correction (FEC) based on Convolution Turbo Coding at a code rate of 1/2. For the EMC measurements described in this paper, a 40 MHz channel was used with a sub-carrier spacing of 24.414 kHz. All sub-carriers were modulated between 2-42 MHz. Each sub-carrier was modulated with QPSK providing a PHY data rate of approximately 32 Mbps. The resulting PLC signal has a constant nominal power spectral density (PSD) between 2-42 MHz. Outside that band it decays quickly, as seen by the measured PSD in Fig. 2. This measurement is obtained by connecting a PLC modem via a balun to a spectrum analyzer.

III. TEST SET-UP

This section describes the test set-up that has been used for EMC testing of PLC. In general, all tests have been performed according to EUROCAE ED-14G/RTCA DO-160G [2], unless otherwise specified. The title of this test standard is “Environmental conditions and test procedures for airborne equipment,” and is dedicated to the testing of Line Replaceable Units (LRUs) intended for use onboard aircraft. In the application to PLC, some interpretations are required, since PLC by itself is not really an LRU, rather a communications interface over a power line for which two PLC modems are attached, one at each side of the transmission line. Specifically, with respect to requirements in terms of cabling, some interpretation of the standard was needed. The following sections discuss the test set-ups for the three types of EMC tests performed.

A. Conducted Susceptibility

A schematic drawing of the test set-up for CS testing is shown in Fig. 3, while Fig. 4 shows a picture of the test set-up. Requirements in ED-14G for power lines connected to an equipment under test (length of >1 m) and interconnecting bundles (length of >3.3 m) have been combined into the given set-up. In terms of high-frequency loading, a Line Impedance Stabilization Network (LISN) is connected on one side of the

power line, and a load is connected to the other side. This loading depends on the wiring configuration, and the applied loading for all three wiring types is shown in Fig. 5. From the LISN, 1 m of power line is connected to a junction, to which the couplers of the PLC are connected. From here, a transmission line of 3.3 m will propagate the combined power and PLC signals. This part is terminated at another junction, to which a PLC second modem is attached, as well as a twisted cable terminated to the load. Since this cable does not carry the PLC signal its characteristics will not affect test results. Other properties of the test, such as the height of the PLC cable above the ground plane and positions of injection and monitor probes, are all in correspondence with ED-14G. The disturbance currents are injected onto the cable carrying power and PLC data in CM. Finally, dwell times were equal to 1 second and the frequency range for testing was equal to 10 kHz – 400 MHz.

During testing the PLC modems generated bi-directional traffic, in which each modem sends about 830 messages per second. This message transmission rate is significantly higher than a typical avionics application, however the intent was to test PLC under a worst-case scenario. The communication performance was monitored while injecting currents onto the line corresponding to increasing ED-14G test categories (i.e. test level), until communication failed. A pass/fail condition of 3% message loss over the period of testing was used. The tests were performed both in continuous wave, as well as with a 1 kHz square wave modulation with 98% modulation depth.

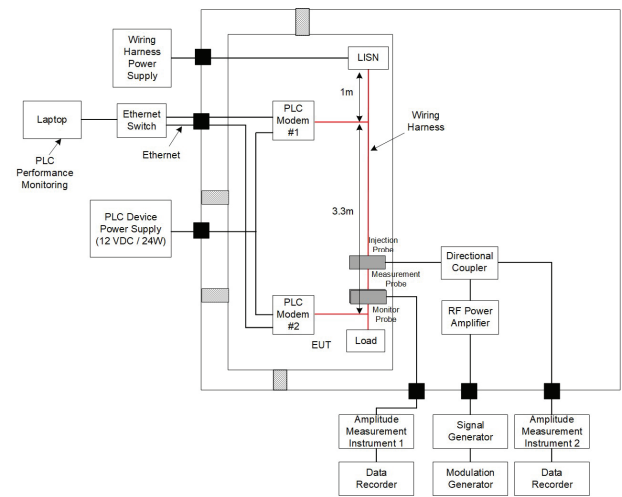


Fig. 3. Schematic drawing of measurement set-up for CS testing of PLC.

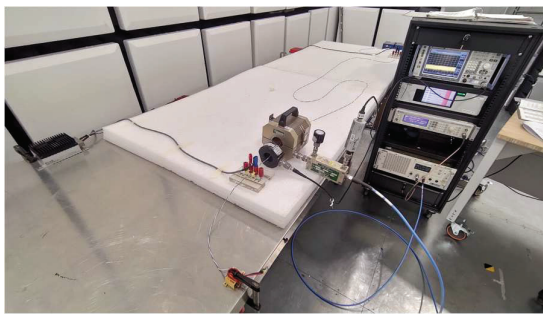


Fig. 4. Picture of CS measurement set-up. Black and red boxes on left and upper side are PLC modems. Furthermore, CS injection and monitor probes, along with appropriate measurement equipment, can be seen.

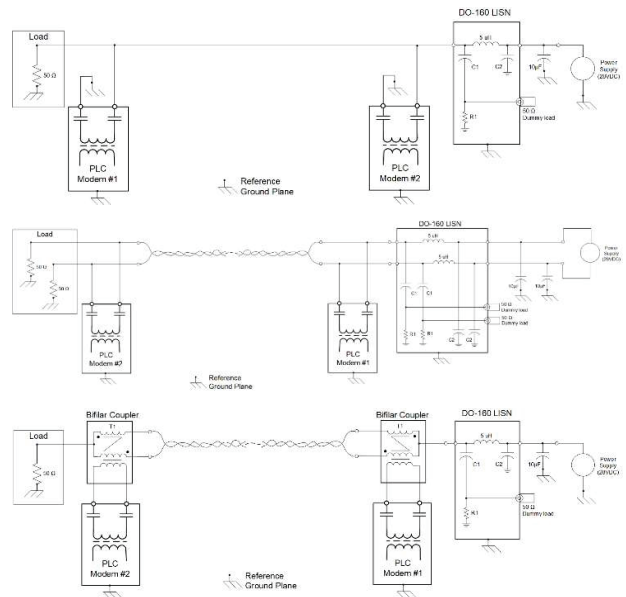


Fig. 5. Schematic representation of the loading for three wiring cases: (top) single wire with return through ground plane, (middle) wire pair, and (bottom) bifilar wire.

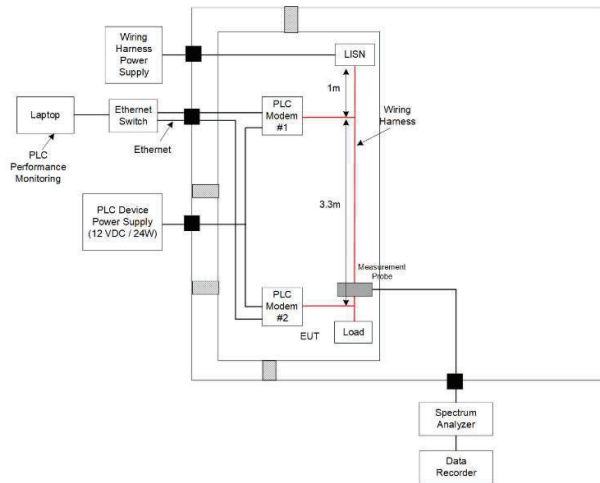


Fig. 6. Schematic drawing of measurement set-up for CE testing of PLC.

B. Conducted emissions

The set-up for conducted emissions is schematically shown in Fig. 6. It is very similar to the CS set-up, except for the fact that the CS injection and monitoring probes are now replaced by the measurement probe for conducted emissions testing, including the corresponding spectrum analyzer and data recorder. The frequency range of testing is 150 kHz up to 152 MHz. During operation of the PLC communication the appropriate CM currents are monitored on the line, and compared against ED-14G CE limit lines. In ED-14G there are limits for power lines, as well as for interconnecting bundles. While PLC is deployed on a power line, in the set-up of Fig. 6 it could also be interpreted as an interconnecting bundle. This is a topic for future discussion. In this paper the powerline limits are used to consider the worst case.

C. Radiated emissions

Starting with EUROCAE ED-14 version E, RE is only measured from 100 MHz upwards. This would be irrelevant

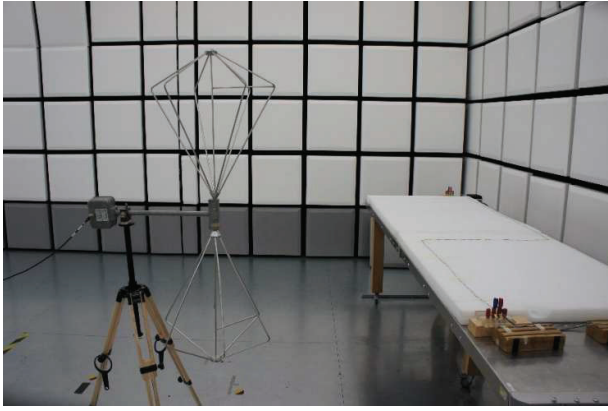


Fig. 7. Picture of RE measurement set-up with biconical antenna.

TABLE I. DATA LOSS DURING CS TEST WITH CONTINUOUS WAVE

Cat.	UTP		Bifilar	Single wire		STP
	<i>M</i>	<i>W</i>	<i>W</i>	<i>R</i>	<i>M</i>	<i>W</i>
1→2	7e-5%	0.66%	0.66%	23%	55% ^a	0.002%
2→1	7e-5%	0.00%	0.68%	27%	66% ^a	0.00%

^a. During single wire test Modem 1 lost communication completely and had to be rebooted

TABLE II. DATA LOSS DURING CS TEST WITH SQUARE WAVE MODULATION

Cat.	UTP		STP		UUP
	<i>M</i>	<i>W</i>	<i>W</i>	<i>Y</i>	<i>W</i>
1→2	0.69%	1.45%	0.61%	0.33%	1.672%
2→1	0.79%	0.97%	0.55%	0.97%	0.53%

for PLC, since the PLC signal only has frequency content between 2 MHz and 42 MHz. However, RE measurements were performed to gather some insight and, since some specific EMC test standards may still require lower frequency testing, experiments from 150 kHz up to 50 MHz. The RE tests were performed according to ED-14 version D. The test set-up is nearly equal to the CE case, except for the fact that the measurement probe is replaced by the appropriate antennas: a rod antenna from 150 kHz – 30 MHz, and the biconical antenna from 20 MHz – 50 MHz. Since for radiated emissions 1 m of cable length should be used, the cabling layout was changed such that 1 m of the total 3.3 m was laid out at the appropriate 10 cm from the table edge, while the remaining 2.3 m was directed to the back of the table. The antenna was placed in the middle of the 1 m section, at 90 cm from the table. All of this can be seen in Fig. 7. All other equipment (power supplies, etc.) were placed outside of the EMC chamber, since earlier experiments showed many disturbances that were not associated with the PLC signal.

IV. RESULTS

A. Conducted susceptibility

The results for conducted susceptibility testing are summarized in TABLE I. and TABLE II. for continuous wave and square wave modulation, respectively. As described previously, test levels (i.e. ED-14G categories) were increased until the fail criterion was met. The tables give results for various ED-14G categories (indicated under row ‘Cat.’) and cable types. For bifilar wiring an unshielded twisted pair (UTP) is used at all times, while for the wire pair case

variations were also made between a UTP, an unshielded untwisted pair (UUP) and shielded twisted pair (STP). The tables indicate the percentage of messages that were lost in the bi-directional communication over the period of a test (~30 minutes). Clearly, the single wire configuration suffers a lot from these disturbances since already at category R in continuous wave, much more than 3% of message loss occurs. Twisted wire pair including bifilar show much better results with only about 0.6-0.7% message loss at category W. Results were similar to the case of untwisted wire pairs, which makes sense since the disturbance is injected in common-mode. Once a shield is applied, message loss decrease even further.

Square wave modulation introduces a slightly increased challenge for PLC, caused by additional harmonics. Only the wire pair configuration was tested with this modulation with either UUP, UTP or STP wiring. For these wiring types, message losses are slightly higher with square wave modulation than for the CW testing, however all are below the pass/fail criterion.

B. Conducted emissions

Fig. 8 shows measured conducted emissions for four different wiring configurations, compared with the ED-14G limit for powerline categories L, M & H. The single wire case is shown by the blue line, which again shows that this wiring type does not comply with EMC regulations for this CE category. For the entire frequency range, the measured currents exceed the given limit line. The red line in Fig. 8 shows the results for the wire pair configuration, in which a UUP has been used. Measured conducted emissions have greatly improved and are now below the limit line. Results of a UTP are similar and, therefore, not shown. However, Fig. 8 shows that if an STP is used (purple line), the conducted emissions are reduced to a level indistinguishable from the measured noise floor. Finally, the yellow line in Fig. 8 shows the measured conducted emissions for the bifilar wiring case, for which an unshielded twisted pair was used. The results are not as good as for a shielded twisted pair, however they show a significant improvement over both the single wire and unshielded wire pair configurations. Most importantly, all results are clearly below the ED-14G limit.

A remarkable effect, shown particularly well in the conducted emission results of the UTP, is that there appears to be a steep increase due to a resonance around 40 MHz. This is

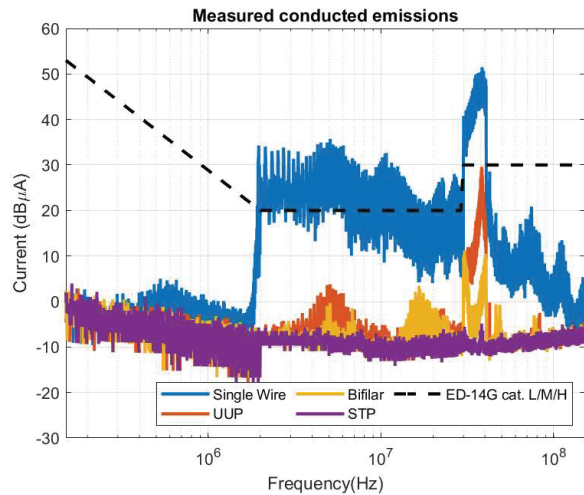


Fig. 8. Measured CE of PLC in four wiring configurations

atypical for OFDM-based PLC communications, since the PSD is roughly constant over frequency (see Fig. 2). Further experiments showed that the resonance at 40 MHz disappears when the 3.3 m cable is replaced by a 0.95 m alternative, shown in Fig. 9. Contrary to expectations, decreasing the cable length introduces a new resonance at a lower frequency. Simulations were performed with CST Cable Studio to better understand this behavior, since the 40 MHz resonance has very little margin with respect to the given limit line. In this simulation, all geometric aspects of the test set-up have been accounted for, and so are specific details of the PLC modem with capacitive coupler. Results of CM currents for the two cable lengths, shown in Fig. 10, confirm the effect of a first resonance at lower frequency for the 95 cm case. Impedance analysis has shown that the combined effects of cable and coupler impedances cause a peak in impedance, which is reflected in transmission (see S_{12} in Fig. 11), implying a very well-matched system at that specific frequency. Luckily, in actual aircraft installations it may be expected that these particular resonances cause little risk, since having multiple cables with varying lengths and branches in a bundle tends to make resonances less pronounced [3]. Further testing in ADENEAS will investigate these effects.

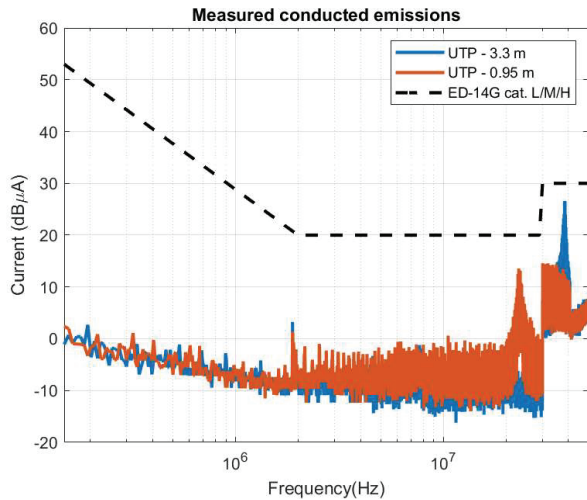


Fig. 9. Measured CE on unshielded, twisted wire pair PLC configuration with the original and reduced cable lengths

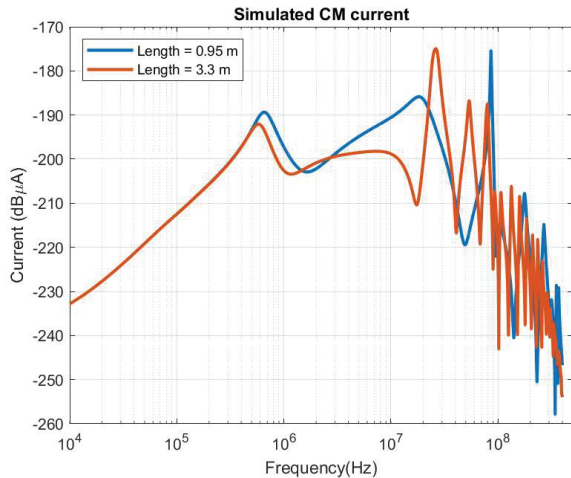


Fig. 10. CST simulated CM currents for the original cabling layout (red) and a reduced cable length between the two junctions of 0.95 m (blue).

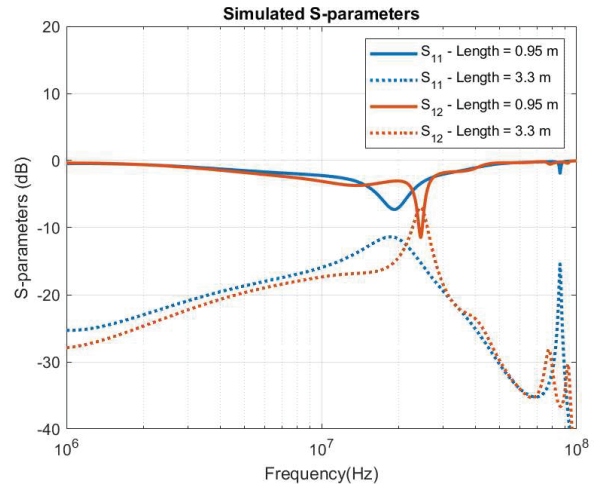


Fig. 11. CST simulated S-parameters for the original cabling layout (red) and a reduced cable length between the two junctions of 0.95 m (blue).

C. Radiated emissions

Radiated emissions are separated in two frequency ranges, one measured with the rod antenna between 150 kHz and 30 MHz, while the region from 20 MHz up to 50 MHz is measured with a biconical antenna. The latter has been measured in horizontal and vertical polarization, but only vertical polarization is shown (conclusions for the other polarization are similar). Some overlap in frequency range is intended, since it is known that these two antenna types can yield slightly different results.

Fig. 12 and Fig. 13 show the measured radiated emissions for the four wire configurations of PLC, compared to the category M limit line of ED-14D. For the single wire case shown in blue, radiated emissions clearly exceed the limits over nearly the full frequency range of PLC. The return signal via the ground plane creates a large loop that radiates. If this loop is decreased by having a dedicated return wire (the wire pair case), the radiated emissions decrease (red line). In the lower frequency range, the limit line is only exceeded by 5-10 dB around 25 MHz. This is not observed in the measurement of the same frequencies with the biconical antenna. In the higher frequencies, the results nearly comply with the given limit. Only a few frequency points exceed the limit by a few dB. The purple line shows results when shielding is applied. The results from the lower frequency range show only a slight change, resulting in the fact that at 25 MHz the emissions are only a few dB above the limit. For the higher frequency range, the results are actually better, and the radiated emissions fully comply with the limit. Finally, the yellow line shows the measured radiated emissions for the bifilar wiring case. Clearly, in terms of RE, the bifilar case seems to be superior to all other wiring cases. For this wiring type PLC complies with the given limit over the entire frequency range.

D. Summary

The results of all three test types, and all wiring types included in testing, are summarized in **Error! Reference source not found.** Here, P indicates pass under the given categories, F indicates that in all categories, the configuration failed the given test, and C indicates a conditional pass. This overview shows that PLC on the single wire configuration is not robust in terms of EMC. All other wiring configurations

perform well, since all tests are passed (some conditionally with respect to RE). The bifilar

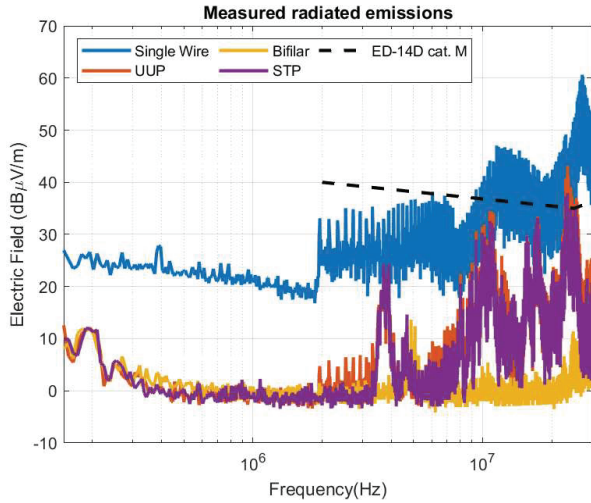


Fig. 12. Measured RE with rod antenna on PLC in four wiring configurations

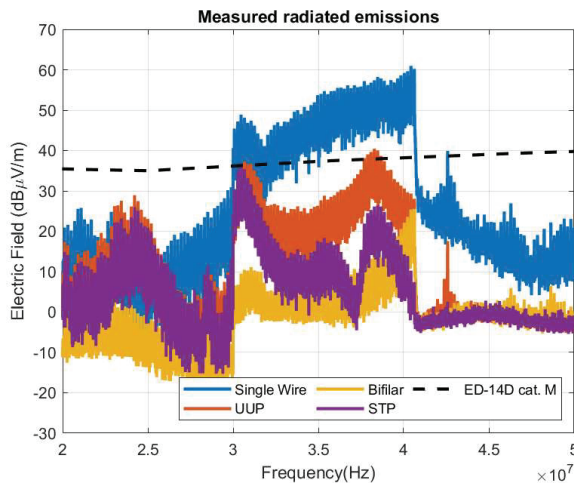


Fig. 13. Measured RE with biconical antenna in vertical polarization on PLC in four wiring configurations

TABLE III. SUMMARY OF EMC TEST RESULTS ON PLC^a

	STP	UTP	UUP	Bifilar	SW
CS	P cat Y	P cat W	P cat W	P cat W	F
CE	P cat L/M/H	P ^b cat L/M/H	P ^b cat L/M/H	P cat L/M/H	F
RE	C ^c	C ^c	C ^c	P (cat M)	F

^a. P = Pass, under given category. F = Fail. C = Conditional pass

^b. Risk of resonance at 40 MHz reduced by physical explanation by measurements/simulations

^c. A few frequencies slightly exceed given limit

wiring case outperforms the STP, UTP and UUP configurations in radiated emissions. This is most likely due to the use of inductive coupling for the bifilar case which has a more constant impedance over all frequencies compared to a capacitive coupling. However, for conducted susceptibility, the STP configuration passed a higher category, and also conducted emissions were lower for this wiring type.

V. CONCLUSIONS

The robustness of PLC with respect to EMC has been analyzed by an EMC measurement campaign covering conducted susceptibility, as well as conducted and radiated emissions. Three wiring types have been evaluated: single wire with structure as return, bifilar wire with structure as return, and a wire pair with dedicated return wire. The single wire configuration has proven to be the least robust in terms of EMC, since it resulted in a fail for all given tests. Therefore, in cases where the single wire with return via structure is applied, such as for DC power in existing aircraft, the bifilar wiring concept would be a very suitable alternative. This wiring type replaces the single wire with two smaller conductors. It does not change the power distribution since these currents still flow in common-mode over the two conductors and back via structure. However, the main advantage is the differential-mode superposition of the PLC signal, making this configuration very robust with respect to EMC, since it passed all the given EMC tests. Finally, in cases where wire pairs are applied for power distribution, for instance AC power in existing aircraft, the application of PLC is always resilient to EMC. Already for UUP all tests resulted in a (conditional) pass. Twisting does not affect the measured results much, while shielding does improve both conducted emissions and susceptibility. If compliance with CS categories higher than W is required, shielding should be applied.

Finally, a resonance around 40 MHz in the conducted emission measurements of UUP and UTP cables was observed. Since these resonances leave very little, or even no, margin with respect to the given limit line, a physical explanation was sought by means of further experiments and simulations. This yielded the conclusion that such resonance is caused by a resonance in the combined coupler and cabling impedance. This implies a very well-matched system at that specific frequency, yielding the resonance in conducted emissions. In real aircraft installations, this effect is anticipated to be less pronounced, which should be confirmed by future measurements.

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