

PROJECT FINAL REPORT

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1 **DAPHNE final publishable summary report: executive summary**

Developing Aircraft PHotonic NEtworks (DAPHNE; 233709) www.fp7daphne.eu

The target of the project was to bring the benefits of photonics to aircraft data communications by implementation of a highly integrated optical infrastructure capable of supporting multiple aircraft networks over a lighter and more modular physical layer, thereby improving performance (connectivity, flexibility, bandwidth and channel count) and aircraft cost-of-ownership compared with today's diverse electrical data communications infrastructure. This objective was tackled at three technical levels:

1. Networks: Adapt optical network technology for aircraft platforms

New aircraft network elements and technologies using photonics were developed through DAPHNE:

- High definition camera data over optical fibres
- Differential GPS system incorporating optical fibre for aircraft attitude determination
- Fibre structural health monitoring data through an optical rotary joint
- Prognostic Health Monitoring devices integrated in a fibre network
- Software models of optical networks for system design
- Through Life Support equipment.

2. Modules: Define a modular infrastructure for aircraft fibre optic networks

DAPHNE considered the housings, cables and harnesses necessary to provide a modular network:

- Remote housings with locking mechanism
- Singlemode (SM) and multimode (MM) optical fibre cable for aircraft installations
- SM and MM breakouts from multi-way cables
- Optical and electronic connector interfaces for modular aircraft equipment boxes.

3. Components: Develop existing photonic component technology for aircraft environments

Over twenty photonic components were developed and/or tested for aircraft use, including:

- Single transceivers, quad transceivers and 12 channel emitters and receivers 850 nm
- Single transceivers 1310 nm (DLS)
- WiFi RF over fibre transceiver (INESC)
- 10 GHz RF over fibre transmitter (G&H)
- Wide bandwidth optical receiver for RF optics (G&H)
- Harsh environment fused couplers (G&H)
- Ruggedised planar 1×16 splitters (SQS)
- Simplex in-line splice (AVO).

Throughout the project, DAPHNE has worked closely with the aircraft and photonics industry to disseminate information on its progress, especially through the DAPHNE Advisory Group and the project website.

Conclusion

The widespread application of fibre optic and photonic technology on aircraft is a long-term process, and a host of practical, technical, standardisation, certification and commercial problems must be overcome. DAPHNE has tackled many of these problems head-on, and provided a wide range of new hardware and techniques to help achieve the project objective. The consortium hopes to continue to work towards the DAPHNE objective in the coming years.

2 DAPHNE project context and objectives

2.1 DAPHNE project context

Aircraft data networks have increased dramatically in complexity and functionality throughout the history of powered flight. Modern networks must support a large number of nodes with a wide range of span lengths, bandwidths and communication protocols. Existing systems, chiefly based on copper conductors of electrical signals, have evolved to support these ever-increasing demands. Despite improvements in copper cable technology, these networks have consequently become more complex, larger, heavier and more expensive, and this trend is set to continue. A coordinated step change to fibre optic technology would reduce size, weight and cost and improve the modularity, flexibility and scalability of the network. By defining networks according to a DAL-based hierarchy using the latest optical components, the flexibility of photonic technology can be harnessed in a practical system within the constraints of safety certification restrictions. Moreover, fibre optics brings other implicit advantages including EMC immunity and improved security.

The boom in photonic technologies for terrestrial telecoms markets has provided a rich source of techniques and components, which may be adapted for aerospace environments. However, research and development work is required in order to put photonics on a level playing field with legacy technologies so that the advantages of photonic networks may be brought to avionic systems. Several key explicit technology developments have been identified, through work already carried out by members of this consortium. DAPHNE has addressed these technology gaps and helped to drive forward solutions within the recognised standardisation bodies, to bring the advantages of integrated photonics networks to avionics. The DAPHNE consortium has identified cabin systems as the most immediate application area for implementing photonic networks. Here the need for high flexibility/re-configurability (driven by customisation), high bandwidths (driven primarily by information-to-the-seat), large number of nodes, and the increased use of composite fuselage structures mean that the technology and business case for photonic networks is compelling.

2.2 DAPHNE project objectives

DAPHNE objective: Enable the use of integrated modular photonic networks on aircraft

To bring the benefits of photonics to aircraft data communications by implementation of a highly integrated optical infrastructure capable of supporting multiple aircraft networks over a lighter and more modular physical layer, thereby improving performance (connectivity, flexibility, bandwidth and channel count) and aircraft cost-of-ownership compared with today's diverse electrical data communications infrastructure.

This objective was tackled from four directions:

- Networks: Adapt optical network technology for aircraft platforms
- Modules: Define a modular infrastructure for aircraft fibre optic networks
- Components: Develop existing photonic component technology for aircraft environments
- Dissemination: Disseminate project results to aircraft industry to ensure effective uptake

2.2.1 Networks

A wide range of fibre optic network topologies and communication techniques have been developed for terrestrial systems: these were analysed, adapted and optimised for representative aircraft platforms (large and small aircraft; rotary and fixed wing).

- *Analysis of photonics network techniques modified for aircraft topologies:* Many networking techniques have been developed in photonics for a wide range of network systems. DAPHNE assessed the requirements for existing and future aircraft networks, and considered the application of these optical networking technologies to next generation aircraft.
- *Optimisation of network architectures:* Software modelling of physical optical layers for various airframes, including embedded physical layer, with quantified analysis of performance with “real” modelled components and the effect of environmental factors was carried out to optimise topologies for future aircraft networks.
- *Network validation:* Extended network functional and environmental testing under aircraft operating conditions was carried out to verify the networks’ performance. Critical system safety testing including reliability and failure modes was considered. Compatibility of the individual network components was studied and the network data transmission characteristics measured.

2.2.2 Modules

DAPHNE aimed to define draft standards for a scalable, modular infrastructure for aircraft fibre optic networks. This infrastructure includes node and interconnect concepts aimed at integrating networks distributed throughout an aircraft. The recognised avionic standards bodies were kept informed of the project progress and requirements:

- *Blade-based module design:* A modular “blade” concept building block system suitable for aircraft environments was studied, compatible with the optimised network architecture. Fibre handling and routing within a confined environment was examined. Standard practices for optical signal management from circuit board level to the external connector interface were considered.
- *Modular scalable avionic housing recommendations for photonic systems:* Standard avionic boxes (*i.e.* ARINC 600 or ARINC 404 series) have a standardised set of widths and depths which are used to house a wide range of equipment. This series of housings was designed to accommodate electronic interfaces, and is unnecessarily large and heavy for photonic applications. Photonic modules tend to be small in size, with the external size largely defined by the bend radius of the fibre within the module. DAPHNE has proposed a new standard series.

2.2.3 Components

A range of COTS photonic components has been developed for commercial terrestrial markets. Key devices and components for the DAPHNE infrastructure require specific adaptation and will be developed to make them suitable for use in aircraft operational environments. The detailed requirements were identified from baseline studies. In addition, several elements were identified by the DAPHNE partners that would greatly improve the prospects of an aircraft fibre optic common platform:

- *Ruggedisation of COTS components for aircraft environments:* Components may be required to operate in a number of different environments; some are relatively benign (*e.g.* inside a conditioned avionics bay) but others are extremely demanding (*e.g.* near an engine, on landing gear). Development work is required in order to ruggedise COTS photonic components, both passive and active, for these harsh environments.
- *Development of compact intra-module fibre handling:* Fibre within an LRU (line replaceable unit: *i.e.* a module containing electronics) is not subject to such a harsh physical environment as that outside the protection of the module, *e.g.* in the loom itself. Consequently the fibre and connectors within housings may be smaller and lighter; this in turn can reduce the size and weight of module housings.

- *Full duplex MM fibre-optic transceivers:* It is common for several closely spaced point-to-point nodes to have their own individual long copper links routed along the same path, *e.g.* sensors mounted in the wing or tail. These signals could all be carried (at different wavelengths) over a single fibre using a simple WDM system, or through different fibres in a ribbon.
- *Symmetric bend radius ribbon fibre:* Ribbon cable is a light and efficient method of routing and terminating many fibres simultaneously. However, there has been limited utilisation in of this fibre in the aerospace industry because it has different bend radii perpendicular and parallel to the plane of the ribbon. This has often been reported as making it too difficult to use in space-critical avionic wiring looms. Consequently a ribbon fibre with more symmetric handling properties was developed.
- *Single and multiple ribbon fibre break-out:* The infrastructure for ribbon fibre will be developed to permit easier access to individual fibres within the ribbon. This work includes single and multiple break-out from the ribbon for peripheral fibres (*i.e.* the fibres on the outside of the ribbon) and those within the centre of the ribbon.
- *Standardised interfaces:* a well-defined mating point interface between the component and the network would greatly improve the compatibility of components from different manufacturers without needing to specify the connector itself.

2.2.4 Dissemination

The uptake of the results by industry is essential to the project success: as with most standards-based activities a “critical mass” is required in order for the results to be efficiently exploited. DAPHNE has used the industrial and standards body connections of its consortium to disseminate the project results.

- *Initiate and encourage standardisation of project results:* It is essential that the results of the work are well publicised, in particular with the avionics standards bodies, so that the momentum required to establish the common platform may be gathered. The DAPHNE consortium benefits from high level participation on the relevant committees within Europe (both at ASD-STAN and various national-level bodies) as well as key international bodies (primarily ARINC and SAE-ASD). Throughout the project, the results were recommended for standardisation to the appropriate committees, and the painstaking task of issuing standards has begun.
- *Dissemination of project results to industry:* In order to build support within the aerospace and specialist photonic industries for the DAPHNE common platform, the aims and results of the project have been publicised to target organisations and individuals through the judicious use of conference presentations, peer-reviewed journal publications and existing industrial relationships. There have also been technology transfer workshops to promote the project results.
- *Establish Advisory Board:* The creation of the DAPHNE Advisory Board has enabled the consortium to engage relevant actors in the aerospace value chain, from component suppliers, through equipment manufacturers to end-users (*e.g.* airlines and MROs (maintenance, repair and overhaulers)) to ensure that a wide section of industry is aware of and given the chance to validate the concepts and solutions developed in the DAPHNE project.
- *Encourage the EU dominance of avionic technology:* The use of photonics for aircraft communications systems is still in its infancy. DAPHNE will improve the position of the EU avionics industry by establishing the centre of mass of avionic photonic expertise firmly in Europe.

3 DAPHNE S&T results

3.1 Overview

DAPHNE has had an extremely active technical programme which has greatly advanced the technology of fibre optics on aircraft. The project has made significant achievements in each of the three target technical areas. In the following few pages the headline results are listed. Then a slightly more detailed analysis of some of these results is presented.

For more information please look on the DAPHNE website (www.fp7daphne.eu) or contact:

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For details on specific technologies, contact details are given in the descriptions later in the document.

3.1.1 Networks

New aircraft network elements and technologies using photonics were developed through DAPHNE:

- High definition camera data over optical fibres
 - HD cameras are used in an aircraft for taxi aids, all weather flying and internal security applications. Typical signal data rates are c. 1.5 Gbps, which requires heavy high grade electrical cable. Replacement of this cable by an optical fibre enables a considerable weight reduction, noise immunity and multiplexing with other services. G&H with advice from AgustaWestland demonstrated photonic solutions suitable for aircraft environments.
- Differential GPS system incorporating optical fibre for aircraft attitude determination
 - INESC developed and demonstrated the transmission of differential GPS signals over singlemode fibre for aircraft attitude determination, as an important application among the different possible subsystems suitable for RF over fibre deployment. Results show that the system has an RF gain around 0 dB at the frequency of interest (1.5 GHz), a high 1 dB compression point of +5dBm and an SFDR of 91 dBHz^{2/3}.
- Fibre structural health monitoring data through an optical rotary joint
 - G&H has built and tested a singlemode rotary joint and its performance has exceeded specifications. They have also evaluated the transmission of RF over fibre signals through the rotating joint with no significant signal degradation.
- Prognostic Health Monitoring (PHM) devices integrated in a fibre network
 - Fibre structural health monitoring data through an optical rotary joint (AW, G&H, BAES) on helicopters were evaluated on rotating parts in an aircraft such as rotor blades, turrets and undercarriages. Strains in a rotor blade up to the 360 rpm operating speed of a helicopter main rotor were measured. BAES developed a sub-network that highlights the ability of the optical network to multiplex disparate data types onto a single fibre, i.e. PHM devices integrated in a fibre network.
- Software models of optical networks for system design
 - Software models of optical avionic networks for system design on aircraft were developed at TUI and DTU. A number of physical parameters characteristic for avionics were identified. Based on practical requirements identified within the project, experiments on how to upgrade an already existing deployed infrastructure in an aircraft have been carried out.
- Through Life Support equipment
 - Using the MR³ philosophy, existing through-life support equipment was tested by AVO & BAES, adapted and/or developed to meet the requirements of new fibre optic technologies

being investigated for aircraft. Development of existing tooling was performed to produce prototypes of tooling and a bill of materials for a kit that could support MT and ribbon technologies.

3.1.2 Modules

DAPHNE considered the housings, cables and harnesses necessary to provide a modular network:

- Remote housings with locking mechanism
 - SQS & Airbus developed and tested the LASIN lock mechanism on RM boxes with EN4165 connector shells and inserts as well as optical contacts with an operating temperature range from -70°C up to +155°C. This form factor and locking mechanism, both developed in DAPHNE, are being proposed by Airbus as an international (ARINC) standard. The RM boxes were vibration tested according to RTCA D0-160E standard (for up to 2kHz and 20g). The system offers secure and controlled insertion with uniform insertion of the rail-guided box into the rack and protection against damage of hidden mechanical parts.
- Singlemode (SM) and multimode (MM) optical fibre cable for aircraft installations
 - Draka, BAES and AVO worked on a comprehensive review of the technologies for supporting SM and MM fibre optics in airframes. This study included looking at installation techniques such as looming and mounting as well as testing, training and system design. As a result of this work several recommendations were formulated; these included a common maintenance strategy known as MR³ (Maintain, Renew, Repair, Replace) which represents how fibre optics should be dealt with on-board an airframe. The MR³ philosophy has also been presented to the ARINC fibre optic subcommittee.
- SM and MM breakouts from multi-way cables
 - SQS and BAES developed and tested SM and MM breakouts on an avionic grade 12-channel round ribbon cable, a 12-channel flat ribbon cable and tubing.
- Optical and electronic connector interfaces for modular aircraft equipment boxes
 - D-Lightsys looked at optical and electronic connector interfaces for modular aircraft equipment boxes. The solutions developed include rectangular modular connectors for optical and electrical contacts that provide more flexibility, improved performance and higher density compared to standard circular MIL-spec connectors.
- Avionic Gigabit Ethernet
 - The general purpose avionic Gigabit Ethernet module is based on a modular rugged avionic (harsh environment) housing that fully exploits and implements the modularity requirements together with the optical routing network technology. Avionic Gigabit Ethernet provides a long term answer to the modularity concept, implementing demanding architecture in terms of reliability, portability and reusability.
- Gigabit Ethernet media converters for aircraft installations
 - The Gigabit Ethernet media converter architecture consists of a conduction-cooled mechanical enclosure containing a PCB board with outline dimensions similar to PC104 standard and modular connector EN4165. This module implements Gbit Ethernet electrical to optical conversion from 1000BASE-T to 1000BASE-SX/LX.

3.1.3 Components

Over twenty photonic components were developed and/or tested for aircraft use, including:

- Single transceivers, quad transceivers and 12-channel emitters and receivers for 850 nm and single transceivers at 1310 nm (DLS)

- D-Lightsys has developed modules (single transceivers, quad transceivers, 12 channel emitters and receivers at 850 nm with a high bit data rate which are already qualified for military and avionics application. Today these modules are integrated in embedded equipment in civil and military aeronautics programs. In collaboration with VCSEL developers, a 1310 nm transceiver was developed with the optical power coupled into a SM fibre.
- WiFi RF over fibre transceiver (INESC)
 - INESC has developed a network which consists of a bi-directional fibre optic transmission of WiFi RF signals over MM optical fibre, for example for the distribution of infotainment services to passengers inside the aircraft cabin.
- 10 GHz RF over fibre transmitter and wide bandwidth optical receiver for RF optics (G&H)
 - G&H has made a 10 GHz transmitter module based on a 1310 nm distributed feedback laser and a 20 GHz InGaAs receiver for a wavelength range between 1260 and 1620 nm.
- Harsh environment fused couplers (G&H)
 - G&H developed a range of fused couplers specifically designed for harsh environments, including a wide band fused 50:50 coupler and a WDM coupler for 1300 and 1550 nm.
- Ruggedised planar 1×16 splitters (SQS)
 - SQS built and tested PLC splitters in a number of common configurations up to a splitting ratio of 1x16 for harsh environment applications.
- Simplex in-line splice (AVO)
 - At AVO two prototype designs for in-line splicing of an optical fibre loom were developed, produced to specification and subjected to system testing. The results for optical and mechanical performance were good.

3.2 DAPHNE network technology

3.2.1 High definition camera data over optical fibres (G&H)

Contact: Mark Farries (G&H): mfarries@goochandhousego.com

HD cameras are used in an aircraft for taxi aids, all weather flying and internal security applications. The signal data rate of 1.48 Gbit/s requires high grade electrical cable which is heavy. Replacement of this cable by an optical fibre enables a considerable weight reduction, noise immunity and multiplexing with other services as shown in Figure 1.

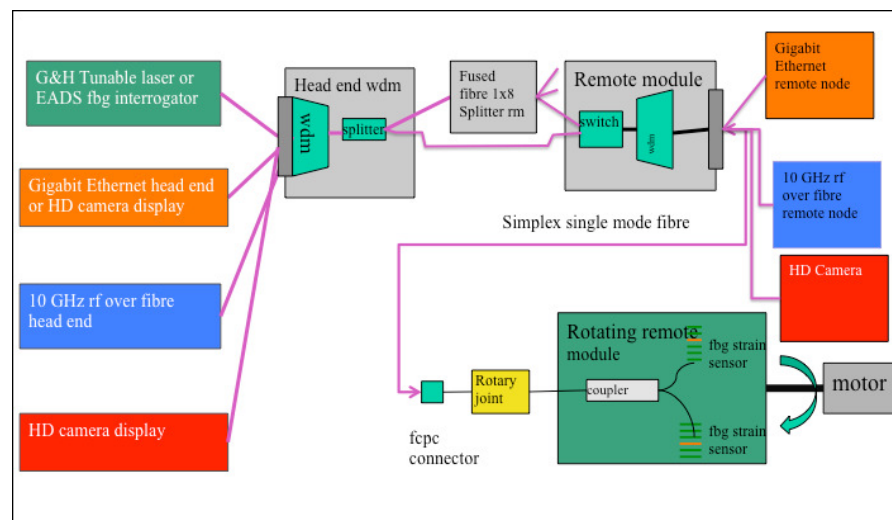


Figure 1 SM network for HD camera transmission

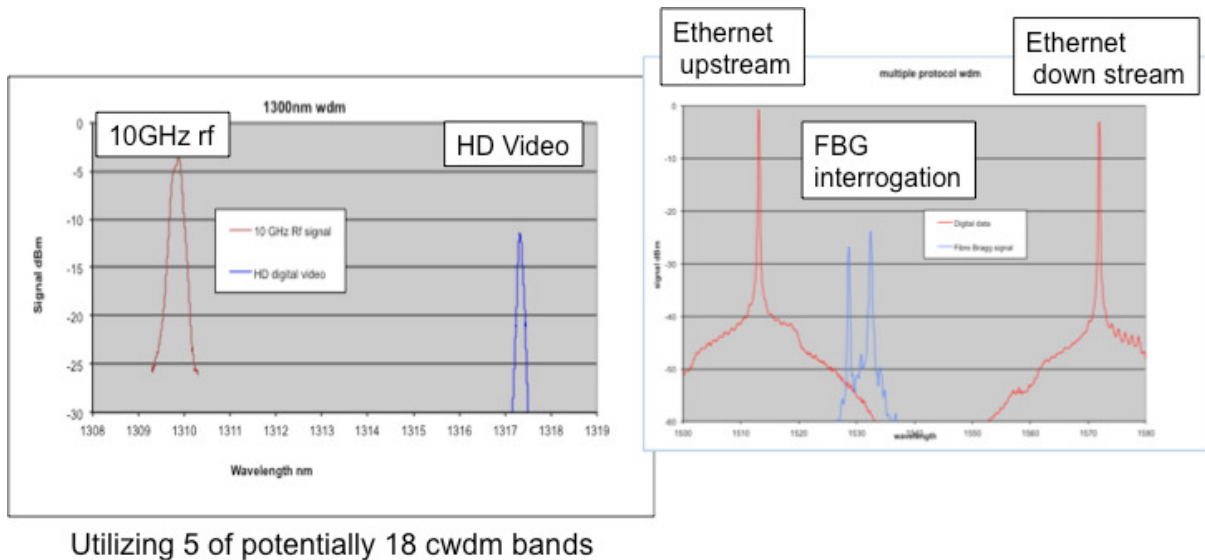


Figure 2 HD video combined with other protocols on a fibre network

G&H will exploit this work through the development of single mode fibre systems for aircraft.

3.2.2 Differential GPS optical fibre system for aircraft attitude determination (INESC)

Contact: Joao Oliveira (INESC): jmbo@inescporto.pt

We emphasize the transmission of differential GPS signals over SM fibre for aircraft attitude determination, as an important application among the different possible subsystems suitable for RF over fibre deployment. It consists in performing carrier-phase differential processing of measurements from GPS antennas affixed to the frame of the aircraft, which yields centimeter- or millimeter-level accuracies, provided that integer phase ambiguities are resolved. The attitude algorithm consists in a highly accurate real time kinematic (RTK) technique, given the short baseline distance between antennas, in which the main antenna acts as a Base station and two auxiliary antennas as Rovers. In the project demo, we consider a setup consisting of two-antennas (Base and Rover), which is enough to evaluate the RTK performance. The novelty of this demo stems from the different aspects of carrying such GPS signals over optical fibre, which according to our knowledge, has not been previously addressed in the literature.

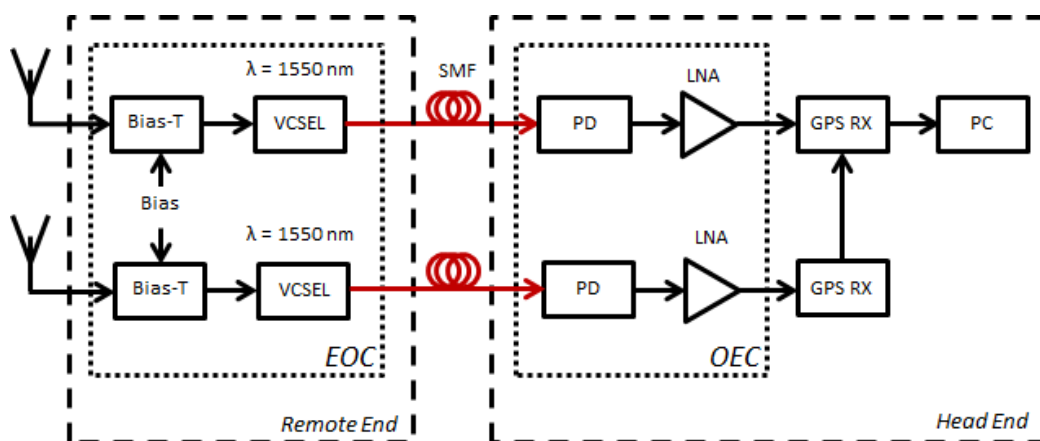


Figure 3 GPS over fibre network diagram.

Specifically, the DAPHNE optical fibre infrastructure may provide connectivity from external antennas (through remote nodes) to RF transceivers installed in the cockpit and avionics bay (head-end nodes). A key aspect of concern stems from the fact that the transmission of optical signals through a complex optical fibre network is subject to the occurrence of reflections in the multitude of connectors spanning the

path between a remote node and a head-end node. Therefore, this demo focus on the performance impact induced by optical reflections, specifically on the power level stability of the optical source which may have significant impact on the GPS receiver performance, not only in the positioning accuracy but more importantly in the time required to resolve the integer phase ambiguities of the GPS signal.

This network consists of a unidirectional transmission of GPS signals over SM optical fibre, up to the avionics bay where the GPS receiver is placed. By sending GPS signals over optical fibre and comparing the phase of signals received from antennas at different locations on the aircraft, its attitude (pitch, roll, yaw) may be deduced with high precision without the need for bulky copper cables.

The remote end is composed by two antennas and two PCBs that contain identical electric to optical converter circuits, one for each antenna signal. Each circuit is composed of a 1550 nm VCSEL and bias circuits for both antenna and laser, which are deployed in a custom RF shielded metal box.

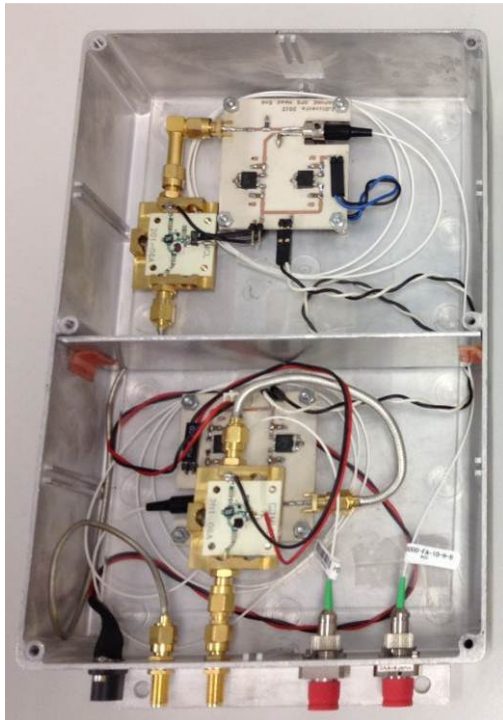


Figure 4 GPS over fibre head end

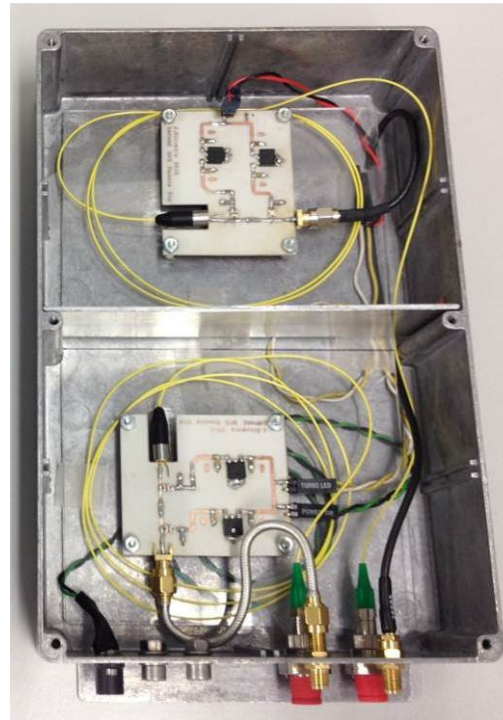


Figure 5 GPS over fibre remote end

At the head end, two PCBs with photodiodes followed by low noise amplification are responsible for the optical to electrical conversion. Bias circuits for both LNAs and photodiodes are also present. Then, the electrical signals are fed into the GPS receivers and to the PC.

Several experimental tests were conducted in order to evaluate the performance of the system, namely the RF frequency response, SFDR and compression point. Results show that the system has an RF gain around 0 dB at the frequency of interest (1.5 GHz), a high 1 dB compression point of +5dBm and an SFDR of $91 \text{ dBHz}^{2/3}$.

Furthermore, the system performance to common optical network impairments (e.g. optical reflections, attenuation, cross-talk, different fibre lengths) was tested. Results show that the maximum optical return loss to obtain a fix of phase ambiguities of the GPS signal below 50 s (counted from the restart of the algorithm) is -25 dB. Regarding optical attenuation, a maximum value of 11 dB was obtained in order to obtain the same time to first fix mark of 50 s. For the crosstalk test a standard gigabit Ethernet signal was added to the setup at a nearby wavelength, as happens in WDM systems. No influence on the GPS fix position was observed for optical isolation values higher than 26 dB. Additionally, it was also observed that the GPS is still able to process the phase ambiguities with isolation values as low as 10 dB. Regarding the different optical fibre path lengths test, no GPS position changes were observed. The explanation for this relies on how carrier-phase (CP) GPS receivers make their measurements. With hardware that solves

double differences between satellite signals and receiver signals (such as those tested at INESC), unknown delays (such as the ones due to cable length) cancel out.

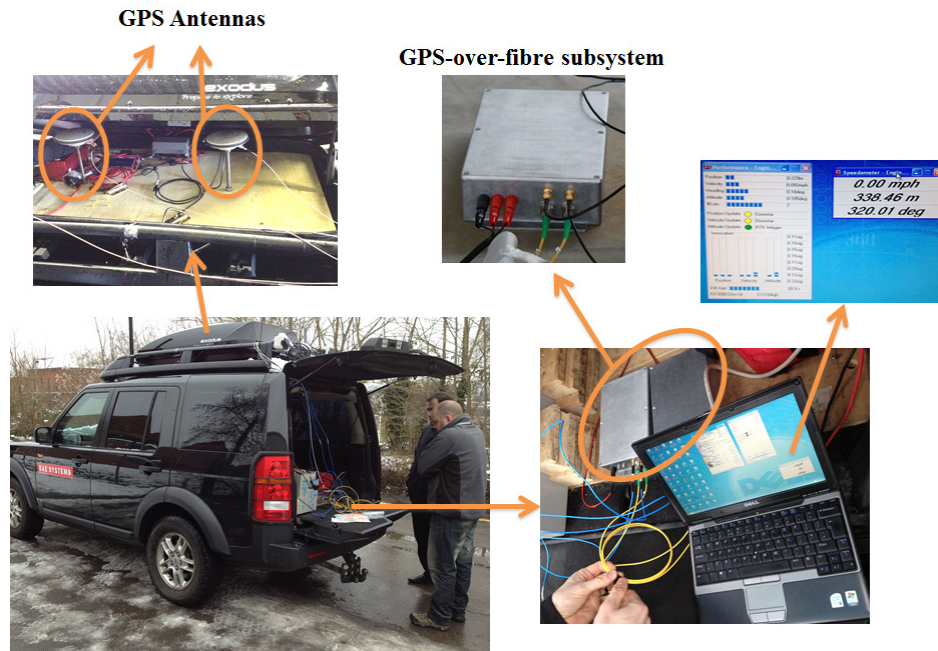


Figure 6 GPS over fibre demonstration at BAE Systems facilities.

3.2.3 Fibre structural health monitoring data through an optical rotary joint (G&H)

Contact: Mark Farries (G&H): mfarries@goochandhousego.com

The rotary joint provides a means of transmitting light from an optical fibre to and from an optical fibre in a rotating part. Typical applications in an aircraft include connections to:

- Sensors on helicopter rotor blades
- Sensors on landing gear
- Cameras and radar on turrets.

The SM rotary joint has been tested and its performance exceeded specifications. The rotary joint has been evaluated for connection to fibre Bragg gratings for structural health monitoring in rotor blades and undercarriages. The low loss variation and low return loss are critical parameters for a fibre Bragg interrogation system that requires a double pass of the rotary joint with no spurious reflections. G&H also evaluated the transmission of RF over fibre signals through the rotating joint with no signal degradation.

G&H plans to exploit this work in avionics sensor systems.

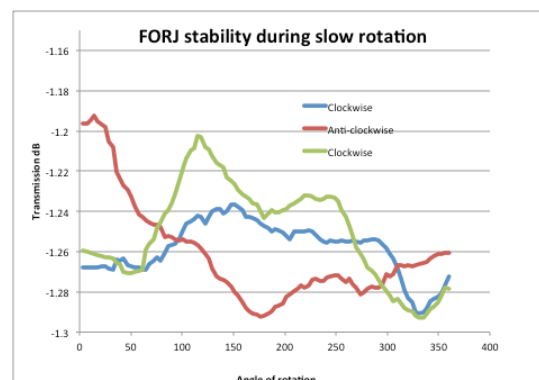


Figure 7 Stability tests on rotary joint

3.2.4 Fibre structural health monitoring data through an optical rotary joint (G&H)

Contact: Mark Farries (G&H): mfarries@goochandhousego.com

Helicopters are unusual in that many of the flight critical systems are not in the main body of the aircraft, but are rotating at high speed in the rotor head and rotor systems. Recent advances in sensor technology especially in the field of optical structural health monitoring lend themselves to the embodiment in aerodynamic structures such as composite rotor blades. One of the limiting factors to the exploitation of these reliable and relatively low cost sensors has been the difficulty in providing a reliable and effective optical pathway from the fixed helicopter fuselage to the rotating components in both the main and tail rotor heads.

Currently electrical slip rings provide an electrical path between the fixed aircraft and rotating components, but these are primarily used for high power electrical transfer (for rotor electrical de-icing systems) and in development aircraft for instrumentation. Whilst generally reliable these slip rings suffer from electrical noise and cannot support very high bandwidth signal transfer.



Figure 8 Rotary test bench with integrated rotary joint and FBGs

The availability of a SM optical slip ring provides in addition to optical sensing an extremely high bandwidth channel which could allow the installation of such systems as antennas (RF over fibre) and high bandwidth sensors such as radar and high definition camera to be installed in the rotor head. Such systems have already been used but their exploitation has been severely constrained by the high cost and complexity of their implementation.

The DAPHNE project has demonstrated an optical slip ring which has been designed such that it can be retro-fitted co-axially to an existing helicopter electrical slip ring to provide an optical channel. In addition it has developed and demonstrated RF and HD video transmission over an optical network which further reduces the risk of implementing the photonic technologies in a helicopter environment.

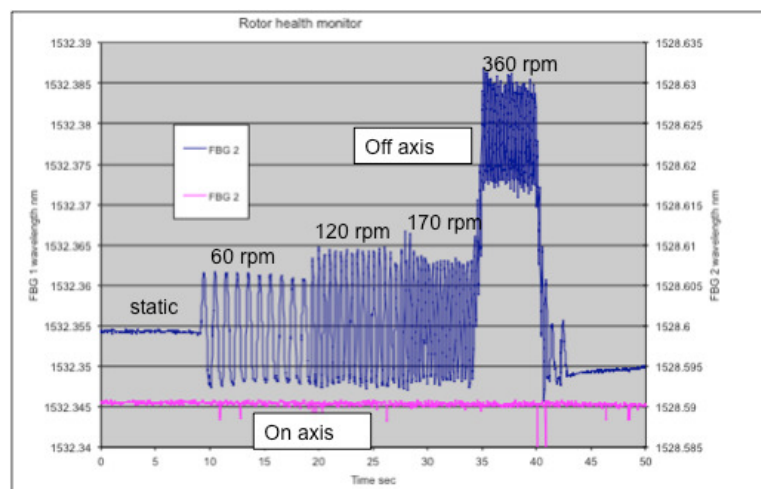


Figure 9 Measured data from strains in rotor blade

The use of an optical slip ring is not limited to helicopters and can be used where optical signals need to bridge a rotating interface. To that end, Airbus is considering the exploitation of the optical slip ring in aircraft landing/wheel systems.

The project also evaluated structural health monitoring on rotating parts in an aircraft such as rotor blades, turrets and undercarriages. This is important so that weaknesses in the parts can be detected before failure and also for dynamic control surface manipulation. Strains in a rotor blade revolving at up to 360 rpm (typical maximum for a helicopter main rotor) were successfully measured. This work will be exploited through the development of sensor systems for aircraft.

3.2.5 Prognostic Health Monitoring devices integrated in a fibre network (BAES)

Contact: Henry White (BAES): Henry.White@baesystems.com

This sub-network highlights the ability of the optical network to multiplex disparate data types onto a single fibre. An electrical Prognostic Health Monitoring (PHM) device is connected to the network by means of a suitable media converter.

A suitable serial device server was chosen and connected to the MEPHM device shown in Figure 10. This enables the MEPHM to be connected to the Ethernet network. The devices are small enough that mounting within an RM box alongside a media converter would be possible (see Figure 11) to give a self-contained optical node capable of providing details on the environmental conditions it faces.



Figure 10 Tiny Micro Electronic Prognostic Health Monitor (MEPHM)



Figure 11 MEPHM and media converter in size comparison to remote module (RM) box

For the purposes of the demonstration network, it was decided to use a PC running virtual com port software to communicate with the networked PHM device using the manufacturer supplied software. Future use would communicate directly using TCP/IP packets and this method has been proven by establishing communication with the networked device.

3.2.6 Software models of optical networks for system design (TUI, DTU)

Contact: Karin Schulze (TUI): karin.schulze@stud.tu-ilmenau.de

Inspiration for how to introduce optics to aircraft can be found in commercially deployed terrestrial systems, but aircraft applications are a niche with special requirements. During the DAPHNE project, a number of physical parameters characteristic for avionics were identified which all, to some degree, will have an impact on an actual implemented avionic systems. These include:

- Number and distribution of nodes throughout an aircraft
- Different security levels (DAL-level)
- Data formats
- Line rates (up- and downstream)
- Wide variety of zones with different environmental and physical constraints
- Vibration impact on coupling between fibres.

For the software modelling groups (TUI and DTU) the airframers were able to provide invaluable background knowledge, allowing the groups to adapt standard models to aircraft environments. Both groups have commercially adapted available software tools to address both the physical and the network layer. Models based on terrestrial technology with avionic node distribution and realistic data traffic patterns been implemented

Optical components

In both tools a wide range of components have been implemented with the necessary abstraction level needed for either physical or network simulations. A library of components was developed based on real data from commercial devices and new components developed in DAPHNE. These included: transmitters, receivers, splitters & couplers, WDM multiplexers & de-multiplexers (including CWDM), connectors, cables and optical switches. This library provides a flexible, modular tool for future modelling work.

Physical assessment

The library of building block components was used to implement software models of realistic aircraft optical networks, which were assessed on a number of parameters, including: bit error rate, optical signal to noise ratio (SNR), eye-diagrams and power budgets. These could be compared with data from real systems.

Network model features

The developed network model tool provides the following features:

- Fully executable specifications
 - Network model is connected to a database which stores all component specifications
- Generic network model (intelligent network system with self-identification and routing functions)
- WDM
- GUI for setting up and controlling the model and simulation
- 3D view of the functional network model, showing nodes and cable routes (see Figure 12).

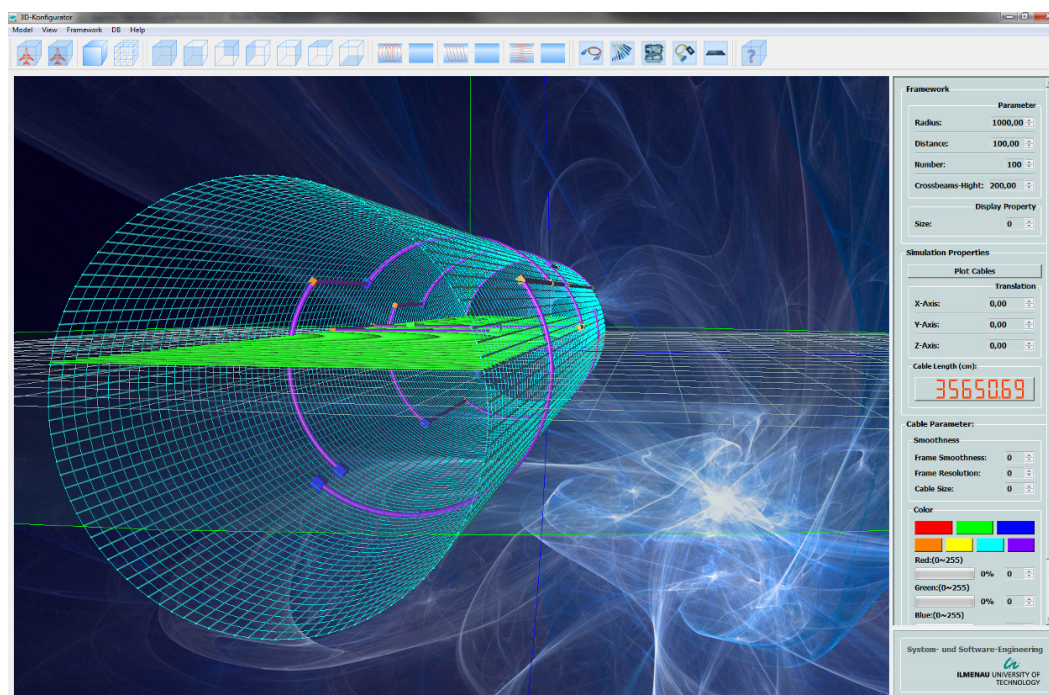


Figure 12 3D view of cable routes across frames, stringers and crossbeams

The software models for optical networks were used to model system design including the implementation of systems and sub systems (e.g. IFE and HMS). Evaluation parameters (e.g. cost, weight, energy consumption, latency, packet loss, end-to-end reliability and BER) could be compared with real data. This included experiments on how to upgrade existing deployed aircraft infrastructure.

The outcome of the project has been very rewarding for the two modelling groups and a solid knowledge base within avionics have been established, paving the way for future projects within the field, in collaboration with industry both nationally and internationally. Additionally a number of papers have been generated within the project due to this work.

3.2.7 Through Life Support equipment (AVO & BAES)

Contact: Andrew Lee (AVO): andrew.lee@avoptics.com

Using the MR³ philosophy existing through-life support equipment was tested, adapted and/or developed to meet the requirements of new fibre optic technologies being investigated by DAPHNE. Most tooling for the supporting of fibre optic systems in accordance with the MR³ philosophy was already available in kits developed by AVoptics (examples can be seen below). [NB These kits were designed to support older fibre optic technologies and did not support the new ribbon fibre MT-based technologies.]

	Maintain	Renew	Repair	Replace
Simplex Fibre Optic cables	 AVsparkle – Insitu Inspection and Cleaning	 Insitu simplex polisher	 AVLiterepair – Simplex fibre optic repair kit	Out of scope in DAPHNE

Multiway fibre optic cables	 Testing of technologies for inspection and cleaning of MT technologies	 Testing and development of methods for insitu polishing of MT technologies	 Generation of kit for support of MT technology fibre optics in an aerospace environment.	Out of scope in DAPHNE
DAPHNE Developments				

Table 1 – Table showing development of tooling in accordance with MR³

Development of existing tooling was performed to produce prototypes of tooling and a bill of materials for a kit that could support MT and ribbon technologies. Where tooling already existed it was trialled and assessed. One of the most difficult areas of fibre optic manufacture regarding the MT style connector is polishing as this typically requires a large machine polisher in order to achieve the required finish. Several options were assessed and a portable battery powered polisher was selected for polishing MT termini type *in situ*. (This can be seen in Table 1).

AVoptics will continue this work performed under DAPHNE to develop a new kit to offer renew and repair support for the use of the new MT fibre optic technologies

3.3 DAPHNE module technology

3.3.1 Remote housings with locking mechanism (SQS & Airbus)

Contact: Ilja Kopáček (SQS): ilja.kopacek@sqs-fiber.cz

SQS developed and tested the LASIN lock mechanism on RM boxes with EN4165 connector shells and inserts as well as other commercial contacts, in the temperature range from -70°C up to +155°C and vibration tested according to RTCA D0-160E standard (for up to 2kHz and 20g). This form factor and locking mechanism, both developed in DAPHNE, are being proposed by Airbus as an international (ARINC) standard. Figure 13 shows the RM box with the LASIN lock mechanism.



Figure 13 DAPHNE remote box with LASIN lock mechanism from SQS

Main features of this LASIN lock mechanism are:

- 1) Secured and controlled insertion of the rail-guided box into the rack, which eliminates potential for damage due to human error
- 2) Uniform insertion of the rail-guided box into the rack up until the moment when inserting/locking lever snaps into locking position under the beak of guillotine mechanism.
- 3) Consequent protection against damage of less visible mechanical parts in the back end of the rack.

3.3.2 SM and MM optical fibre cable for aircraft installations (Draka, BAES, AVO)

Contact: Stephane Gauchy (Draka): stephane.gauchy@prysmiangroup.com

A comprehensive review of the technologies for supporting fibre optics by the main air-framers was reviewed and assessed. This study included looking at installation techniques such as looming and mounting as well as testing, training and system design. As a result of this work several recommendations were formulated; these included a common maintenance strategy known as MR³, a recommendation for several accredited fibre optic training courses and a proposed set of standardised test conditions.

The MR³ philosophy stands for Maintain, Renew, Repair, Replace which represents how fibre optics should be dealt with on-board an airframe. Each step increases with severity of action required in order to keep a system functional. This process has been disseminated through presentations at conferences such as FOHEC and AVOptics now use this philosophy as their approach to supporting fibre optics on aerospace platforms. The MR³ philosophy has also been presented to the ARINC fibre optic subcommittee for inclusion in standard ARINC 806 – Fibre Optic Installation and Maintenance.

The training recommendations were also presented to the ARINC subcommittee for potential inclusion into ARINC 807. These recommendations suggested four levels of training for people who were to work on or near fibre optics on airframes. AVOptics is continuing to pursue agencies to see if some or all of the training levels can become accredited qualifications.

3.3.3 SM and MM cable break-out (SQS)

Contact: Ilja Kopáček (SQS): ilja.kopacek@sqs-fiber.cz

SQS developed and tested SM and MM breakouts on commercially available avionic grade 12-channel round ribbon cable, 12-channel flat ribbon cable and tubing. Both types of cable are suitable for temperature ranges from -60°C up to +125°C. However, due to limited temperature range of MPO connectors and its ferrules (as well as the connectors at the simplex ends of the breakouts) testing was limited to the temperature range -55°C up to 85°C.

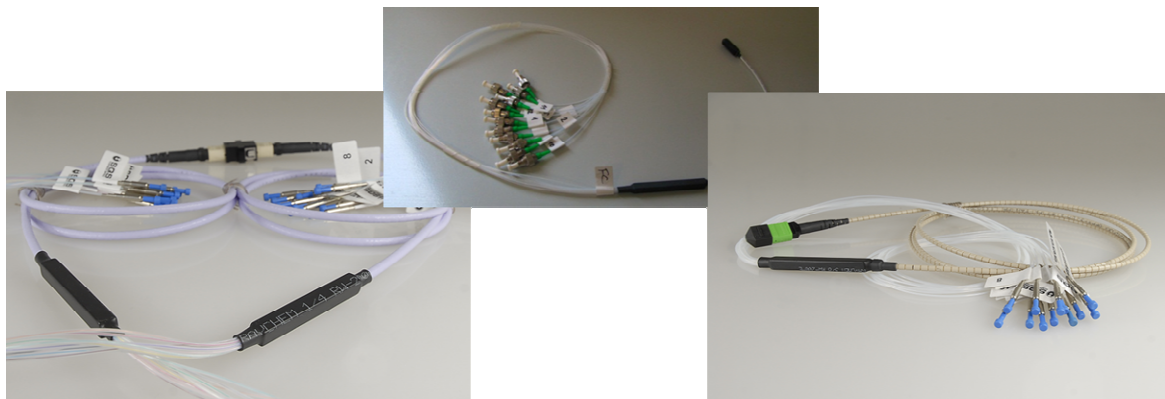


Figure 14 SM and MM breakouts with 12-channel round ribbon and flat ribbon

3.3.4 Optical and electronic connector interfaces for modular aircraft equipment boxes (DLS)

Contact: Vincent Foucal (DLS): vincent.foucal@radiall.com

DAPHNE has helped to develop connector technology that includes rectangular modular connectors for optical and electrical contacts that provide more flexibility, improved performance and higher density compared to standard circular MIL-spec connectors. DLS can now offer a wide range of solutions based on two insert sizes with a large variety of shells sizes and contacts. It provides an excellent trade-off between the number of available contacts and the space actually used.

3.3.5 Avionic Gigabit Ethernet

Contact: Massimo Traversone (SELEX Galileo): massimo.traversone@selex-es.com

Avionic Gigabit Ethernet (Head-End) provides a long term answer to the modularity concept, implementing a demanding architecture in term of reliability, portability and reusability. The Head-End developed in DAPHNE is conceived for several applications and implements the RTM (rear transition module) philosophy that helps the avionic system designers to adapt the Head-End to the Avionic System.

The RTM philosophy splits the internal connections (i.e. the motherboard) into two parts: the usual connections in relation to the chosen standard (in this case the OpenVPX VITA65) and the custom/functional part that implements all the remaining connections (i.e. the I/O signals including all the necessary interface to adapt them to the module installed into the Head-End). Therefore different avionic applications can be easily adapted by re-designing only the custom RTM.



Figure 15 : Head end developed in the DAPHNE project (SELEX Galileo)

The Head-End architecture consists of a conduction cooled enclosure with a 2 MCU (ARINC 600) electronic unit hosting EN4165 modular connectors. It interconnects the mother board (i.e. the standard part), n°2 VPX Rear Transition Module (i.e. the custom/functional motherboard), n°2 OpenVPX 3U module and a Power Supply module to convert the external avionic 28 V BUS BAR to internal OpenVPX standard voltages (+3.3 V, +5 V, +12 V, -12 V).

The chosen approach for the Head End for DAPHNE was a versatile and flexible system solution offering the possibility to switch between data streams having different physical characteristics, e.g. 100 Mbit or Gbit Ethernet, Electrical (10/100/1000 BASE-T standard) or optical interfaces (1000BASE-SX/LX standard) with different wavelengths (850 nm, 1300 nm, 1550 nm).

The Custom RTM implements all the electrical to optical transition with all the necessary peculiarities to implement the optical routing (transceiver, optical connectors etc.) and it has adopted and implemented the results of the DAPHNE project study regarding optical routing/connections.

3.3.6 Gigabit Ethernet media converters for aircraft installations

Contact: Massimo Traversone (SELEX Galileo): massimo.traversone@selex-es.com

The Gigabit Ethernet media converter architecture (Remote End) consists of a conduction-cooled mechanical enclosure containing a PCB board with outline dimensions similar to PC104 standard and modular connector EN4165. This module implements Gbit Ethernet electrical to optical conversion from 1000BASE-T to 1000BASE-SX/LX. An external power voltage of 5V is also provided.

The result of the Remote End came from a wide analysis of all the existing avionic/non-avionic housing/blade standards connected with all the implementation requirements of the optical fibre. The Remote End media converter is intended to take full advantage of technical progress in electronic equipment packaging and provide improved mechanical, electrical and environmental interface techniques for the installation of avionics equipment.

The Remote End housing can be easily placed in a system of Remote End housing where each remote end can host different functionalities, i.e. sub-module building blocks, with different blocks executing different functionalities.

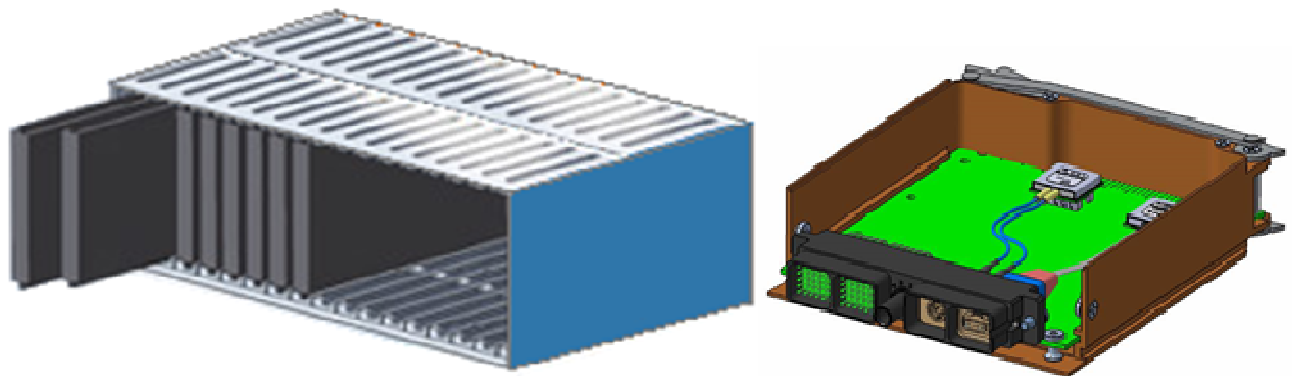


Figure 16 – Remote End pictorial view

The Remote End media converter module converts five Gbit Ethernet 1000BASE-T channels from electrical to optical (four using 850 nm MM transceivers, one using a 1310 nm SM transceiver). Since the SM transceiver is pluggable, it can easily be replaced to test different wavelengths and allows a high level of modularity. Ethernet transformers are provided to interface the electrical channels to an external standard network.

3.4 DAPHNE component technology

3.4.1 Single transceivers, quad transceivers and 12-channel emitters and receivers (DLS)

Contact: Vincent Foucal (DLS): vincent.foucal@radiall.com

D-Lightsys designs and manufactures innovative optical interconnect solutions for severe environment applications. The single transceivers, 4-channel transceivers and 12-channel emitters and receivers at 850 nm for MMF are COTS devices. The single transceiver is available for a throughput up to 4.25 Gbps and 10 Gbps. The 4-channel transceiver and the 12-channel emitter and receiver are available for a throughput up to 4.25 Gbps.

Thanks to its proprietary advanced silicon micro-machined optical sub-assembly (OSA) design, D-Lightsys is able to offer high coupling efficiency optical sub-assembly that enables harsh environment and low power consumption compatible design.

Key factors of this technology:

- OSA integrates the optoelectronic dies and pigtailed into a ruggedized part in order to improve the optical coupling and to avoid any dust, humidity or mechanical displacement between the fibres and the optoelectronic components (VCSEL and photodiode) under mechanical shocks or vibration.
- Modulation & bias current are monitored to keep a steady eye diagram over the temperature range.
- Technology qualified according to the ARINC 804 standard.

These modules can be soldered or plugged on the customer's board.

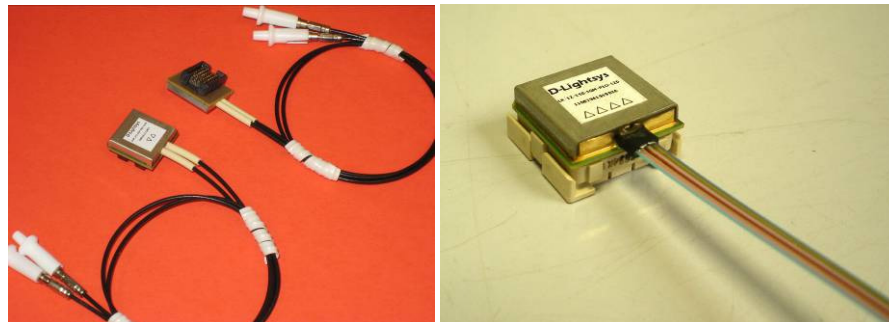


Figure 17 : D-Lightsys MM single transceiver (left) and multichannel transceiver (right)

Figure 18 shows the variation of the Tx average optical power, the Tx extinction ratio and the Rx sensitivity at 1.25 Gbps over the temperature range for a single transceiver. Figure 19 shows the variation of the Tx average optical power, the Tx extinction ratio and the Rx sensitivity at 1.25 Gbps over the temperature range for a 4-channel transceiver.

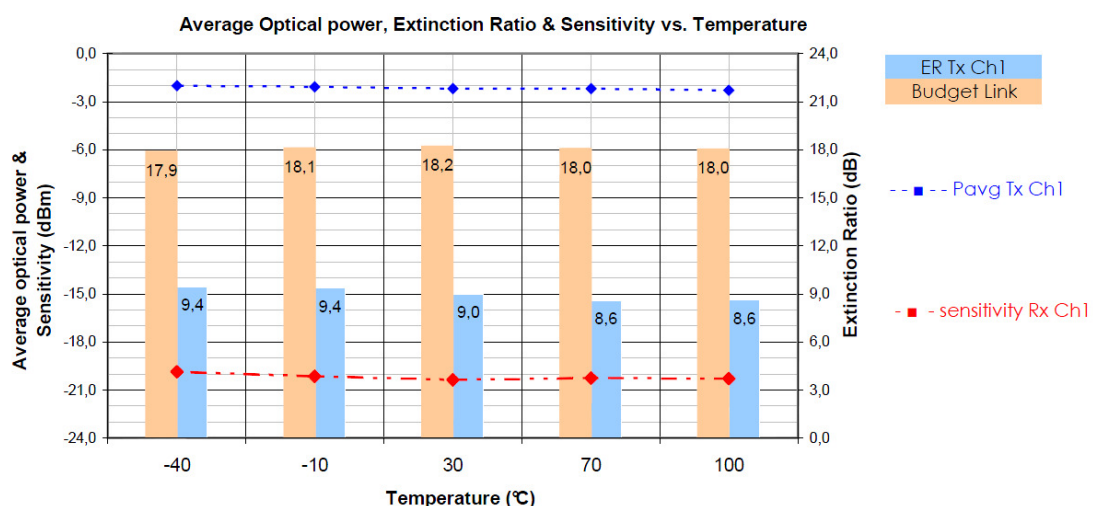


Figure 18: Tx average optical power and sensitivity as a function of temperature for a 850 nm transceiver module

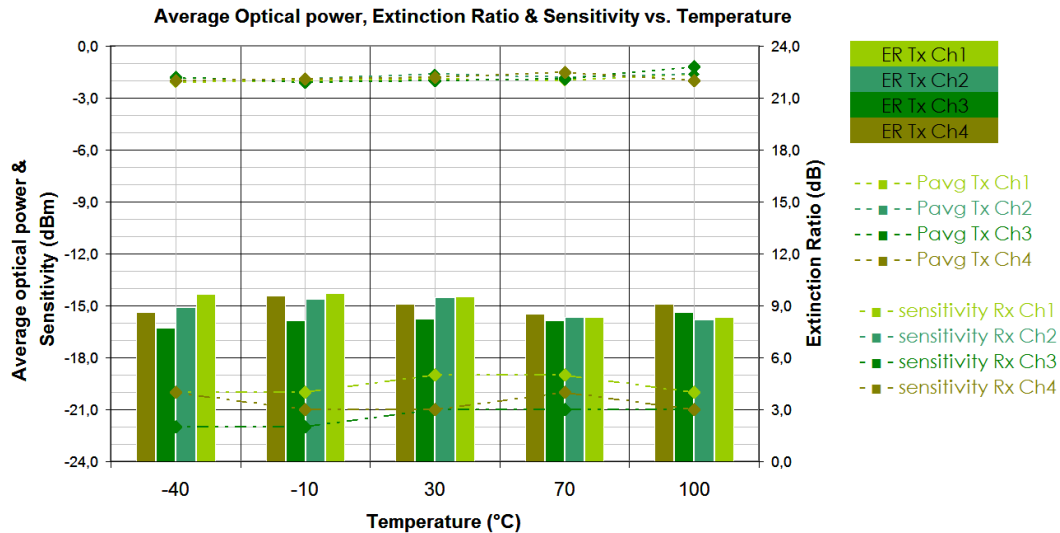


Figure 19: Tx average optical power and sensitivity as a function of temperature for a 850 nm 4-channel transceiver module

D-Lightsys modules with a high bit data rate are already qualified for military and avionics applications. Today these modules are integrated in embedded equipment in civil and military aeronautics programs.

3.4.2 Single Transceivers 1310 nm (DLS)

Contact: Vincent Foucal: (DLS): vincent.foucal@radiall.com

The 1310 nm modules are based on long-wavelength VCSELs (LW-VCSELs). These laser diodes have not been developed as fast as 850 nm ones because of technological and reliability issues. The 850 nm technology cannot be used because there is a lattice mismatch between InP-based and GaAs-based materials. However, new techniques by VCSEL manufacturers have provided devices with record output power of 2.3 mW at room temperature and 1.3 mW at 70°C with 10 Gbps operation. Moreover, they have a wavelength shift of 14 nm between -40°C and +100°C over 6 mA of bias current. This could be a very useful VCSEL source or CWDM applications.

A typical D-Lightsys OSA has been prototyped using a LW-VCSELs coupled into SMF in order to get a 1310 nm transmitter in a transceiver packaging. Figure 21 shows the variation of the Tx average optical power, extinction ratio and Rx sensitivity at 1.25 Gbps (over temperature) for a SM transceiver.



Figure 20 : D-Lightsys SM transceiver

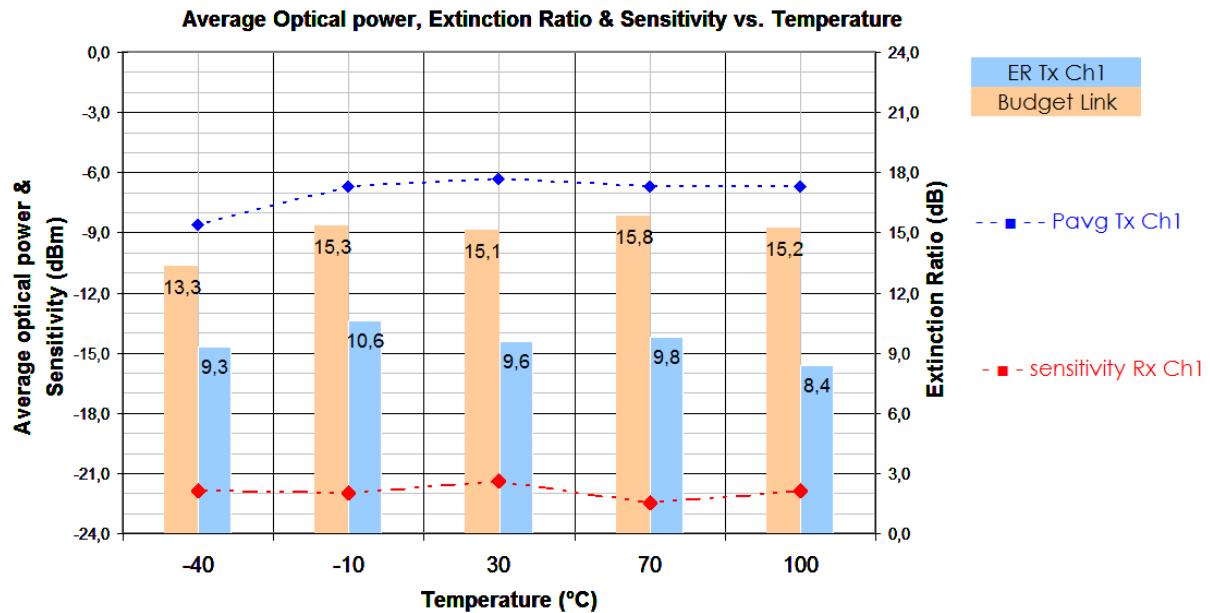


Figure 21 Tx average optical power and sensitivity as a function of temperature for a 1310 nm SM transceiver module

The D-Lightsys optical sub-assembly technology was designed for MM coupling. However during this project it has been proved compatible with the stringent constraints of a SM alignment. This is a major breakthrough on the development of a SM transceiver within D-Lightsys. Therefore D-Lightsys will be able to manufacture robust SM transceivers compliant with aeronautics requirements as soon as the maturity of these VCSEL is sufficient. The costly improvement of the manufacturing tools to achieve a very accurate and repeatable alignment in an industrial production phase.

3.4.3 WiFi RF over fibre transceiver [EAM based] (INESC)

Contact: Joao Oliveira (INESC): jmbo@inescporto.pt

The radio-over-fibre (RoF) concept involves the transmission of RF signals by an optical fibre between a control station (CS) and a number of base stations (BSs). In the base stations, the RF signal is transmitted to end users by a wireless link. Integration of both optical and wireless broadband infrastructures into the same backhaul network leads to a significant simplification and cost reduction of BSs since all routing, switching and processing are shifted to the CS. This centralization of signal processing functions enables equipment sharing, dynamic allocation of resources, and simplified system operation and maintenance.

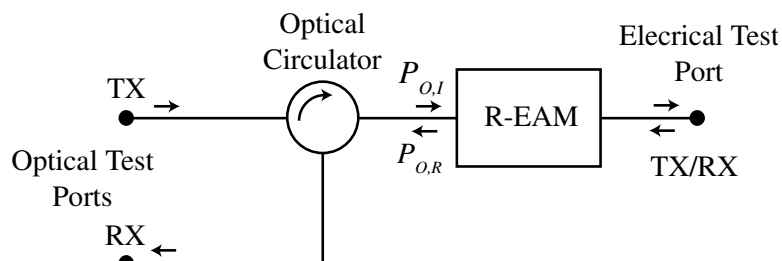


Figure 22 Functional diagram

An electro-absorption waveguide device in which a single component acts as a modulator for the uplink and as photoreceiver for the down-link, allows for a source free base-station. Therefore, this transceiver device is a very attractive solution for a full-duplex RoF transmission. The reflective EAM is an interesting device for operation simultaneously as a modulator and photoreceiver, which is possible due to the rear facet being coated with high reflection layer.

The performance of a reflective electro-absorption modulator (R-EAM) transceiver was assessed in terms of both slope efficiency (SE) and responsivity in a Radio-over-Fibre (RoF) network. Different biasing schemes were analyzed, specifically, zero bias (passive solution), bias for maximum SE and bias for maximum responsivity. A case study on Wi-Fi was considered, and the optimum parameters determined.

Results show that the best performance is obtained for a wavelength of 1560 nm, when the EAM is biased for maximum SE. However, when zero biased, the optimum wavelength is reduced to 1530 nm for $P_{0,I} = +7$ dBm, where a penalty of 13 dB is incurred, compared to the case of maximum SE. It has also been verified experimentally that, as expected, the slope efficiency is proportional to the input optical power until it saturates at high optical powers. Nevertheless, high optical input powers should be used in order to maximize the SE. The best responsivity values for both cases of biasing for maximum Re and SE are $Re = \{-9.6, -18.6\}$ dBA/W, respectively. For the zero bias case, the responsivity decreases with wavelength, reaching a maximum of -31 dBA/W for an optical input power of -6 dBm and a wavelength of 1530 nm.

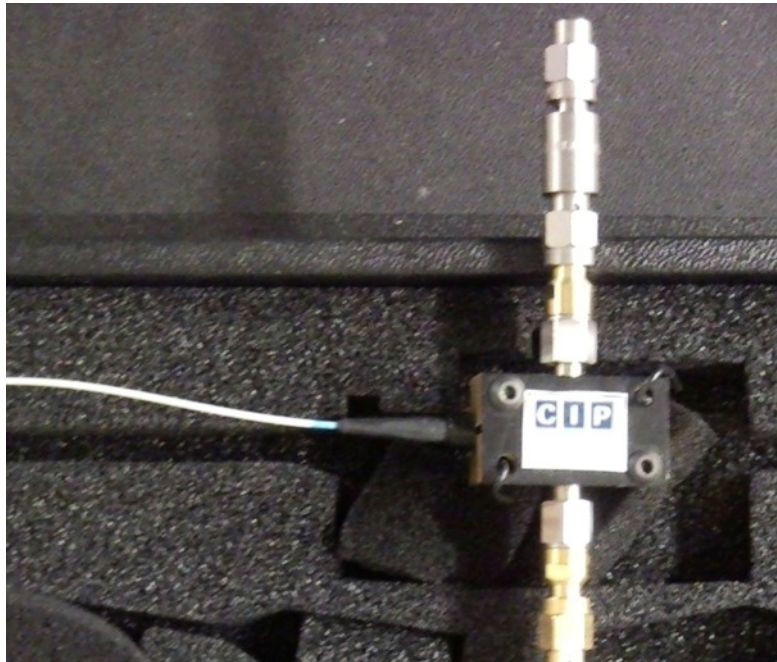


Figure 23 Photograph of the R-EAM used.

The R-EAM performance was also assessed in terms of reflected optical power for different values of input optical power. The reflected optical power is a relevant parameter with impact in the optical to electrical conversion. Therefore, this analysis considered the wavelengths of 1550 nm and 1560 nm, because these provide the best performance according to the measurements of slope efficiency. The results given by the current analysis indicate that the reflected optical power tends to decrease with increasing reverse bias voltage. Furthermore, the optical power reflected at the wavelength of 1550 nm is generally lower than that reflected at 1560 nm, except for higher reverse bias at low optical input powers.

3.4.4 WiFi RF over fibre transceiver (INESC)

Contact: Joao Oliveira (INESC): jmbo@inescporto.pt

This network consists of a bidirectional transmission of WiFi signal over MMF for the distribution of infotainment services to passengers inside the aircraft cabin. The head end is composed of a commercial access point, an electrical circulator and an electrical-optical-electrical conversion PCB. This transceiver is composed of amplifiers, photodiode and an 850 nm VCSEL. The head end components are deployed in a custom RF shield metal box.

The remote end (housed in a custom RF shielded metal box) is composed of a transceiver with an 850 nm VCSEL and PD, ultra-low noise amplifiers, an electrical circulator and an automatic gain controller (AGC). The aim of the AGC is to deliver a constant power WiFi signal to the transceiver PCB in the uplink direction. It is composed by a variable gain amplifier and a true power detector in a feedback loop configuration. A bandpass filter is also used to eliminate unwanted out-of-band noise and signals. Additionally, both the VGA and power detector were implemented by means of evaluation boards. In a second stage, optical transceivers will be provided by D-Lightsys.

The VCSEL measured slope efficiency is 0.059 W/A and its measured threshold current is 1.4 mA, and a maximum of 0.5 mW of optical power is achieved at the bias current of 10 mA. It was concluded that the transceiver has a useful response up to 7 GHz, exhibiting a combined TX+RX gain of -8.5 dB at that frequency, while having approximately 4 dB of gain at low frequencies, which accounts for a total decay of 12.5 dB. This decay is approximately equally due to both VCSEL and PD responses. For the frequency of interest in the context of WiFi, 2.4 GHz, the 1-dB compression point is found to be at -25 dBm of output power, for an input power of -22.5 dBm. Finally, the amplifier cascade used for driving the VCSEL provides a gain of 25 dB, and a 1-dB compression point of 26.4 dBm for an input power of 1.4 dBm. This is perfectly suitable for the remote station transceiver. However, a variable gain amplifier is needed, in addition to the fixed gain amplifier cascade, in order to allow for user mobility.

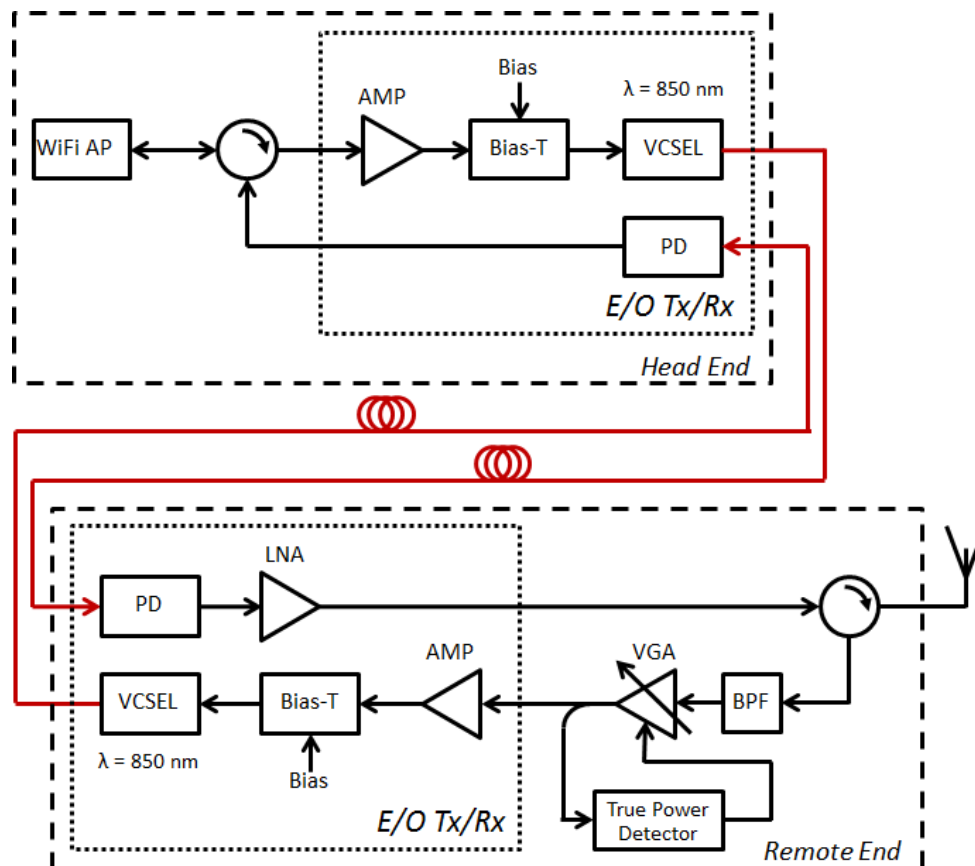


Figure 24 WiFi over fibre network diagram

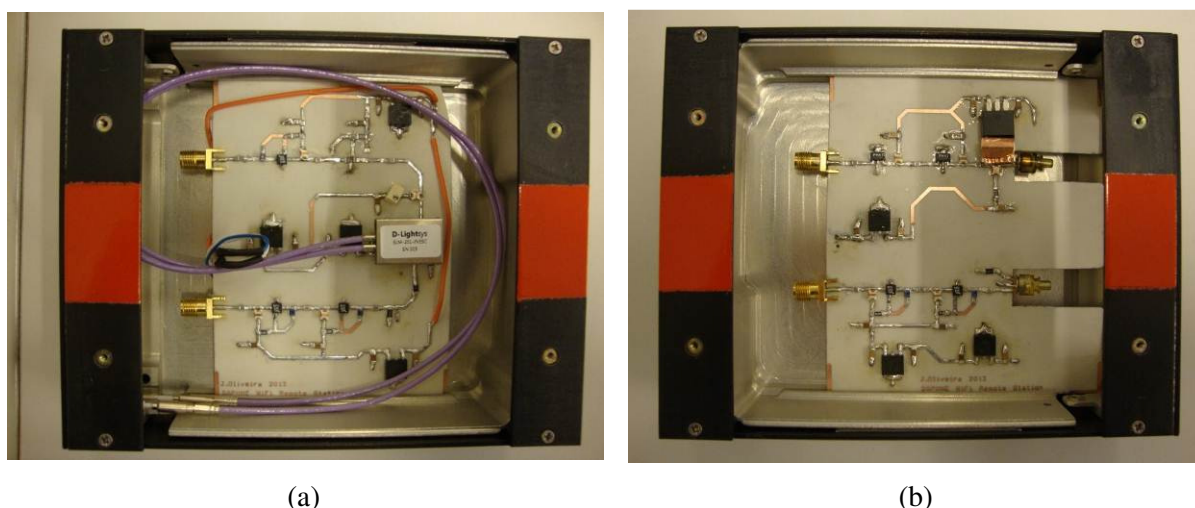


Figure 25 Final prototypes based on (a) DLS transceivers and (b) Finisar and JDSU VCSEL and PD

3.4.5 10 GHz RF over fibre transmitter (G&H)

Contact: Mark Farries (G&H): mfarries@goochandhousego.com

The 1310 nm distributed feedback laser (DFB) is an In-GaAsP/InP multi-quantum well (MQW) laser diode. The module has been designed for applications where high bandwidth, mode stability, low RIN and stable output power is needed. The module contains a cooler, thermistor, monitor detector and bias-T. The module is designed for high reliability for aerospace applications. Short high gain DFB chips were selected so that the laser can be driven directly over 11 GHz and therefore can be used for optical transmission of satellite and X band radar.

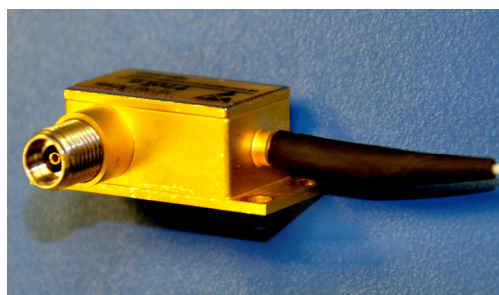
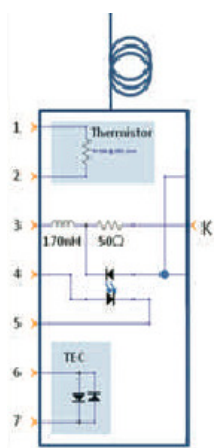


Figure 26 10 GHz RF over fibre transmitter

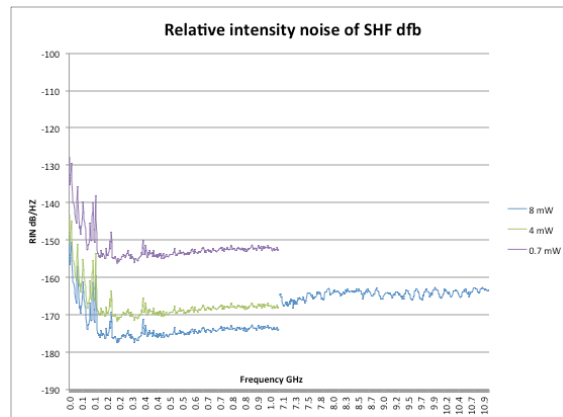


Figure 27 Relative intensity noise measurements

The key performance characteristics of this laser transmitter are:

Parameter	Measured level
Bandwidth	>10.9 GHz
RIN	<-160 dB/Hz
Wavelength	1310 nm
Power out	18 mW
Line width	<1 MHz

The DAPHNE project has enabled G&H to establish fabrication of transmitters for RF optics in the UK. It has demonstrated that the key characteristics of these devices are suitable for direct modulation at frequencies up to 10.6 GHz for applications such as the distribution of satellite signals and X band radar signals throughout an aircraft.

The outcomes of the project will be exploited through the development of RF over fibre systems for aircraft. Manufacture will be established at G&H in Torquay, UK.

3.4.6 Wide bandwidth optical receiver for RF optics (G&H)

Contact: Mark Farries (G&H): mfarries@goochandhousego.com

The InGaAs receiver has the following characteristics:

- Bandwidth >20 GHz
- Wavelength range 1260 nm to 1620 nm
- Responsivity 0.95 A/W
- Operating temperature -40°C to 85°C

The high speed detector is suitable for direct modulation RF over fibre systems up to 11 GHz and indirect modulation system to at least 20 GHz and potentially 30 GHz.

The technology exploitation route for this device is via the development of RF over fibre systems for aircraft, ground based radar and ships. Manufacture will be established at G&H in Torquay, UK.

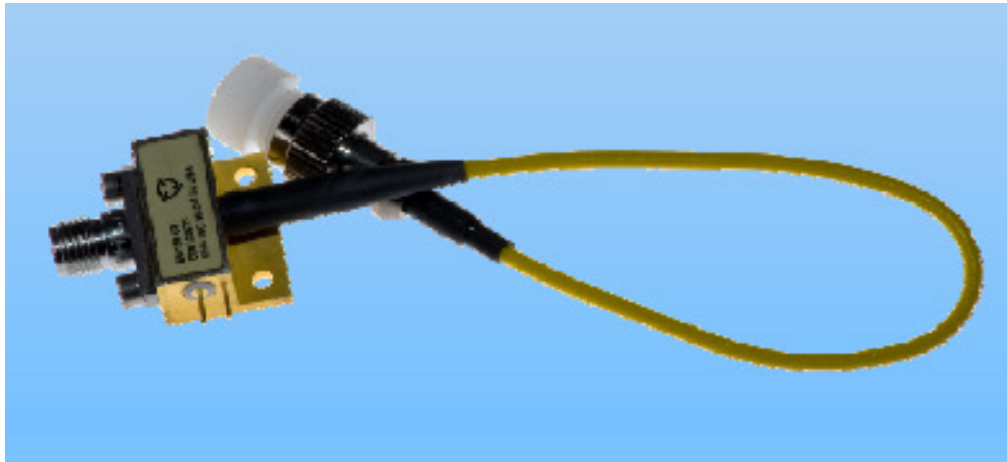


Figure 28 G&H 20 GHz InGaAs receiver

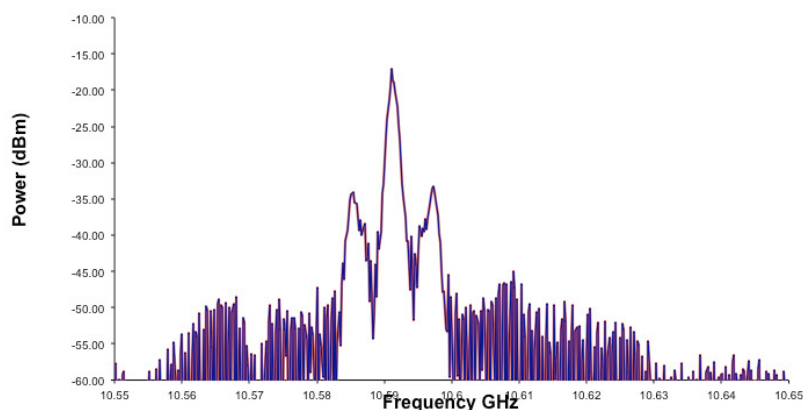


Figure 29 Detection of 10.6 GHz RF over optics signal

3.4.7 Harsh environment fused wideband 50:50 coupler (G&H)

Contact: Mark Farries (G&H): mfarries@goochandhousego.com

Fused fibre splitters have been developed within the DAPHNE project. The devices have been designed to operate over the wide temperature range of -55°C to $+125^{\circ}\text{C}$ and all environmental zones within an aircraft as defined RTCA DO-160F (except the power-plant zone E2). The devices have passed the performance, temperature and vibration tests that have been carried out. These devices have been built into $1 \times n$ remote splitter modules that have been used within the DAPHNE networks.

The DAPHNE project has enabled G&H to extend the range of applications that its products serve from terrestrial telecommunications to harsh environment aerospace applications. The exploitation of this technology will primarily be through the deployment of fibre optic network on commercial aircraft. There will also be spin off applications in space, ships and mining which all require devices that are more rugged than telecommunications grade parts. Manufacture will be established at G&H in Torquay, UK.



Figure 30 Harsh environment coupler

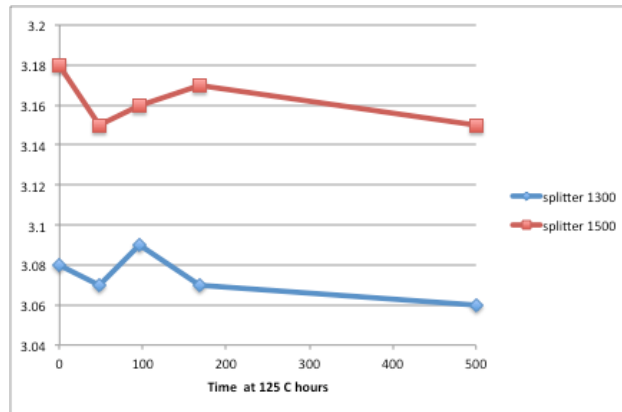


Figure 31 G&H fused fibre coupler 125°C endurance testing

3.4.8 Harsh environment fused WDM coupler (G&H)

Contact: Mark Farries (G&H): mfarries@goochandhousego.com

The harsh environment fused WDM devices are fabricated with a similar method to the 50:50 couplers that are described above. However the taper region is extended so that the light cycles between the two outputs depending on wavelength.

Ruggedised fused fibre wavelength multiplexers have been developed within the DAPHNE project. The devices have been designed to operate over the wide temperature range of -55°C to +125°C and all environmental zones within an aircraft as defined RTCA DO-160F (except the power-plant zone E2). The devices have passed the performance, temperature and vibration tests.

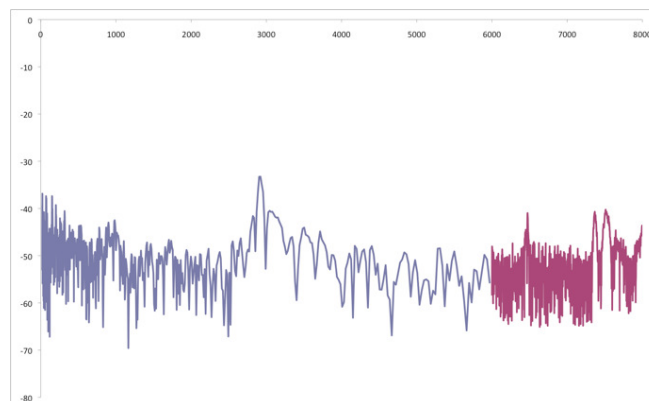


Figure 32 20g helicopter vibration test results show less than 0.1% (-30 dB) signal change.

The WDM devices will be used to combine multiple data protocols on to one fibre, so that for example, analogue and digital data can be sent via a rotary joint to a helicopter rotor blade or an undercarriage wheel. This technology will be exploited through the deployment of fibre optic networks for sensor and control systems on commercial aircraft. Manufacture will be established at G&H in Torquay, UK. The harsh environment fused coupler platform can also be applied to other devices such as:

- Wavelength combiners for other wavelengths
- Polarisation splitters and multiplexers
- High power combiners for fibre laser systems.

3.4.9 Ruggedised planar 1x2, 1x8 and 1x16 splitters (SQS)

Contact: Ilja Kopáček (SQS): ilja.kopacek@sqs-fiber.cz

Within DAPHNE project SQS has managed to bring its technology based on Telcordia standards up to avionic standards. SQS developed and tested PLC splitters in common configurations up to the splitting ratio of 1x16 in temperature range from -70°C up to 155°C and vibration tested according to RTCA D0-160E standard (for up to 2 kHz and 20g) at -40°C, room and 80°C as well as 100 cycles of temperature shocks from -70°C to 155°C (using Draka's high temperature acrylic SM fibre).



Figure 33 PLC 1x8 splitter from SQS for aeronautic applications

They did so for plastic as well as metal housing with similar testing results for up to 125°C, however, metal housing should be suitable for higher temperature ranges.

3.4.10 Simplex in-line splice (AVO)

Contact: Andrew Lee (AVO): andrew.lee@avoptics.com

With the development of new fibre optic cable comes the question of how to develop a solution to repair damage to a cable mid-loom. Whilst tooling was being developed for repair and renewal of connectors, a system was required for fixing breaks and damage in the middle of a loom. To meet this requirement a specification for an in-line splice was produced. As design of a multi-way fibre type was still in development during the programme this was initially focused on developing a simplex solution.

A prototype was designed and produced to this specification and underwent system testing. After a design review it was felt that certain areas of the splice could be improved, included reducing the mass, the number of piece parts and the overall size of the splice. Using this information a new splice was designed, manufactured and then tested. Optical performance was unchanged and a summary of key performances can be found in Table 2:

Key Requirement	Splice Version 1	Splice Version 2
To reinstate full mechanical cable integrity	✓	✓
The Splice shall utilise existing tooling (no custom tooling)	✓	✓
The splice shall be loom or airframe mountable	Mass considered too high for loom mounting	✓
The splice shall be able to reinstate a system in 15 minutes	20 min	✓
The splice should be a fit and forget component	✓	✓

The splice should require low training for a fibre optic operator.	✓	✓
The splice should be capable of supporting multiple cable types.	✓	✓
Insertion loss shall be less than 0.75dB	✓	✓

Table 2 Splice – Key parameters

After DAPHNE the splice will now undergo further testing and then a final version of the splice will be designed and produced which will be able to be deployed with the new DAPHNE cable types.



Figure 34 Splice Version 1 (upper) and version 2 (lower)

4 **Project Impact**

The DAPHNE project has yielded a broad range of advances in technology which will have a significant impact on the individual partners, and on European industry as a whole. The nature of the project was as a technology enabler: to identify, tackle and reduce or remove obstacles to the implementation of fibre optics on aircraft. This has resulted in many elements of new technology:

- *New technology* which may be applied to fibre optics in aircraft
- *New products* to increase the portfolio of the manufacturing partners
- *New techniques* for aircraft networks which take advantage of fibre optics and photonics.

4.1 **New technology**

4.1.1 **Modelling**

The DAPHNE modelling partners (TUI, DTU with support from GMV) have developed standard commercial modelling software packages into tools specifically for the design of aircraft photonic networks. These tools are available for TUI and DTU researchers for on-going research in this area. In particular, TUI works closely with Airbus on cabin systems, and spin-off commercial projects are already proposed.

Features of the new packages include:

- Library of real commercial photonic components in ML Designer
- GUI for aircraft network design, including 3D cabin visualisation of fibre routing
- Modular “drag and drop” photonic network builder with for aircraft cabins
- Evaluation of VCSEL + MMF simulations in aircraft environments
- Modelling the effect of aircraft vibrations on high speed (>10 Gbps) Ethernet networks based on VCSELs and MMF physical layers.

TUI will continue to support other partners that have interest in aircraft optical network modelling. It plans to continue the development of MLDesigner library for optical networks and the framework for evaluation of network model designs.

DTU intends to add more systems to the same modelled infrastructure and include protection switching. Student projects will be announced and based on additional results, the results will be distributed to relevant DAPHNE consortium members as input for future work.

4.1.2 **Use of COTS hardware in aircraft environments**

One of the reasons for the slow uptake of photonics in aircraft is that the hardware is not tested in aircraft environments. The technology is not considered by air-framers since it is not qualified, and is not qualified by photonics manufacturers since it is not considered by air-framers. To try to break this “chicken and egg” situation, DAPHNE has used a range of COTS hardware in aircraft photonic networks, including:

- Gigabit Ethernet media converters (BAES)
- Prognostic Health Monitoring devices integrated in a fibre network (BAES)
- Optical by-pass switch (G&H)
- SM optical rotary joint (G&H)
- WDM add-drop dielectric filters (G&H).

4.1.3 New applications proof-of-principle

The DAPHNE air-framers suggested several potential applications which have been slow to be considered since the basic proof-of-principle has not been demonstrated in a suitable format. Therefore DAPHNE showed the following functionality in aircraft-compatible architectures:

- High definition (HD) camera data over optical fibres (G&H)
- Fibre structural health monitoring of rotor blades through SM fibre optical rotary joint (G&H)
- RF over fibre using shared optical fibre (with non-RF traffic) (INESC)
- 10 GHz RF over fibre (G&H)
- Optical and electronic connector interfaces for modular aircraft equipment boxes (DLS).

4.2 New products

The DAPHNE manufacturing partners have a wide range of new products from the project.

4.2.1 SELEX

Head End (Avionic Gigabit Ethernet): This module provides a long term answer to the modularity concept, offering an architecture for demanding applications in term of reliability, portability and reusability. The Head-End architecture consists of a conduction cooled enclosure with an Electronic Unit sized as per 2 MCU (ARINC 600), hosting modular connectors EN4165. It interconnects the mother board (i.e. the standard part), n°2 VPX Rear Transition Module (i.e. the custom/functional motherboard), n°2 OpenVPX 3U module and a Power Supply module to convert the external avionic 28 V BUS BAR to internal OpenVPX standard voltages (+3.3 V, +5 V, +12 V, -12 V).

Gigabit Ethernet media converters for aircraft installations: The Remote End Gigabit Ethernet media converter consists of a conduction cooled mechanical enclosure containing a PCB board with outline dimensions similar to PC104 standard and modular connector EN4165. This module implements Gbit Ethernet electrical to optical conversion from 1000BASE-T to 1000BASE-SX/LX. An external power voltage of 5V is also provided.

4.2.2 SQS

Remote housing with LASIN lock: Remote housings with integrated connector, internal PCB guiding/mounting, internal fibre/cable routing, locking mechanism and external chassis. This product was developed by SQS & Airbus and is being proposed as an international standard to ARINC.

Ruggedised planar 1x2, 1x8 and 1x16 splitters: It is expected that these harsh environment splitters will be used for aircraft PONs and structural health monitoring applications.

Multi-fibre cable break-out: The performance is limited by commercially available cables and connectors: i.e. the harness fails before the break-out. This flexible break-out solution will be promoted in a wide variety of air-frames

4.2.3 G&H

RF over fibre hardware: DAPHNE has enabled the development and verification of both SM transmitters and receivers for 10 GHz RF over fibre, as well as MM 850 nm transceivers. In combination with the new applications which have been pioneered (attitude sensing, WiFi for IFE), G&H expects a significant new market for these components to develop in both aircraft and marine environments.

Harsh environment fused couplers: Through the DAPHNE project G&H has improved the packaging and manufacture process of its fused couplers (including wideband 50:50 couplers, power splitters and CWDM devices). This is a significant advance in the capabilities of these devices and opens up new market in harsh environments, particularly aircraft and marine.

4.2.4 Draka

Draka has developed its cable technology in line with the requirements specified by the DAPHNE air-frame partners, to create a suite of aircraft-compatible cable solutions for a wide range of network types:

- Multimode OM2 fibre cable
- Singlemode simplex cable
- Ribbon flat cable
- Round section ribbon fibre cable tight structure
- Round section ribbon fibre cable loose structure
- Bend-insensitive MM OM4 fibre
- Bend-insensitive MM OM4 fibre with high temperature acrylate coating
- Bend-insensitive SM fibre with high temperature acrylate coating

These prototype products are now on the path to aircraft environment testing or qualification.

4.2.5 D-LightSys

DAPHNE has enabled the advancement of transceiver technology at DLS and has paved the way for three new product families specifically targeted at the aircraft fibre optic network market.

850 nm transceivers: Devices based on 850 nm VCSELS have been developed and will be eventually offered as products, including MM single transceivers, quad transceivers and 12-channel emitters and receivers

Singlemode Transceivers: The advancement in longer wavelength VCSEL technology has enabled DLS to improve the performance of 1310 nm SM transceivers suitable for aircraft harsh environments

Single emitters and single receivers for free space: DAPHNE helped to highlight the importance of short range free space link, for example between neighbouring transceivers in an avionics cabinet, and these will be offered as aerospace grade products

4.2.6 AV Optics

AV Optics has used the opportunities offered by the DAPHNE project to increase its knowledge on the practical requirements of the aircraft industry for fibre optic and photonic technology. This has led to the production of advanced prototype products which will cement AVO's position in this vital niche market.

Through life support equipment: A range of tool kits and techniques (e.g. the AVO in-line splice: see below) based on lessons learnt from real installed networks

Ribbon Fibre Optic Repair Kit: A unique solution to repairing ribbon fibre in-situ in an installed aircraft fibre optic harness. This entirely portable and self-powered system includes fibre polishing and curing. A design right has been applied for and a patent application is under consideration.

4.3 New techniques

4.3.1 RF over fibre hardware (INESC)

INESC has made some major advances in the development of WiFi RF over fibre transceivers. Two potential solutions have been worked on: electro-absorption modulator (EAM) based hardware and a VCSEL-based transceiver system. Both these techniques have potential roles in the distribution of infotainment services to aircraft cabin systems, avionics as well as residential indoor LANs and pico-cell LANs.

Both systems support the bidirectional transmission of WiFi signals over optical fibre for the distribution of infotainment services to passengers inside the aircraft cabin. The EAM-based system is suitable for colourless source-free base stations and for specific networks where base stations are passive or powered by means of small batteries.

Although this system was not publicly demonstrated, experimental results showed that it can be used to distribute internet service and infotainment to the passengers. It allows a complete centralization of the WiFi electronics at a common facility thus reducing the remote end complexity, size and cost. Although it was addressed in the avionics industry context, this system is suitable for the deployment of wireless standards in any local area network scenario. (The hardware of the system is in a prototype stage.)

This system provides enough bandwidth to accommodate 2.4 GHz, 5 GHz and even 60 GHz signals. Therefore, as future research, the simultaneous transmission of several standards up to 60 GHz should be considered.

By centralizing the WiFi electronics at a common facility it is possible to reduce installation and maintenance costs. Additionally, since the RF signals are transmitted in a transparent way through the fibre, and the system is not only suitable for WiFi signals, this system can be easily upgraded to be used with almost every wireless standard in the market. Among them, the new broadband 60 GHz standards may also be used. This characteristic makes this system a truly future proof solution.

4.3.2 Differential GPS for attitude monitoring (INESC)

INESC demonstrated for the first time that it is possible to use differential GPS system carried over optical fibre to measure the attitude of an aircraft. This technology was not considered in the original proposal and arose through the commercial need of AgustaWestland. This use of fibre optics rather than the cumbersome copper systems currently deployed will lead to significant cost and weight savings and improved performance.

The invention supports the unidirectional transmission of differential carrier phase GPS signals over SMF from the antennas to the avionics bay, where GPS receivers are placed. The carrier phase differential GPS signal over optical fibre system has received positive reviews from the partners, particularly the avionics manufacturers. Through DAPHNE it has been experimentally demonstrated that optical fibre can be used to connect the GPS antennas to their receivers. This is of extreme importance in the avionics industry since the antennas can be placed anywhere in the aircraft while the receivers are accommodated in a specific room where maintenance is easier.

This system has potential to be used in both fixed and rotary wing aircraft. It allows antennas and receivers to be placed at different locations. Moreover, in carrier-phase systems where the cable length difference between paths is critical, optical fibre offers the advantage of the low weight and size relatively to the coax solution.

4.3.3 Through life support technology (AVO)

In the framework of the DAPHNE project AVO has developed two versions of a simplex in-line mechanical splice which may be used in installed aircraft fibre optic harnesses. This development work was a response to identified commercial requirements of airframers using fibre optics. Design right protection is being applied for and a patent application is currently under consideration.

4.3.4 Improved network reliability techniques (DTU, INESC, SQS)

Several techniques to improve reliability of aircraft networks were conceived and advanced in the DAPHNE project.

Micro-ring resonators: DTU proposed the use of micro-ring resonators for modulation speed or quality enhancement of signals generated by directly modulated lasers, including VCSELs. Proof of concept was demonstrated for edge emitting DFBs and VCSELs, using discrete components. Further academic study is planned since the technique has the potential for commercial application.

All-optical network coding: DTU developed an all-optical network coding technique for improving the resilience of optical networks. Proof of concept was demonstrated for phase modulated signals. Further academic study is planned since the technique has the potential for commercial application.

Ultra-fast protection switching: In the framework of DAPHNE, DTU proposed a method for ultra-fast all-optical protection switching using bistable laser diodes. Proof of concept was demonstrated. Whilst this may have applications in aircraft networks, more likely markets are high speed telecoms systems. Further academic study is planned since the technique has the potential for commercial application.

PON fault location: During the PON hardware development and network studies, INESC invented a fault location method for PON, based on a single photon counting OTDR. This has the potential to be developed into hardware and software to detect and identify events in a PON. Applications could be any PON network, including aircraft systems, but also terrestrial systems.

The system is a time-correlated v-OTDR experimental setup for automatically identifying, locating, and estimating faults in a short span PON, from a central location. This technology could be exploited by companies manufacturing and selling OTDR based products for monitoring passive optical networks and/or optical fibre cables.

A two-point resolution of 27 cm was demonstrated, and improvement is possible with easily available modifications. The OTDR single photon detector noise measurements indicate that a sufficiently high SNR is possible even after the PON splitter, in spite of other sources of noise which need to be eliminated. Further development is necessary to attain the target performance.

Further development of the OTDR probe, especially using VCSELs may become the object of IPR protection.

4.3.5 Other techniques

Network monitoring using PLC: SQS invented a method for pulse monitoring of composite materials (e.g. fuselage) through the use of a combination of PLCs (1xN and Nx1). This technique permits effective structural health monitoring of composite materials and could be developed into new hardware (integrated component PLC/MPO).

Fibre management in RM box: SQS has identified a method of securing the optical fibre in remote module housing in a harsh environment. This technique would be suitable for either SM or MM fibre

4.4 Contributions to standards

The issuing of international standards is a process which typically takes several years, and so the implementation of DAPHNE recommendations was never expected within the timescale of the project. Nevertheless DAPHNE has endeavoured to promote its outputs at a range of standards bodies throughout the course of the project. These topical areas include:

- Practical installation and through-life support issues (AVO)
- Method for determining the "polarity" of ribbon fibre (AVO)
- Offset launch conditions for optical loss measurement using MM fibres (Airbus)
- Colour standards of aerospace fibre optic cables (Draka & Airbus)

- VITA 66.0, Optical Interconnect on VPX - Base Standard (Airbus)
- VITA 66.1, Optical Interconnect on VPX - MT Variant (Airbus)
- SAE AS5659 - ARINC Specification 859 WDM LAN Specification (Airbus)
- ARINC Specification 802: Fiber Optic Cables (Airbus)
- ARINC Report 805: Fiber Optic Test Procedures (Airbus & SQS)
- ARINC Report 806: Fiber Optic Installation and Maintenance (Airbus & AVO)
- Use of “temperature coefficient = dB/°C” in ARINC standards instead of specific change over specific T= dB/(-temp to +temp) (SQS).

4.5 Dissemination activity

DAPHNE members presented almost fifty papers at around thirty international conferences. ECOC 2011 was certainly a highlight event for the project. Fibre optics on aircraft is still a very small field and there are only two events worldwide: FOHEC (UK) and AVFOP (USA). DAPHNE has had a strong presence at both conferences throughout the course of the project.

4.5.1 ECOC 2011



DAPHNE dominated the “Optical avionic networks” session at this major international conference. The session was chaired by Dr. Mark Farries (G&H). There were ten papers, of which seven were presented by DAPHNE partners. Furthermore, DAPHNE partners were co-authors in two of the other three! The topics presented were:

- | | |
|--|-------|
| • Fault-tolerant designs | GMV |
| • Avionic network design | DTU |
| • Model-based design of avionic optical networks | TUI |
| • PON networks for aircraft | SQS |
| • Wireless services distribution for avionics | INESC |
| • State-of-the-art transceivers for aircraft | DLS |
| • Developing COTS parts for avionic applications | G&H. |

4.5.2 AVFOP

The Avionics, Fiber- Optics and Photonics Conference (AVFOP) is hosted annually in the USA by the IEEE (Photonics Society). It is the largest event which specifically covers the topic of fibre optics on aircraft and is attended by major players from all over the world. DAPHNE members (G&H, BAES) were present at the event in 2009 right at the beginning of the project. The project had a presence at the subsequent three events and presented some key papers:



- 2010 Denver (21- 23 Sep-2010)
 - Attended by several DAPHNE members (G&H, BAES)
- 2011 San Diego (04- 06 Oct-2011)
 - “Developing aircraft photonic networks - an overview of the European DAPHNE project,” BAES
 - “Assessment of noise impact on UWB signals in R-EAM based optical links,” INESC
 - "Wavelength and Fiber Assignment Problems on Avionic Networks,” DTU
- 2012 Florida (11- 13 Sep-2012)
 - Tabletop display of DAPHNE material and hardware
 - “Transmission of Digital and Analogue Data on a Single Mode Fibre Optic Network for Aircraft,” G&H
 - “Transmission of differential GPS signals over fiber for aircraft attitude determinationwo papers,” INESC

4.5.3 FOHEC

FOHEC (Fibre Optics for Harsh Environments) is the main European event for DAPHNE, and it is actually hosted by one of its members (AVO) in the UK. Consequently FOHEC has proved an invaluable dissemination route, and DAPHNE has had a strong presence for the last three years.



- 2010 Yeovilton, UK (19-20 May-2010)
 - DAPHNE presentation “Developing Aircraft PHotonic NETworks” BAES
- 2011 Swindon, UK (18-19 May-2011)
 - “DAG Day”- one afternoon session dedicated to DAPHNE presentations
- 2012 Swindon, UK (20-21 Nov-2012)
 - D6.9 Technology Transfer Workshop: a whole session on the outputs from the DAPHNE project
 - Presentations by related projects (SMARTFIBER, FOS3D & PRIMAE)
 - There were also DAPHNE presentations in the technical session:
 - “Monitoring/sensing applications on AirPON,” SQS
 - “Terminating for the Harsh Environment,” AVO.



4.5.4 Hardware demo days

Two hardware demonstrations were hosted by the DAPHNE consortium to show the technology to a selected group of engineers, managers and decision-makers from partner organisations. The two events were held at:

- BAES, Filton (Jan-2013)
- Airbus, Finkenwerder (Feb-2013)

Hardware on display included:

- Switched Ethernet
- Ethernet PON
- Singlemode WDM system
- Differential GPS (Land Rover)
- Through life support
- Use of modelling software



4.5.5 Other events

DAPHNE has been present at around thirty conferences. Recent events include:

- ICT 2011; 18th International Conference on Telecommunications
 - Ayia Napa, Cyprus (May-2011)
- “Developing A Generic Optical Avionic Network” (DTU)
- PSAM 11; 11th Int. Probabilistic Safety Assessment and Management Conf.
 - Helsinki, Finland (Jun-2012)
- “Model-Based Design and Evaluation of Fault-Tolerant Fibre-Optical Networks for Avionics” (TUI/ GMV)
- Future Network and Mobile Summit 2012
 - Berlin, Germany (Jul-2012)
- “Experimental assessment of WLAN performance supported in a fiber-radio network” (INESC)
- SPIE Security and Defence 2012
 - Edinburgh, UK (Sep-2012)
- “Monitoring/sensing applications on AirPON” (SQS).

