SpaceFibre Network and Routing Switch

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***Abstract* – SpaceFibre is the next generation of the widely used SpaceWire technology for spacecraft on-board data-handling applications. SpaceFibre provides much higher performance, has integrated quality of service and fault detection, isolation and recovery capabilities. It runs over electrical or fibre optic media and is able to operate over distances of up to 5 m over electrical cables and 100 m over fibre optic cables. The SpaceFibre network layer uses the same packet format and routing concepts as SpaceWire, enhancing them with the concept of independent, parallel virtual networks, each of which operates like an independent SpaceWire network running over a single physical network. An essential component in a SpaceFibre network is the routing switch. STAR-Dundee has designed, built and tested a SpaceFibre routing switch in a commercial FPGA, using it to support the testing and validation of the network layer concepts developed for SpaceFibre. The architecture of the SUNRISE router is described and current work transferring this design to radiation tolerant technology is outlined.**

***Index Terms*—SpaceWire, SpaceFibre, Network, Virtual Network, Spacecraft On-board Data-Handling, RTG4, Quality of Service, FDIR, Next Generation Interconnect.**

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1. INTRODUCTION

SpaceFibre [1][2][3] is a multi-Gigabit/s spacecraft on-board data link and network technology which runs over electrical and fibre optic cables. SpaceFibre operate at multi-Gbits/s over distances of up to 5 m using electrical cable and 100 m using fibre optic cable. It includes quality of service (QoS) and fault detection, isolation and recovery (FDIR) capabilities. SpaceFibre is backwards compatible with SpaceWire [4][5] at the Network level, which enables existing SpaceWire equipment to be connected into a SpaceFibre network without modification. SpaceFibre has been designed to have a small footprint, so that is can fit comfortably in flight qualified Field Programmable Gate Arrays (FPGAs).

This paper provides an introduction to SpaceFibre, outlines SpaceFibre links, lanes and virtual channels and then describes the network layer [6] of SpaceFibre in detail. The STAR-Dundee SUNRISE SpaceFibre routing switch is introduced and the results of its implementation in a commercial FPGA outlined. The use of this router design in a prototype next generation mass-memory architecture for ESA is described. Finally, current work transferring the SUNRISE router design to a radiation tolerant Microsemi RTG4 FPGA is presented.

2. SPACEFIBRE

SpaceFibre is a multi-Gigabit/s spacecraft on-board data link and network technology which runs over electrical and fibre optic cables.

SpaceFibre is high performance, operating at 2.5 Gbits/s in current flight qualified technology (Microsemi RTAX FPGA and TI TLK2711-SP SerDes) and at 3.125 Gbits/s in the Microsemi RTG4 FPGA [7][8]. Higher data rate devices are current under development or being planned. Multi-laning can be used to provide much higher data rates [9].

SpaceFibre includes an integrated quality of service (QoS) mechanism which combines priority, bandwidth reservation and scheduling. These QoS capabilities operate together to give a number of highly desirable characteristics including “babbling idiot” protection and fully deterministic data delivery without loss of network bandwidth.

An integrated fault detection, isolation and recovery (FDIR) mechanism provides transparent recovery from transient errors and error containment in virtual channels and frames.

SpaceFibre provides low latency broadcast messages which can carry eight bytes of user information and are particularly useful for event distribution, error signalling and time distribution. For example, it is possible to distribute a CCSDS unsegmented time code to all nodes of a network with a single low latency message.

SpaceFibre is compatible with SpaceWire at packet level. This makes it very easy to bridge between SpaceWire and SpaceFibre. A SpaceWire interface can be directly connected to a SpaceFibre virtual channel. A SpaceWire instrument attached to that SpaceWire interface does not know that its packets are travelling over SpaceFibre, so it can use the same path or logical addressing mechanisms it used previously. The advantage is that now the packets from the instrument benefit from the QoS and FDIR capabilities of SpaceFibre, as well as substantially reduced cable mass, and improved system reliability.

While SpaceFibre was targeted initially at spacecraft on-board payload data-handling applications it can be used to provide a fully integrated spacecraft network which:

- Supports high data rate payloads;
- Carries data from existing SpaceWire instruments;
- Performs low latency time-distribution;
- Provides low latency event signalling;
- Supports deterministic data delivery to support guidance and navigation control applications.

3. SpaceFibre Links

Links and Lanes

A SpaceFibre link is made up of one or more lanes, which carry information from one end of the link to the other. SpaceFibre lanes can run over an electrical or fibre optic physical layer. In a multi-lane link, some of the lanes can be unidirectional provided that at least one lane is bi-directional [9]. The SpaceFibre link provides quality of service and error recovery [3].

SpaceFibre Virtual Channels

SpaceFibre links carry traffic (application information) through one or more virtual channels. There is a maximum of 32 virtual channels on a link, which are numbered consecutively starting at 0. Traffic entering virtual channel N comes out of virtual channel N at the other end of the link.

Each virtual channel is provided with a quality of service (QoS) which has three components: bandwidth reservation, priority and scheduling. Bandwidth reservation, reserves a portion of the link bandwidth for the virtual channel. Priority assigns a priority-level to the virtual channel so that higher priority virtual channels are able to send before lower priority ones. Scheduling divides time into 64 sequential time-slots and specifies in which of those time-slots a virtual channel is permitted to send information. These three different QoS components are not alternatives, they work together. [3]

4. SpaceFibre Networks

In this section the operation of a SpaceFibre network is described [5].

SpaceFibre Packets

SpaceFibre packets are identical to SpaceWire packets. They are formed from data characters, end of packet markers, and error end of packet markers, as illustrated in Figure 1.

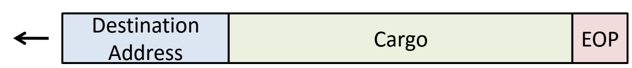

Figure 1 SpaceWire Packet Format

The "Destination Address" is the first part of the packet to be sent and is a list of data characters that represents either the identity of the destination node or the path that the packet has to take through a SpaceFibre network to reach the destination node. In the case of a point-to-point link directly between two nodes (no routers in between) the destination address is not necessary.

The "Cargo" is the data to be transferred from source to destination. Any number of data bytes can be transferred in the cargo of a SpaceFibre packet.

The "End_of_Packet" (EOP) is used to indicate the end of a packet. The data character following an End_of_Packet is the start of the next packet. There is no limit on the size of a SpaceFibre packet. “Error End of Packet” (EEP) is a form of EOP which is used to indicate the premature end of a packet due to the occurrence of an error.

SpaceFibre Virtual Networks

A SpaceFibre network is effectively a set of independent parallel SpaceWire networks. These parallel, independent networks are called "SpaceFibre virtual networks". Each virtual network runs over its own, distinct set of SpaceFibre virtual channels, comprising a virtual channel across each link used by the virtual network. Several virtual networks can then operate concurrently over a single physical SpaceFibre network. The overall physical network and the collection of virtual networks that run over that physical network is called the "SpaceFibre network".

The traffic running over each virtual network is constrained by the SpaceFibre quality of service mechanism to remain within its allocated bandwidth and to observe the priority and schedule allocated to it. A virtual network is able to opportunistically use more bandwidth than it has been allocated, when no other virtual network has traffic to send over the links of the SpaceFibre network that the particular virtual network wants to use.

As far as the addressing of packets and their routing across the network is concerned, SpaceFibre operates in the same way as SpaceWire. This has the substantial advantage that existing application software or SpaceWire equipment can be used with a SpaceFibre network by simply tying a SpaceWire link interface to a SpaceFibre virtual channel interface. The application does not need to know that it is running over SpaceFibre, but gains all the QoS and FDIR advantages of SpaceFibre. This make the integration of existing SpaceWire equipment both simple and advantageous.

Packet Addressing

SpaceFibre uses both path and logical addressing, which operate in the same way as SpaceWire. It is not possible to route a packet between two different virtual networks in a routing switch. As already stated virtual networks on a SpaceFibre network are like a set of parallel, independent SpaceWire networks. The packet routing is within one virtual network.

Path addressing uses the leading data character of a packet to determine how the packet should be routed at the next routing switch. If the value of the leading data character is in the range 0 to 31, it determines which port of the routing switch the packet will be forwarded through. For example, if the leading data character is 2, the packet will be forwarded through port 2 of the routing switch. If the leading data character is 0, it will be routed to port 0, the internal configuration port of the routing switch. If the leading data character is 31 and there are only 9 ports in the router, the packet will be discarded. Note that the ports of a router are number consecutively, starting at 0 for the internal configuration port.

If the leading data character is in the range 32-255, it is a logical address. The value of the leading data character is then used as the index into a routing table, which once configured, determines which port the packet is to be forwarded through. For example, if the leading data character is 40 and the entry in the routing table for index 40 contains the value 3, the packet will be routed to port 3 of the router. The routing table is configured using Remote Memory Access Protocol (RMAP) commands sent to the router configuration port [10]. Before configuration of the routing table has been done, any logical address will result in the packet being discarded. Path addressing operates at all times, before and after the routing table has been configured.

Virtual Network Masters

A "network master" is a node on a SpaceFibre virtual network which is a source of SpaceFibre packets able to send packets autonomously, i.e. without first receiving a request from another node. Note that a network master is different to a network manager, the latter is a network master that configures, controls and monitors the status of the entire SpaceFibre network.

If there is one network master on a virtual network then that virtual network can be deterministic. For example, the network master might be a control processor sending Remote Memory Access Protocol (RMAP) packets to other instrument nodes to control them and collect data from them, using RMAP. The traffic on the virtual network is controlled by the one network master node. The set of virtual channels that the specific virtual network runs over is allocated the bandwidth and priority according to its needs. If the virtual network is to provide time-bound determinism, its virtual channel will also be scheduled by the SpaceFibre QoS mechanism.

Within a single SpaceFibre virtual network, if there are two independent network masters, it is possible that they both send a packet to the same node, or through the same link to a router and then on to different nodes. Whenever these two network masters want to send a packet over the same link at the same time, there is a "collision" and one packet will have to wait for the other one to be sent. This is the same as the temporary "packet blocking" that can occur in a SpaceWire network. Each SpaceFibre virtual network operates just like a separate SpaceWire network, including temporary packet blocking.

Now, in some applications the temporary network blocking was a significant issue in a SpaceWire network, especially if long packets were being used. Traffic from one application could delay traffic from another one, which could be difficult to handle under some circumstances. SpaceFibre solves this problem, by having multiple, independent virtual networks. If there is a single network master on each of these virtual networks, the packet blocking is avoided completely. It is still possible to have multiple network masters on the same virtual network, provided that packet blocking is not an issue for the traffic flowing over that virtual network, or provided that another mechanism is used to control the flow of traffic over that network.

This approach maintains full backwards compatibility with SpaceWire at the network level, which is essential if the large legacy of existing SpaceWire equipment is not to be squandered. Reuse of existing, proven equipment, reflected by the Technology Readiness Level (TRL), is an important way of improving reliability and reducing the cost of space missions. SpaceFibre offers a path for substantially upgrading the capabilities and performance of an onboard network without losing that valuable legacy.

5. SpaceFibre Routing Switch

A SpaceFibre router has been designed and implemented in the SUNRISE project funded by the UK Space Agency and STAR-Dundee. The architecture of this router is shown in Figure 2.

The SUNRISE router has eight SpaceFibre ports, numbered 1 to 8, each with four virtual channels. There is a configuration port (port 0) which is used for device configuration and which can be accessed using virtual channel 0 of any of the other ports. Another port (port 9) provides an interface to four SpaceWire ports using four virtual channels, one for each SpaceWire port. SpaceWire and SpaceFibre packets are switched by the routing switch in the same way, using the leading data character of a packet to determine the output port that the packet is to be switched to. Both path and logical addressing can be used with the SUNRISE router.

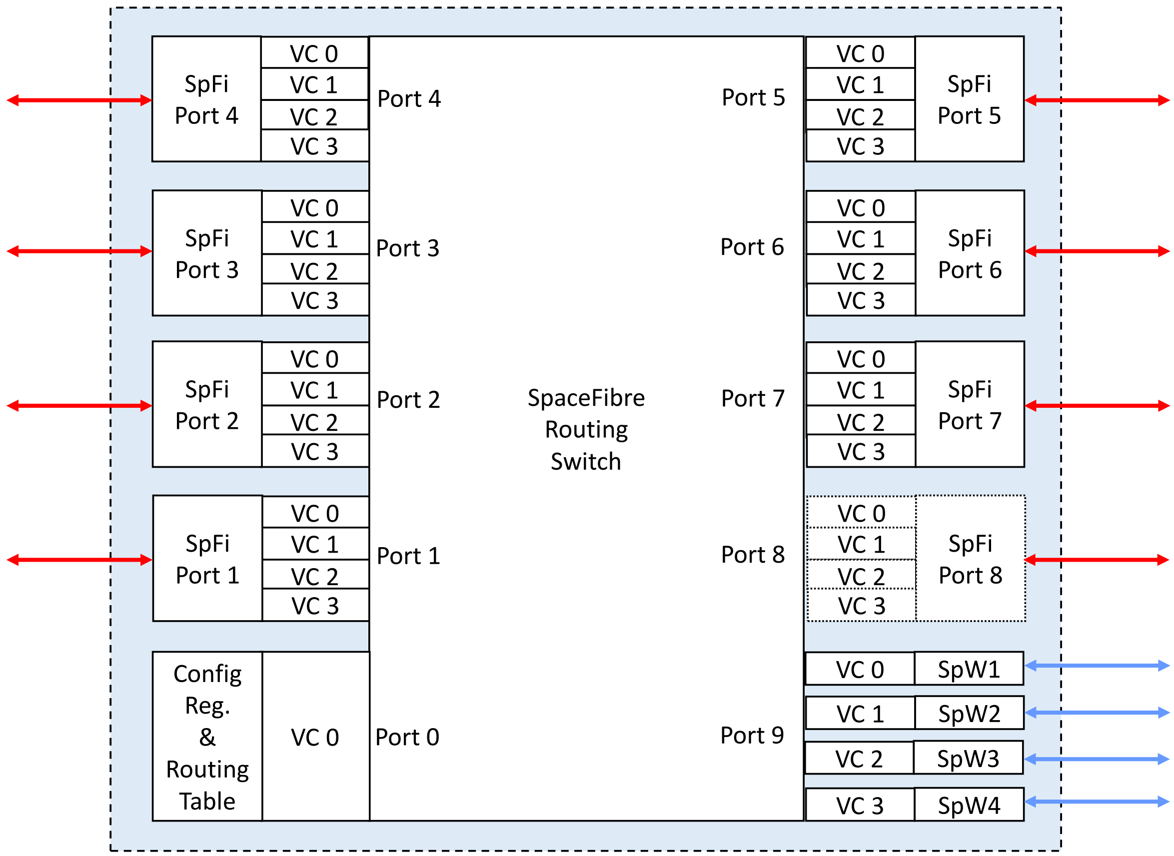

Figure 2 SUNRISE SpaceFibre Router Architecture

The SUNRISE router was implemented initially in a Xilinx Spartan 6 FPGA on a STAR-Dundee PXI board [11]. Power is taken from the backplane and the eight SpaceFibre and four SpaceWire ports are available on the 40mm wide front panel. The prototype SUNRISE router is shown in Figure 3.

Various experimental modes of operation were included in the SUNRISE router design to explore different routing concepts. This was used to help validate the characteristics of the SpaceFibre network layer as the standard document was being written.

Figure 3 SUNRISE SpaceFibre Router

6. SUNRISE ROUTER TESTING

Extensive testing has been carried out on the prototype implementation in the Spartan 6 FPGA. Two of the SUNRISE routers are shown under test in Figure 4.

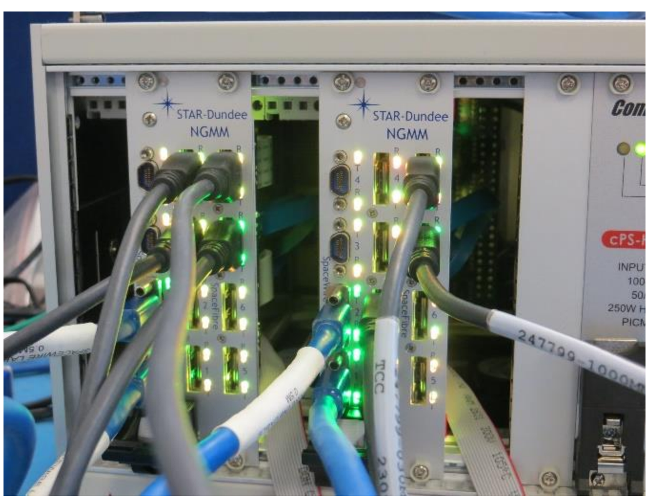

Figure 4 SUNRISE SpaceFibre Routers Under Test

The following features of the routing switches have been validated and demonstrated.

- Initialisation and operation of all SpaceFibre ports;
- Initialisation and operation of all SpaceWire ports;
- Path addressing;
- Logical addressing;
- Configuration of links and routing switch operation using RMAP via port 0;
- Link error recovery;
- Routing errors, including routing to a non-existent port and routing to a not-configured logical address;
- Group adaptive routing;
- Quality of service.

The SUNRISE routing switch is being used in the ESA Next Generation Mass Memory project being led by Airbus DS in Germany, with IDA and University of Dundee as partners. The SUNRISE router provides the high-performance interconnect between memory boards. SpaceFibre and SpaceWire interfaces are provided as the input/output ports to the mass-memory unit. Different virtual networks are used inside the mass-memory unit to write data, read data and pass control information between the input/output and memory modules.

7. RADIATION TOLERANT SUNRISE ROUTER

The SUNRISE router is now being implemented in a STAR-Dundee PXIe-RTG4 board which uses the radiation tolerant Microsemi RTG4 FPGA as shown in Figure 5 and Figure 6 [7][8][11].

The PXIe-RTG4 board is a versatile development board for the Microsemi RTG4 FPGA. There are two banks of 32-bit wide DDR memory attached to the RTG4, each with EDAC parity protection. The board is a 3U PXIe board with 5 Volt power taken from backplane connector. A four lane PCIe interface is provided on the backplane along with PXI triggers. Programmable clock generators are also provided on the board.

A set of STAR-Dundee “flexi” connectors are provided for attaching SpaceWire, CAN bus, UART and other IO functions to the board. In addition there are two, four lane SpaceFibre interfaces using the SerDes integrated into the RTG4 FPGA. These SpaceFibre interfaces can be used to provide eight, single-lane SpaceFibre interfaces or two, four-lane interfaces, or other combinations. For the SUNRISE routing switch eight, single-lane ports are provided for the router. In addition, four SpaceWire interfaces are provided using four flexi connections. In the photograph of the PXIe-RTG4 board in Figure 6, the flexi connections can be seen in the top right hand side of the photograph. The two banks of DDR memory on either side of the RTG4 device are also clearly visible in this photograph.

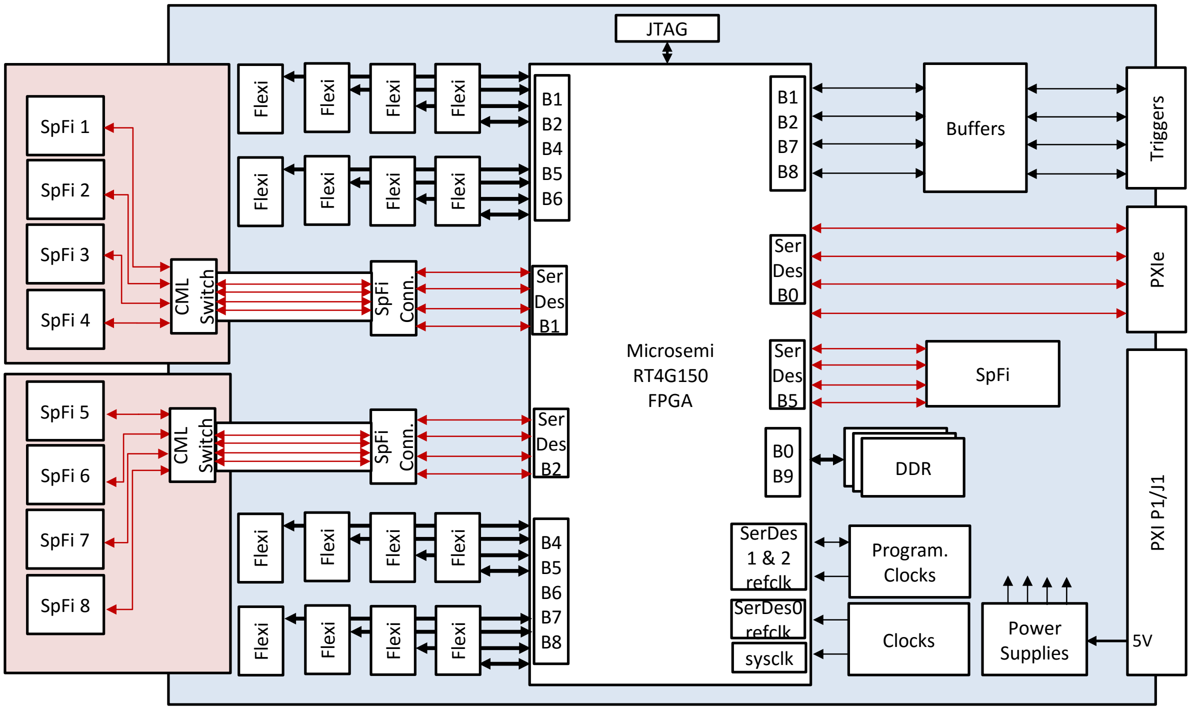

Figure 5 PXIe-RTG4 Board

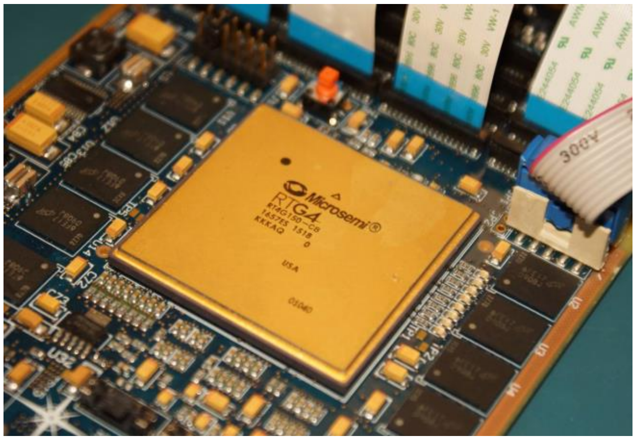

Figure 6 Prototype Microsemi RTG4 board for SUNRISE SpaceFibre Router

At the time of writing the prototype PXIe-RTG4 board has been tested and the SUNRISE router code is in the process of being transferred to the RTG4 FPGA. It is expected that the results will be able to be included in the final version of this paper.

8. CONCLUSIONS

SpaceFibre is the next generation of SpaceWire on-board data-handling network technology for space applications. The SpaceFibre network layer uses the same packet format and the routing concepts of SpaceWire, including path and logical addressing. It builds on this foundation with the concept of independent, parallel virtual networks, each of which operates like an independent SpaceWire network running over a single physical network. This overcomes the temporary packet blocking of critical information which was a feature of SpaceWire networks. An essential component in a SpaceFibre network is the routing switch. STAR-Dundee has designed, built and tested a SpaceFibre routing switch in a commercial FPGA, using it to support the testing and validation of the network layer concepts developed for SpaceFibre. The architecture of the SUNRISE router has been described and the current work transferring this design to radiation tolerant technology has been presented. Its use in the ESA Next Generation Mass Memory Architecture has been outlined.

ACKNOWLEDGMENTS

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BIOGRAPHIES

Steve Parkes *is the Director of the Space Technology Centre at the University of Dundee leading research on spacecraft on-board data-handling networks (SpaceWire & SpaceFibre), planet surface simulation, autonomous lander navigation, and digital signal and image processing for satellites. Steve wrote the ECSS-E-ST-50-12C SpaceWire standard with inputs from international spacecraft engineers, a technology that is now being used on more than 100 spacecraft. He is currently researching deterministic SpaceWire networks for integrated avionics and payload networks, SpaceFibre a multi-Gbit/s network technology for spaceflight applications, vision-based navigation for planetary landers, and FFT based spectrometers for an atmospheric chemistry instrument.*

Albert Ferrer-Florit *has a PhD in high-speed interconnection networks for space applications awarded by the University of Dundee. His PhD research was funded by ESA's Networking /Partnering Initiative after he worked in the on-board data processing group (TEC-EDP) in ESTEC. He is specialised in SpaceWire and SpaceFibre networks, being one of the key developers of the SpaceFibre standard. He is currently working for STAR-Dundee Ltd as a Network and Systems Engineer.*

Alberto Gonzalez Villafranca *holds a doctorate in data compression for space applications and has been connected to the space field his entire professional career. Alberto has been deeply involved in the definition and implementation of SpaceFibre since he joined STAR-Dundee Ltd. Before working with SpaceFibre he had collaborated with the Gaia mission and worked on a hardware implementation of a deterministic variant of the SpaceWire protocol at the European Space Agency.*

Chris McClements *is lead chip designer at STAR-Dundee Ltd. He worked at the University of Dundee from 2003 to 2016, where he was responsible for the RTL-level design of the SpaceWire 10X router (Atmel AT7910E). This radiation tolerant ASIC is being used in many ESA missions including the BepiColombo and Solar Orbiter missions. Dr McClements was also the author and developer of the SpaceWire-B and SpaceWire RMAP VHDL IP cores which are available through the ESA IP core service. He is currently working on test and development equipment for high speed serial SpaceFibre devices.*

David McLaren *received his MEng degree in Electronic Engineering from Durham University, UK, in 2005 and EngD in System Level Integration from the University of Glasgow, UK, in 2010. He has experience in hardware and software development within industry and academia, including spacecraft simulator development, FPGA design, and research into space internetworking and on-board computing architectures. His current research at the University of Dundee concerns development and testing of microchips implementing the SpaceFibre protocol.*