

SpaceFibre Payload Data-Handling Network

Steve Parkes
STAR-Dundee
Dundee, Scotland, UK
steve.parkes@star-dundee.com

Albert Ferrer, Alberto Gonzalez and Marti Farras,
STAR-Barcelona
St Cugat, Barcelona, Catalonia, Spain
enquiries@star-dundee.com

Dave Gibson, Blair Winton, Pete Scott, Chris McClements, Keith Carruthers, Neil Purves, Balint Furdek and Gareth McPherson
STAR-Dundee
Dundee, Scotland, UK
enquiries@star-dundee.com

Abstract— The Hi-SIDE project [1] is a European Union project carried out by several leading aerospace organisations from across Europe. It aims to develop satellite data-chain technologies for future Earth observation and Telecommunication systems. Hi-SIDE has made substantial advances in the major elements of the data chain including networking, processing, compression, and downlink transmission to support the next generation of data intensive missions. The data chain elements are interconnected via a SpaceFibre network [2]. This paper introduces SpaceFibre and the Hi-SIDE project and then describes the STAR-Tiger SpaceFibre routing switch which forms the heart of the SpaceFibre network.

Keywords—SpaceFibre, Payload Data-Handling, Serial Communications, Networks, Hi-SIDE

I. INTRODUCTION

SpaceFibre [2] is the latest generation of SpaceWire [3] network technology for spacecraft on-board data-handling. It runs over electrical or fibre-optic cables, operates at very high data rates, and provides in-built quality of service (QoS), and fault detection, isolation and recovery (FDIR) capabilities. Because of these important characteristics, SpaceFibre was selected for use as the equipment interconnect for the Hi-SIDE project. STAR-Dundee developed the SpaceFibre interfaces for all the elements of the Hi-SIDE demonstrator along with the SpaceFibre routing switch.

The STAR-Tiger SpaceFibre routing switch is the primary element of the payload data-handling network for the Hi-SIDE project, which is used for transferring data at high data-rates between instruments, mass-memory, data compressor, data processor and downlink transmitters. It is also used to provide the control network used by the control computer to control both the network and the equipment attached to the network.

The STAR-Tiger SpaceFibre routing switch is shown in Figure 1 and has the following key features:

- 10 SpaceFibre ports
 - Two quad-lane ports
 - Eight dual-lane ports
 - Lane speed up to 6.25 Gbit/s
 - Port data rate 9.6 Gbit/s dual-lane port and 19.2 Gbit/s quad-lane port

- 2 SpaceWire interfaces for programming STAR-Tiger FPGA
- Spaceflight TRL5/6 level design
- Electronic components are radiation tolerant EM flight parts or industrial/commercial equivalents of flight parts
- Power consumption 14.2W typical at 20 °C, all links running with lanes speeds of 6.25 Gbit/s
- Conduction cooled
- Operating temperature range: -25 to +55 °C
- 108 x 108 x 68 mm (excluding mounting brackets)



Figure 1: STAR-Tiger SpaceFibre Routing Switch

II. HI-SIDE PROJECT

The Hi-SIDE project has developed critical satellite data-chain technologies for handling and transferring data from instruments to processing and storage elements on-board the spacecraft, and to the downlink transmitters that send data to ground. The Hi-SIDE project culminated in a comprehensive demonstration incorporating all the critical elements of the High Speed Data Chain (HSDC) from instrument to ground-station. A block diagram of the onboard elements of the demonstration system is shown in Figure 2.

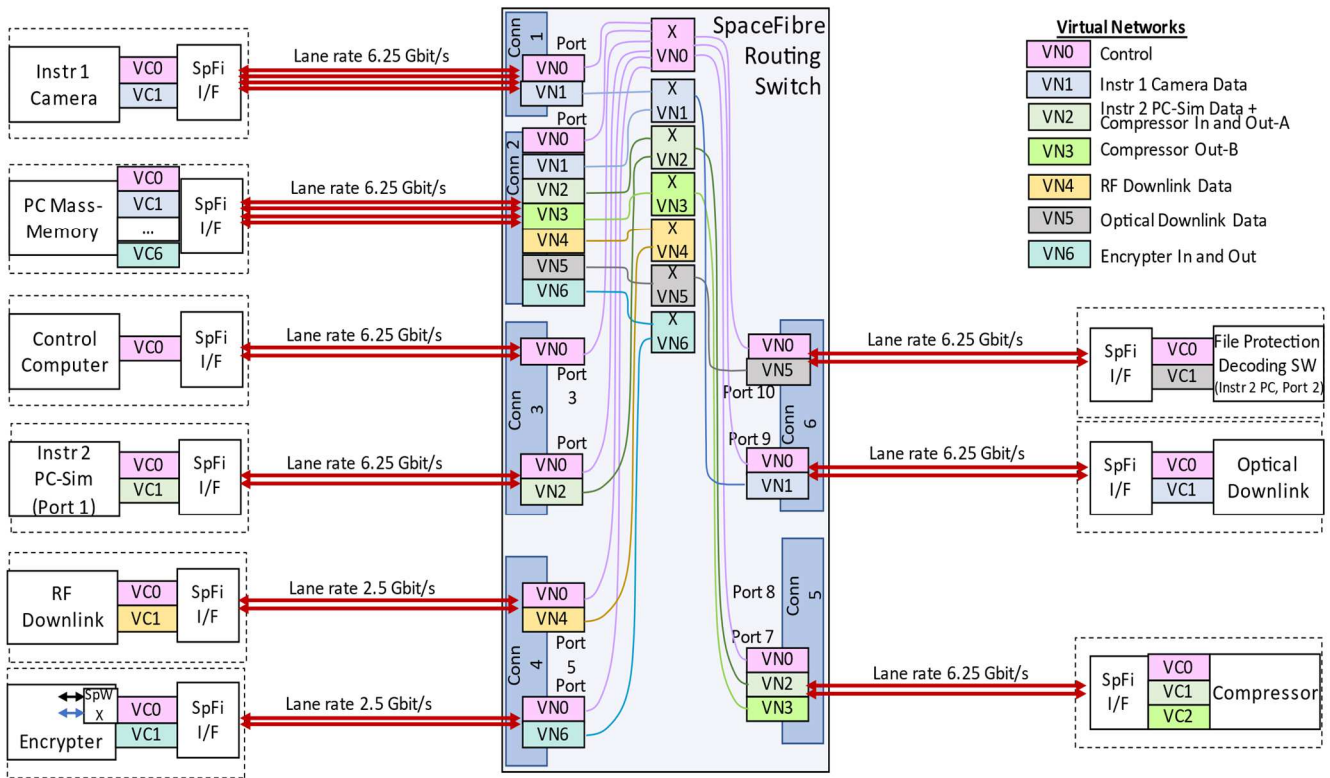


Figure 2: Hi-SIDE Demonstration System Block Diagram

The various elements of the on-board data chain are shown on the left and right sides of the diagram interconnected via SpaceFibre links (red lines) to the routing switch in the middle of the diagram. Each element contains a SpaceFibre interface which connects it to the SpaceFibre network. The interfaces are either quad-lane or dual-lane interfaces, as shown by the number of the lanes in the link to the SpaceFibre routing switch. The interfaces have two or more virtual channels which are mapped by the routing switch to virtual networks. The virtual networks are colour coded and a key to the type of traffic they handle is shown in Figure 2. The configured virtual networks are also illustrated inside the SpaceFibre routing switch (X = virtual network switch).

The HSDC demonstration network includes the following elements:

- STAR-Tiger routing switch connected to all elements via SpaceFibre links.
- Instrument 1 (SpaceFibre camera) connected to STAR-Tiger Port 1, which provides real-time image data at around 4.6 Gbit/s.
- PC-Based Mass-Memory [4] connected to STAR-Tiger Port 2, which stores data from the instruments, passes data to and from data processor/compressor, and sends compressed, encrypted data to the RF or optical downlink.
- Control Computer [4] connected to STAR-Tiger Port 3, which configures, controls and monitors the SpaceFibre network and the equipment connected to the network.

- Instrument 2 (simulator) connected to STAR-Tiger Port 4, which provides hyperspectral data at a data rate of around 9 Gbit/s.
- Radio Frequency (RF) downlink [5] connected to STAR-Tiger Port 5.
- High-Performance Data-Processor (HPDP) [6] connected to STAR-Tiger Port 6, which is programmed to perform data encryption.
- Data Compressor [7] connected to STAR-Tiger Port 7, which is performing CCSDS 123.0-B-2 Low-Complexity Lossless and Near-Lossless Multispectral and Hyperspectral Image Compression.
- Image Viewer (simulating the optical downlink [8]) connected to STAR-Tiger Port 9.
- File Protection Scheme (FPS) Decoder [9] connected to STAR-Tiger Port 10.

The SpaceFibre virtual networks separate different types of traffic on the network so that one type cannot interfere with another type. The virtual networks in the demonstration system are used as follows:

- VN 0 is used for network and equipment management and connects to all of the elements. The Control Computer uses VN 0 to send Remote Memory Access Protocol (RMAP) [10] commands to the elements to read or write to registers, and the elements return the corresponding RMAP replies to the Control Computer.
- VN 1 is used by the SpaceFibre Camera to send images either directly to the Image Viewer or for

storage in the Mass-Memory before the Mass-Memory plays back the images to the Image Viewer.

- VN 2 is used by the Instrument Simulator to send data for storage in the Mass-Memory. It is also used by the Compressor to send one half of the compressed files for storage in the Mass-Memory.
- VN 3 is used by the Compressor to send the other half of the compressed files for storage in the Mass-Memory.
- VN 4 is used by the Mass-Memory to send files to the RF Downlink.
- VN 5 is used by the Mass-Memory to send protected files to the FPS Decoder.
- VN 6 is used by the Mass-Memory to send files to the HPDP for encryption, and by the HPDP to send the encrypted files to the Mass-Memory for storage.

A photograph of the integrated demonstration system is shown in Figure 3.

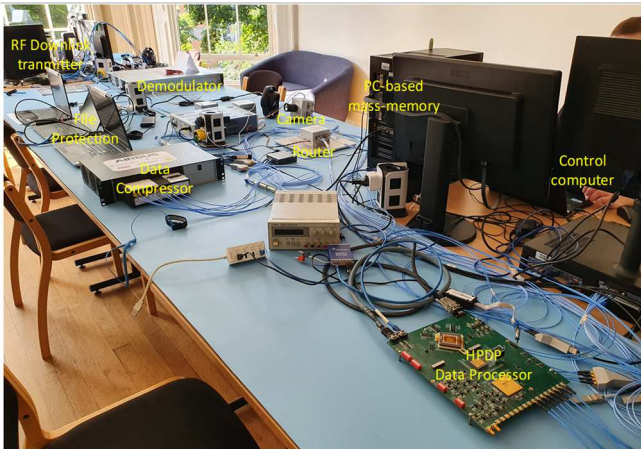


Figure 3: Photograph of the Integrated Hi-SIDE Demonstration System

The control computer was able to monitor and display the data rates of the traffic flowing through each virtual network during the demonstration. Figure 4 shows an example of traffic going to the mass-memory for storage. The chart shows data rates plotted over time for the VCs going into the Mass-Memory used to store data. In this diagram, the following data flows are shown:

- VC 1 (blue line): SpaceFibre Camera sending 8 GB of images to the Mass-Memory for storage.
- VC 2 (green line): Instrument 2 sending 16 GB of data to the Mass-Memory for storage and Data Compressor sending one half of the compressed data to the Mass-Memory for storage.
- VC 3 (purple line): Data Compressor sending the other half of the compressed data to the Mass-Memory for storage.

When these operations overlap, the total data rate of traffic being stored simultaneously in the Mass-Memory is around 14 Gbit/s (the SpaceFibre Camera is approximately 4.5 Gbit/s, Instrument 2 is approximately 9 Gbit/s and the Data Compressor is approximately 0.5 Gbit/s for each of the two compressed streams).

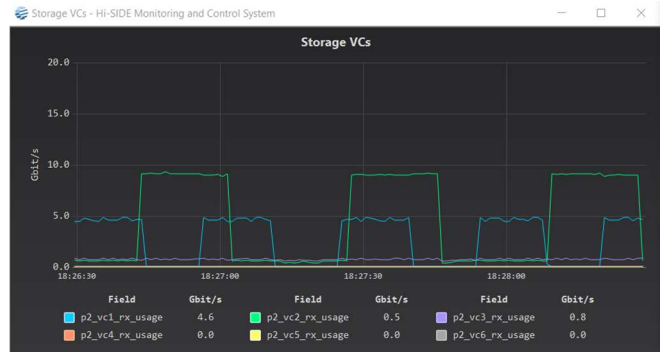


Figure 4: Example of Monitored Network Traffic to the Mass-Memory

Further information on the Hi-SIDE demonstration system is available in [4].

III. STAR-TIGER SPACEFIBRE ROUTING SWITCH

The on-board network is formed by the STAR-Tiger routing switch, the SpaceFibre cable assemblies and the SpaceFibre interfaces in each element. In this section the STAR-Tiger routing switch is described. The design of STAR-Tiger unit, the router FPGA design, and the functional and environmental testing of STAR-Tiger are outlined.

A. STAR-Tiger Design

The STAR-Tiger SpaceFibre routing switch unit design is illustrated in Figure 5.

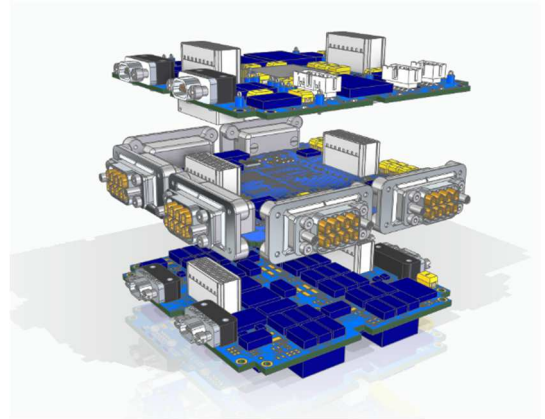


Figure 5: STAR-Tiger Routing Switch Boards

STAR-Tiger comprises three circuit boards:

- A power supply board (bottom) which provides a nominal and redundant power input selection and delivers the five main power rails to the FPGA. TI radiation tolerant power supply components are used. Other power rails are supplied by regulators on the other two boards
- An FPGA board (middle) containing the Xilinx KU060 FPGA. An industrial grade FPGA was used. The PCB footprint accommodates either the commercial/industrial part or the radiation tolerant part. The FPGA is surrounded by six Elara connectors which carry the electrical SpaceFibre signals. Each connector provides four lanes of SpaceFibre.
- A configuration and scrubbing board (top). Configuration is from EEPROM or via a SpaceWire interface. The EEPROM can be programmed over SpaceWire.

These three boards are shown in Figure 6 to Figure 8 in various stages of integration with the STAR-Tiger housing. The complete STAR-Tiger unit is shown in Figure 1.

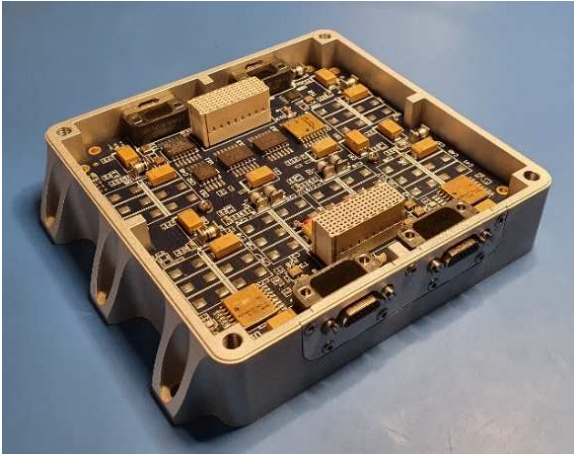


Figure 6: STAR-Tiger Power Supply Board in Housing

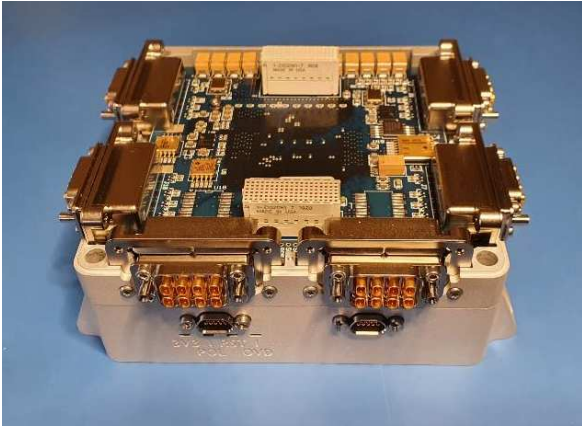


Figure 7: STAR-Tiger FPGA Board in Housing

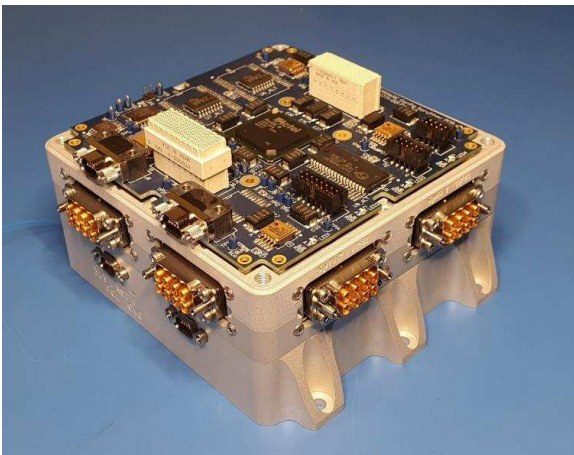


Figure 8: STAR-Tiger Configuration Board in Housing

The SpaceFibre camera used in the Hi-SIDE demonstration was produced by adding an image sensor board to the top of the configuration board which transforms the STAR-Tiger into a high data-rate image sensor.

B. SpaceFibre Routing Switch FPGA Design

A block diagram of the STAR-Tiger SpaceFibre routing switch FPGA is shown in Figure 9. The SpaceFibre routing switch FPGA code was developed by STAR-Barcelona.

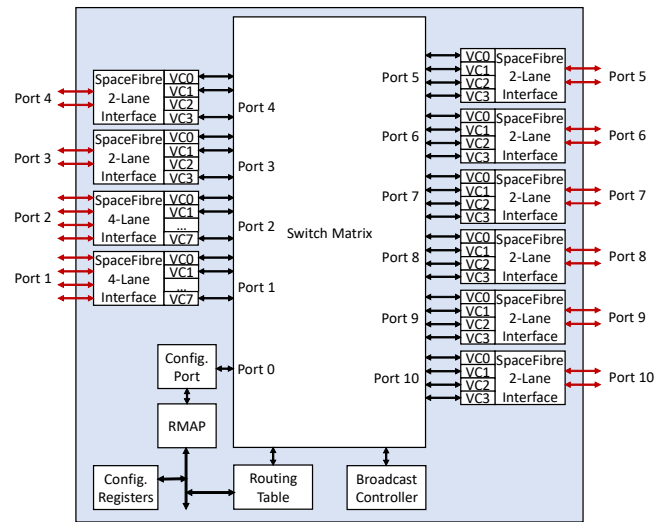


Figure 9: Block Diagram of Routing Switch FPGA

The SpaceFibre routing switch FPGA contains the following:

- A routing switch matrix with ten SpaceFibre ports and an internal configuration port.
- Two quad-lane SpaceFibre ports (ports 1-2) with eight virtual channels each.
- Eight dual-lane SpaceFibre ports (ports 3-10) with four virtual channels each.
- An RMAP configuration port (port 0) which accesses the SpaceFibre router configuration, control and status registers.
- A routing table which is configured over the configuration port and which determines the logical address to output port-number mapping.
- A broadcast controller which broadcasts broadcast-messages on each of the 256 possible broadcast channels. The broadcast controller also provides the time-slot timing for the schedule quality of service.

The placement of each the SpaceFibre ports in the FPGA is illustrated in Figure 10.

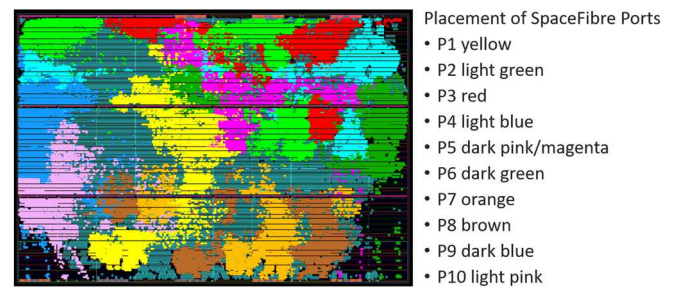


Figure 10: STAR-Tiger FPGA SpaceFibre Port Placement

C. STAR-Tiger Functional Testing

The STAR-Tiger boards were subject to extensive testing during development and integration. Once STAR-Tiger was operational, verification tests were carried out to ensure that the unit performed as required. The test setup used for many of the functional tests is shown in Figure 11.

The STAR-Tiger is in the centre of the photograph, powered by a bench power supply set to 5V with a current limit of 3A. The power lead is connected to the rear of the

STAR-Tiger unit. A cooling fan is used to cool the STAR-Tiger unit. Since the power dissipation of STAR-Tiger is only 14.2W, the cooling fan is set to its minimum setting. The SpaceWire interface device used for programming STAR-Tiger is a SpaceWire Physical Layer Tester (SPLT), with the SpaceWire link to STAR-Tiger being connected to port 3 of the SPLT. Any other SpaceWire interface device could be used. The Python scripts which send command and data to the STAR-Tiger configuration board are run on a laptop PC connected to the SPLT via a USB 2.0 cable. The laptop PC is also connected to a STAR-Ultra PCIe SpaceFibre interface board [11] which is in a Thunderbolt 3 to PCIe unit. The host PC is able to send and receive SpaceFibre packets via the STAR-Ultra PCIe board at the 10 Gbit/s necessary for testing the STAR-Tiger. The STAR-Ultra PCIe is connected to port 2 of STAR-Tiger by a QSFP to Elara cable assembly. To support the testing of all the SpaceFibre ports, port 1 of STAR-Tiger is connected back to itself via a lookback cable and there are cable assemblies between ports 3/4 and ports 5/6, and between ports 7/8 and ports 9/10.

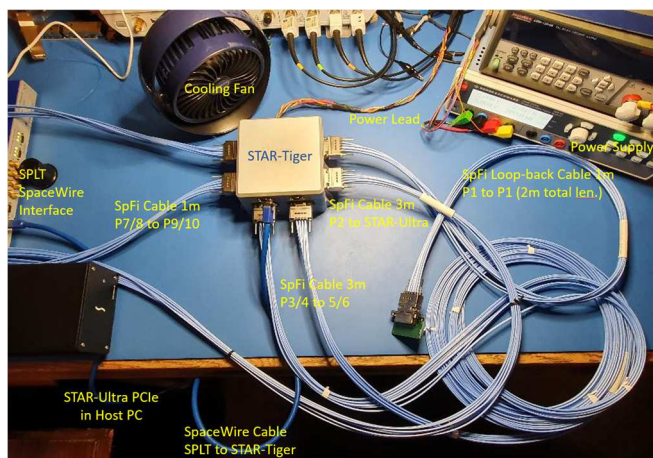


Figure 11: STAR-Tiger SpaceFibre Routing Switch Test Setup Photograph

The STAR-Tiger routing switch was tested using the STAR-Ultra PCIe SpaceFibre interface board which is ECSS-ST-11C compliant. The two quad-lane ports were tested first, using the arrangement illustrated in Figure 12.

The lane speed is 6.25 Gbit/s giving a link speed of 25 Gbit/s, which is 20 Gbit/s excluding the 8B10B encoding and 19.2 Gbit/s excluding other protocol overheads for a bi-directional link. 100 Kbyte packets are sent from the STAR-Ultra PCIe to port 2 of the STAR-Tiger router, then out through port 1, looped back to port 1 and finally back out of port 2 to the STAR-Ultra PCIe (see the red path in Figure 12).

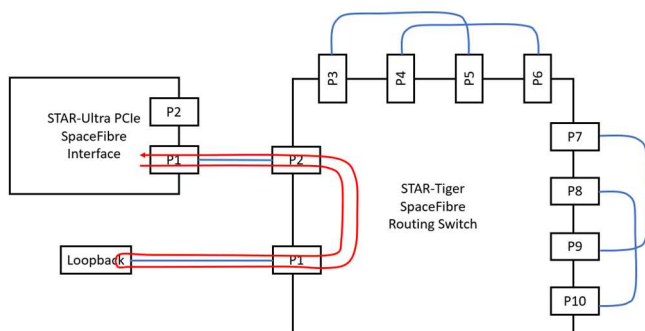


Figure 12: STAR-Tiger SpaceFibre Routing Switch Test Setup

Figure 13 shows a screenshot of the STAR-Ultra PCIe connected to a STAR-Tiger transferring data at a data rate of 13.6 Gbit/s. Data is travelling in both directions of both ports. The source was turned on for around 20s, then switched off for 25s, and then runs continuously. The aggregate data rate being handled by the STAR-Ultra PCIe is 27 Gbit/s (data rate in plus data rate out). The data rate of 13.6 Gbit/s is less than the possible 19.2 Gbit/s because of the time taken by the PC generating the data and performance constraints of the STAR-Ultra PCIe board.

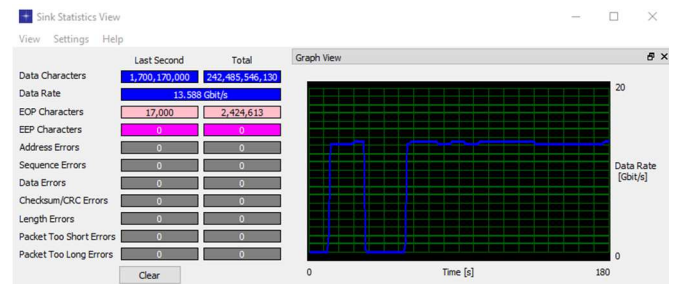


Figure 13: STAR-Ultra PCIe sending and receiving SpaceFibre data at high-speed to/from STAR-Tiger

Tests were then carried out to check all of the links operating together. The test setup is shown in Figure 14. Using path addressing the packets are sent through all the ports of the routing switch and back to the STAR-Ultra PCIe board.

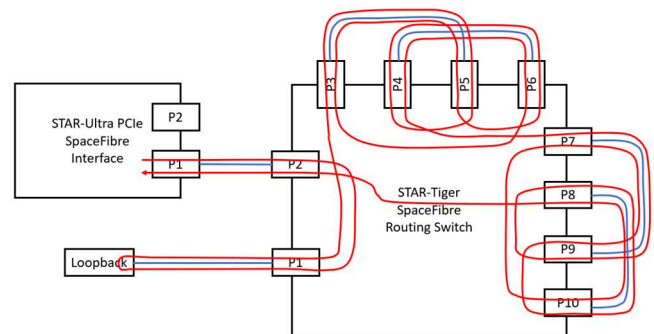


Figure 14: Testing all SpaceFibre ports of STAR-Tiger

The test results are shown in Figure 15. At the start of the trace only the two quad-lane ports were being used, giving a data rate around 13.6 Gbit/s. The path address was then changed to include all the dual-lane ports and the data rate drops to around 9.6 Gbit/s, which is the maximum data-rate that can be supported with two-lanes and a lane speed of 6.25 Gbit/s. Further checks were carried out forming a comprehensive set of verification tests.

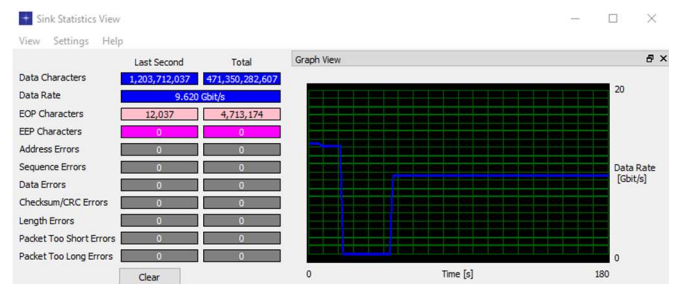


Figure 15: STAR-Ultra PCIe exercising all SpaceFibre ports of the STAR-Tiger

D. STAR-Tiger Environmental Testing

With the functional and performance verification tests complete, STAR-Tiger was subject to some environmental testing, covering thermal, vibration and radiated emission tests.

A thermal simulation of STAR-Tiger is shown in Figure 16.

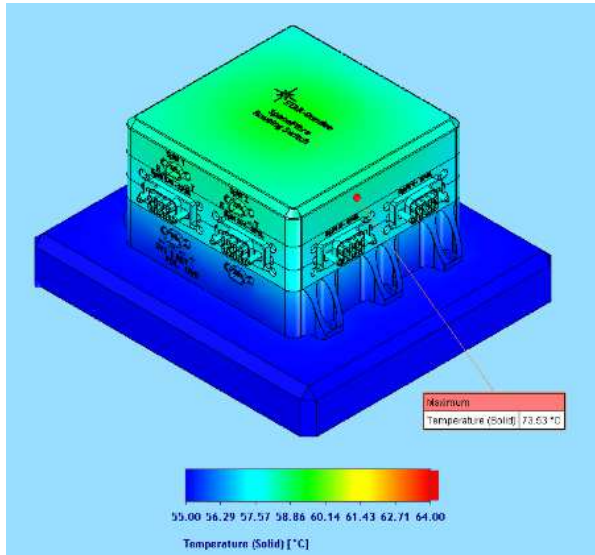


Figure 16: Thermal Simulation of STAR-Tiger (18W)

This particular thermal simulation assumed a worst case power dissipation of 18W, compared to the room temperature power consumption of 14.2W.

The STAR-Tiger unit ready for thermal testing is shown in Figure 17. It is mounted on an aluminium baseplate with heatsinks to keep the baseplate close to the temperature of the thermal chamber. STAR-Tiger is covered with thermal insulation to prevent convection affecting the test results. Thermal cycling was carried out for 15 hours. The results are shown in Figure 18 and correspond to the results of the thermal simulation. There is a temperature drop of around 10°C from the lid of the FPGA to the baseplate. At the end of the temperature test, condensation in the test chamber caused an issue, but STAR-Tiger recovered from this once the condensation cleared.

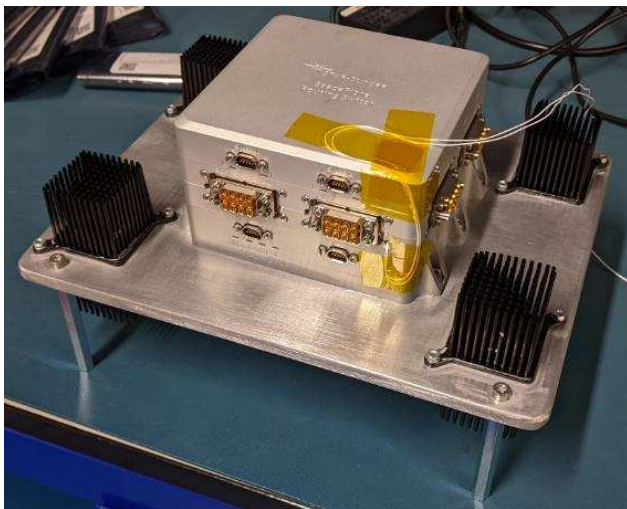


Figure 17: STAR-Tiger Prepared for Thermal Testing

Thermal testing was carried out with a qualification temperature range of -30°C to +60°C for an operational temperature range of -25°C to +55°C.

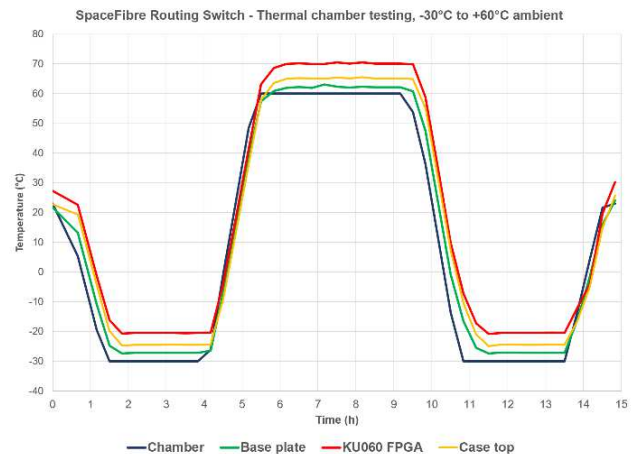


Figure 18: STAR-Tiger Thermal Test Results

Figure 19 shows STAR-Tiger ready for vibration testing. The three axes were tested. For each, an initial scan for resonant peaks was run using a sinewave sweep from 20 Hz to 2 kHz (see Figure 20). Random vibration testing was then carried out for two minutes per axis. A subsequent sinewave scan was then made to see if the resonant peaks had shifted significantly, which would indicate mechanical instability. No significant shift in the frequency and amplitude of the peaks were observed, so the test passed. Note that the limit lines in Figure 20 are for the forcing function, the green line.

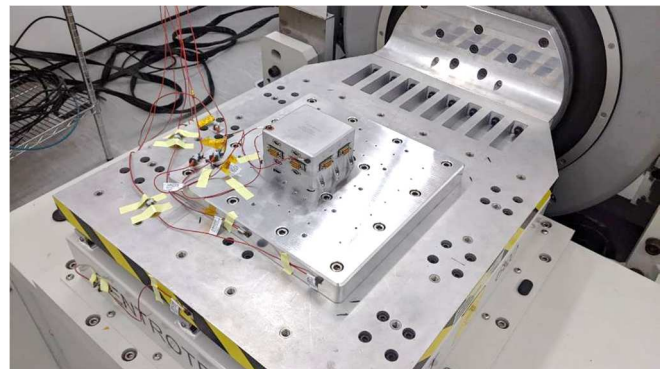


Figure 19: STAR-Tiger Prepared for Vibration Testing

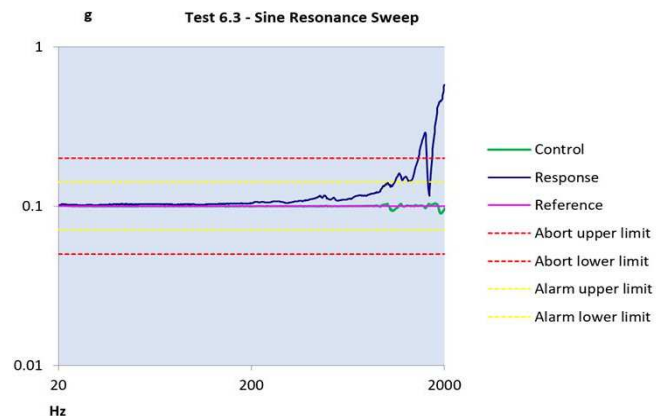


Figure 20: STAR-Tiger Vibration Test Results

EMC radiated emission testing was carried out and those tests were passed (see partial test results in Figure 21). Conducted emission tests have not yet been done.

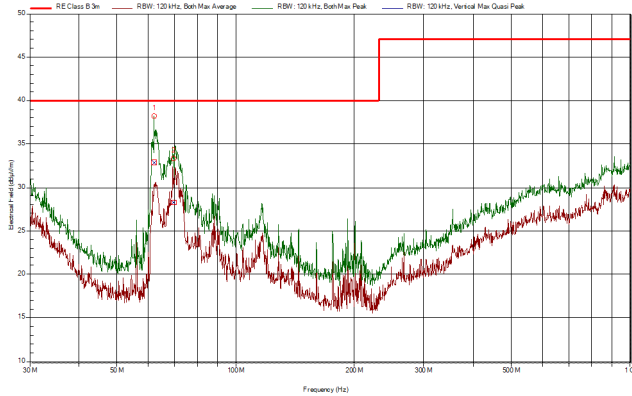


Figure 21: EMC Radiated Emission Testing (30MHz to 1GHz)

IV. CONCLUSIONS

The Hi-SIDE project has successfully demonstrated a high-performance data-handling chain for future Earth Observation missions. The STAR-Tiger SpaceFibre Routing Switch forms the heart of the SpaceFibre network that connects the instruments, data-handling and downlink telemetry elements together. STAR-Tiger is capable of data rates up to 19 Gbit/s on its quad-lane ports and 9.6 Gbit/s on its dual-lane ports. STAR-Tiger has been developed with radiation tolerant components to a TRL level of 5/6. It further demonstrates the capabilities of SpaceFibre for future on-board payload processing network.

ACKNOWLEDGEMENT

The Hi-SIDE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776151.

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