**Proceedings Paper:**
Rowlings, Matthew, Walshe, Michael, Trefzer, Martin et al. (2022) SpacePHYre: Magnetically Isolated SpaceFibre Links using Gigabit Ethernet PHYs. In: 2022 International SpaceWire SpaceFibre Conference (ISC). IEEE.

# SpacePHYre: Magnetically Isolated SpaceFibre Links using Gigabit Ethernet PHYs

Matthew Rowlings, Michael Walshe
*Thales Alenia Space UK*
Bristol, United Kingdom
matthew.rowlings@thalesaleniaspace.com

Martin Trefzer, Mark Post
*Department of Electronic Engineering*
*University of York*
York, United Kingdom
martin.trefzer@york.ac.uk

***Abstract*—SpacePHYre is a new on-board communications CODEC that is compatible with SpaceFibre and SpaceWire networks. SpacePHYre uses magnetically isolated Gigabit Ethernet PHYs at the physical layer to provide a higher degree of electrical isolation between equipment. Deterministic and reliable communication is supported by providing SpaceFibre Virtual Channels to the user, including the Quality of Service mechanisms, as well as a frame retry mechanism based on Space Fibre. In addition, the magnetic isolation allows power delivery over the data cable to be supported, resulting in harness mass savings as dedicated power cabling to the equipment is no longer required. A prototype SpacePHYre interface supporting power delivery based on terrestrial Power-over-Ethernet standards is presented.**

## I. Introduction

The simplicity of SpaceWire networking layer allows avionics networks to be created easily and is highly suitable for FPGA implementation or for use in processor-less applications. SpaceFibre improves on SpaceWire networking by supporting reliable transmission over a link and by adding deterministic data delivery through virtual networks and time slot arbitration provided by Quality-of-Service mechanisms(QoS) built into the virtual channel layer. Despite these new capabilities, a SpaceFibre CODEC is still suitable for FPGA implementation [**?**] or for use in processor-less applications [**?**].

As well as increasing the link speed, the electrical physical layer of SpaceFibre improves on the signal integrity of SpaceWire by offering AC coupling to mitigate the effects of differing ground potentials and by providing protection to the drivers and receivers should a DC transient fault be present on the cable [1]. However, each end of the line is still coupled to a local ground via the discharge resistors and so this will eventually limit the length of the copper cable or maximum transient fault that can be tolerated between two SpaceFibre devices. The AC coupling also does not fully isolate SpaceFibre devices from power supply induced transients that may occur when high-power devices are switched on or off. The fibre optic cables and drivers for SpaceFibre solve this issue but are expensive and difficult to integrate and handle.

The isolation can be improved by moving to magnetic isolation using a transformer between the equipment and the cable, as used in several robust interfaces such as MIL1553 and 10/100/1000BASE-T Ethernet interfaces. Indeed, 1000BASE-T Gigabit Ethernet PHYs combine a suitable combination of high galvanic isolation and a reasonable throughput of 1 Gigabit per second. Space-qualified Gigabit PHY devices are becoming available on the market (Microchip VSC8541RT [2] and Texas Instruments DP83561 [3]), due to their use in Ethernet-based on-board protocols such as Time Triggered Ethernet. Ethernet-based avionics has been used in aerospace applications such as fly-by-wire systems. This technology offers an enhanced full Ethernet stack with extensions for guaranteed delivery of time critical data. However, supporting the full Ethernet stack results in lots of extra features available that are not applicable to spacecraft avionics and as a consequence such avionic solution requires its own ASIC per interface [**?**] as well as the physical layer PHYs and magnetics that provide the electrical isolation. The power consumption for the ASIC is significant [**?**] and is many times more the SpaceFibre FPGA IP core [**?**] which can be combined as part of a System-on-Chip within the same FPGA.

In this paper we propose an alternative 1 Gbit/s physical layer for SpaceFibre using the 1000BASE-T Gigabit physical layer. The magnetic isolation offered by 1000BASE-T provides maximal decoupling of the cable from the interfaces, offering a high level of immunity to power supply induced transients. The use of magnetic isolation also allows the capability of power delivery over the communication cables. The codec implements the SpaceFibre retry mechanism, Quality of Service (QoS) primitives, Broadcast and Virtual Channel interface to allow compliance with SpaceFibre and SpaceWire at the network layer.

The magnetic isolation and Ethernet PHY technology brings several other advantages to on-board avionics networks:

1) ***Cable length:*** The magnetically coupled on-board communication network will be able to support cable lengths of up to 100m, allowing easier integration into larger spacecraft, easier integration with EGSE and new application areas such as space launch systems.
2) ***Power delivery:*** The magnetically coupled on-board communication network will be able to power networked devices (e.g. star trackers, sensors, small instruments) by delivering the power over the same cable as the communication as is done terrestrially with Power over

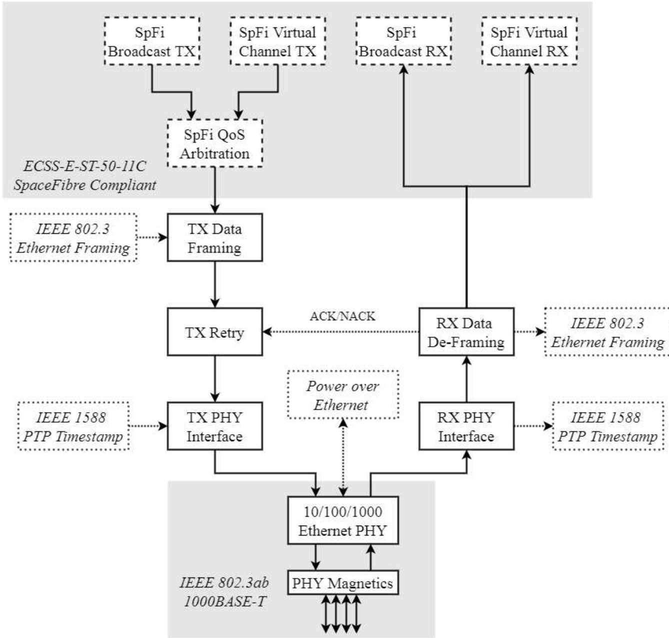


Fig. 1. Overview of the SpacePHYre CODEC. The upper layers of the CODEC implement the SpaceFibre Virtual Channel and Broadcast Interfaces as well as SpaceFibre Quality of Service Mechanisms. The lowest layers of the CODEC interface with IEEE802.3ab 1000BASE-T Gigabit Ethernet PHYs. Several optional features are available and indicated by dashed lines.

Ethernet (PoE). This removes the need for separate power cables, significantly reducing spacecraft mass.

3) ***High-precision time synchronisation:*** The Gigabit Ethernet PHYs used can support a highly-accurate time synchronisation service based on IEEE 1588-2008: Precision Time Protocol. Synchronisation in the region of 100ns is possible due to the PHYs ability to timestamping SOF tokens within the transmit and receive analogue front ends of the PHY. This also removes the need for dedicated PPS cables, reducing spacecraft mass.
4) ***Ethernet Compatibility:*** The use of 1000BASE-T PHYs allows electrical compatible with terrestrial Ethernet networking equipment, allowing easier integration and development of EGSE test equipment and processes.

## II. Overview of SpacePHYre CODEC

SpacePHYre implements the SpaceFibre standard (ECSS-E-ST-50-11C [1]) for the Network layer, Virtual Channel layer and Quality of Service provisioning. This provides the same deterministic and real-time properties of SpaceFibre links and ensures compatibility with other devices when used within a mixed SpacePHYre/SpaceFibre/SpaceWire network.

The Framing and Retry layers are modified to support the characteristics of the Gigabit PHYs, but retain the SpaceFibre frame formats, sizes and required frame headers to support the virtual channel and QoS provision.

The Link layer presents full data or control frames to the PHY and also manages the link running state via the PHY MDIO interface or discrete signals. Control logic within the PHY handles link connection, link runtime management, as well as translation of 8-bit data words to/from tokens to be transmitted or received over the link. This removes the need for the link layer of the CODEC to manage low-level control tokens, perform 8b/10b encoding or manage the elastic buffer on the receive data path. This results in a simpler link layer when compared to SpaceFibre.

Figure 1 indicates the arrangement of the CODEC and which parts are from SpaceFibre, which parts are SpacePHYre specific and which parts need to control the PHY as a standard 1000BASE-T (IEEE802.3ab) interface.

### A. Virtual Channel Interface and QoS

As shown in 1, SpacePHYre fully implements ECSS-E-ST-50-11C for the Virtual Channel interfaces, Broadcast interface and Quality of Service provisioning. This allows compatibility with SpaceFibre networks.

### B. Data Framing Layer

The same framing control tokens (e.g. VC flow control) and framing primitives are used as a SpaceFibre frame (256 bytes per data frame, 8 bytes per broadcast).

The 8-bit PHY interface does not allow identification between control and data words, therefore the framing of packets is vital to extract the data information from the incoming data stream. For this reason, broadcasts and control tokens cannot be injected into data frames that are being transmitted, instead they must wait until the frame has finished transmitting.

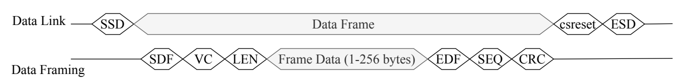


Fig. 2. Virtual Channel Data Framing.

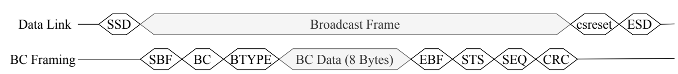


Fig. 3. Broadcast Data Framing.

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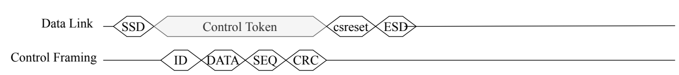


Fig. 4. Control Token Framing.

The frames also require some tokens adding to support transmission over the Gigabit PHY such as SSD (start of stream), ESD (end of stream) and CSRESET (reset of collision sense logic). In the case of an idle link and singular frames then these tokens are added to the header and tail of the frames. If multiple frames are ready for sending then these can be combined, as shown in Figure 5, subject to the maximum stream length characteristics of the particular link.

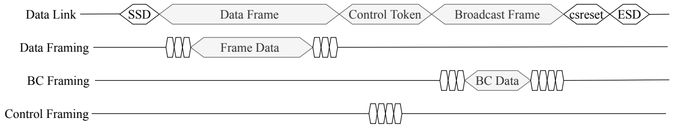


Fig. 5. Example of multiple frames being packed together for continuous transmission, only requiring a single set of SSD and ESD PHY tokens for a number of frames.

### C. Retry Functionality

The frame retry mechanism is based on SpaceFibre's use of ACK and NACK tokens and resending of frames should a CRC error be detected by the far end. All frames for transmission are stored in a retry buffer and are either removed from the buffer or resent on recipient of an ACK or NACK token respectively.

### D. Gigabit PHY Interface

The CODEC can support standard Gigabit PHY interfaces, such as GMII, RGMII and SGMII. Control of the PHY is either via the PHY register interfaces and the MDIO interface or via discrete signals into dedicated control or initialisation pins of the PHY. Management functions via MDIO are asynchronous to the data interface and are slow and sporadic in nature. The MDIO interface can be managed by a small state machine within the CODEC or also by an embedded processor in implementations that include an embedded processor.

### E. Power Delivery

The magnetically coupled data lines allow power to also be provided over the same wiring, using the same methodology as Power-over-Ethernet. The power supply and handshaking will be optimised for the application for spacecraft avionics. The PHYs will report if the far end needs powering, then extra features in the Link Management layer provide power handshaking to ensure the correct amount of power is provided to the remote end. The Link Management layer also interfaces with the power supply at the source end of the link to enable and control the power delivery over the link.

### F. Further Optional Features

The use of Gigabit Ethernet PHYs adds some new possibilities that complement the existing features of SpaceFibre.

*1) IEEE-1588 PTP Timestamping: Precision Time Protocol* is a network time synchronisation protocol that allows very accurate time synchronisation. It achieves this through accurate measurements of link latencies and applying corrections for these latencies. Time synchronisation packets are timestamped as they are transmitted and received by a link. The less jitter between the actual link latency and these timestamps, the greater the precision of the achieved time synchronisation. Some Gigabit PHYs allow very accurate time stamping by detecting the time synchronisation frames within the front-end electronics of the PHY. This can be used to perform very accurate time synchronisation across a SpacePHYre link.

*2) Ethernet Frame Compatibility:* The use of Gigabit Ethernet PHYs and transformer magnetics gives electrical compatibility with terrestrial 1000BASE-T equipment, but not Ethernet compatibility due to the lack of a MAC frame header. An optional feature of the framing layer allows SpaceFibre frames to be wrapped with IEEEE 802.3 Layer 2 Ethernet frame headers and so compatible at the packet level with Ethernet networking products. This removes the need for adaptor bricks for PC to Spacecraft communication during AIT and development activities. The PC would then be responsible for packaging SpacePHYre frames within these Level 2 Ethernet frames such to fulfil the operating requirements of SpacePHYre. In this use, QoS primitives would not be guaranteed to hold due to the non-deterministic operation of Ethernet MACs.

*3) Energy Efficient Ethernet:* The IEEE 802.3az standard gives PHYs the ability to detect when a defined period of no data transmission has occurred [4]. The PHY can automatically power down the transmit circuitry of the PHY into a standby state once this period has occurred. The receiver circuitry is kept active and so the link is quickly re-established once data is ready for transmission.

## III. Prototype Implementation

A prototype SpacePHYre codec is under development. A demonstration PCB hosting two Microchip VSC8541 PHYs (the commercial equivalent part of the VSC8541RT) has been developed for the Ultra96 FPGA board. The CODEC is being developed within the FPGA and tested with this PHY. The VSC8541 can be configured on device power up via the bootstrap pins or via the MDIO interface. The prototype CODEC will showcase demonstrate functionality without the MDIO interface at first, a MDIO controller will be added in a later implementation.

In addition to the VSC8541 prototype, power delivery daughter boards have been developed to demonstrate Power over Ethernet to the IEEE 802.3at standard [4]. Daughter boards for both a power source and a powered sink have been developed based on a COTS fully isolated 802.3at PoE solution. This allows up to 25W to be delivered over the cabling, using up to 57V injected into a pair of the data cables.

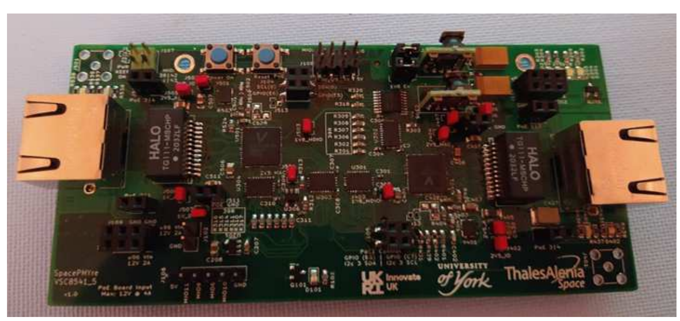

Fig. 6. Prototype SpacePHYre PCB supporting two Microchip VSC8541 PHYs (the commercial equivalent part of the VSC8541RT) and matched magnetics, the board is plugged in to an Ultra96 FPGA board where the CODEC is implemented within the FPGA hardware.

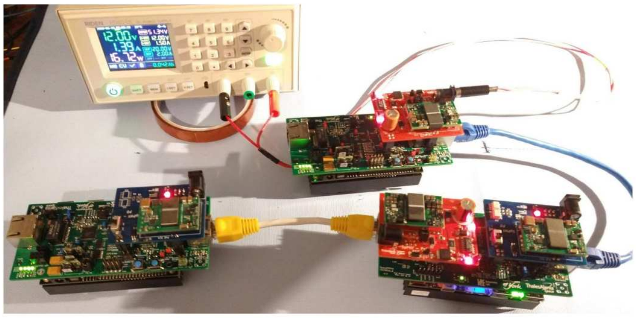

Fig. 7. Power Delivery Test. The prototype board is extended with power source and power sink boards to carry IEEE 802.3at PoE over the magnetics. Up to 25W can be delivered.

## IV. Further Development

Several developments for SpacePHYre are currently being undertaken at TAS-UK or planned for the near future:

1) *VHDL IP Core:* The SpacePHYre CODEC is currently being developed as a VHDL IP core for full testing and evaluation with the VSC8541. It is intended to release a prototyping version of this IP to the Space community in due course
2) *Testing with DP83561-SP PHY:* No commercial equivalent PHY exists for the TI PHY and so an evaluation will need to be made with SpacePHYre IP core and the evaluation board for this device.
3) *Develop and define standards for power delivery:* The IEEE standards for Power-over-Ethernet are focussed on fire and electrical safety in office environments and inline with terrestrial wiring standards. It is expected that efficiencies in operation can be made by tailoring for space applications only. Part of this work would also develop a handshaking and negation procedure, such that the power delivery can be managed and controlled as the required by the space application.
4) *Measurement of time synchronisation precision achievable with PTP:* It is expected that time synchronisation to 10ns can be achieved using PTP and the SoF detection features of the PHYs.
5) *Evaluate the performance of SpaceWire cables:* SpaceWire cables and connectors provide the required number of twisted data pairs for transmission between Gigabit Ethernet PHYs, a study will determine their suitability for Gigabit transmission. Their suitability and limitations for power delivery will also be assessed.

## V. Conclusions

SpacePHYre interfaces will complement existing SpaceFibre and SpaceWire networking by providing a significantly more robust interface, well suited to operation over long cable runs or with equipment that can generate large transients between the two endpoints. The power delivery opportunity presents large savings in harness mass and new technological development opportunities for powering remote units. It is envisioned that SpacePHYre could provide isolation between the platform and instrument avionic networks or for instruments that may operate on the periphery of the spacecraft, with SpaceFibre being used for the higher-speed interconnects required within electronics units e.g. for backplanes. The use of magnetic isolation enables an even greater degree of modular design and reuse, as better guarantees can be made of the isolation between modular units that AC coupling cannot provide.

The technology is in active development and, thanks to the recent availability of flight-suitable Gigabit PHYs, a technology demonstrator of the full CODEC is expected to be presented soon.

## References


[1] ECSS, "SpaceFibre Standard - ECSS-E-ST-50-11C," ECSS, Tech. Rep., 2019.

[2] Microchip, "VSC8541RT - Radiation-Tolerant Single Port Gigabit Ethernet Copper PHY with GMII/RGMII/MII/RMII Interfaces," Tech. Rep., 2019.

[3] T. Instruments, "DP83561-SP Radiation-Hardness-Assured (RHA), 10/100/1000 Ethernet PHY Transceiver with SEFI Handling Sub-System," Tech. Rep., 2021.

[4] TODO, "DP83561-SP Radiation-Hardness-Assured (RHA), 10/100/1000 Ethernet PHY Transceiver with SEFI Handling Sub-System," Tech. Rep., TODO.