

Future Focus: SpaceFibre

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Future Focus: SpaceFibre



Overview

- SpaceFibre Requirements
- Mixed SpaceWire SpaceFibre networks
- Demonstrator Development
- SpaceFibre Codec
- SpaceFibre Optical Link Technology
- Conclusion



SpaceWire Limitations

- Link data rate is currently <200-400Mb/s gross
 - Limited by jitter and skew between data and strobe signal
 - Situation worsens with longer cables length
- SpaceWire link maximum cable length is 10m at high speed
 - In general sufficient for on satellite applications
 - Other applications like Launchers, Space Station and EGSEs for ground testing could require longer cable length
- Cable mass
 - SpaceWire cable contains 4 twisted shielded pairs
 - One for data and one for strobe in each direction
 - Mass about 87g/m
 - Bundling of several SpW links for higher data rates becomes heavy
- SpaceWire does not provide galvanic isolation
 - Often EMC requirement for connections between electronic boxes
 - Enables easier system integration on spacecraft level
 - Characteristic required for Ground Support Equipment
- Link power consumption speed independent
 - No power saving mode at link layer



SpaceWire Features to be maintained

- Simplicity
- Low gate count and memory implementation
- Worm hole routing
- Bi-directional, full-duplex
- Group adaptive routing
- Bandwidth sharing
- Fault detection
- Time code distribution



SpaceFibre Requirements

- Provide symmetrical, bi-directional, point to point link connection
- Handle data rates 1-10Gb/s and support variable signalling rates
- Bridge distances up to 100m at maximum data rate
- Be based on fibre optic link technology which provides galvanic isolation
- Copper version with AC coupling for shorter distances
- Allow for mixed SpaceWire SpaceFibre networks via special SpaceWire-SpaceFibre Routers
- Transmit a scalable number of virtual SpaceWire links over one SpaceFibre
- Compliant to the protocols and routing mechanisms defined in the SpaceWire standard
- Similar bit error rates as specified for SpaceWire
- Fast start up and fine grained power management
- Intrinsic support to quality of service



Mixed SpaceWire – SpaceFibre Router & Networks

- Transfer speed in network is determined by slowest link on the path
- SpaceFibre must not be slowed down by SpaceWire Link in network
- Concept: Several virtual SpaceWire Links over one SpaceFibre
 - Multiplexing of data streams is required
 - This can be performed on character or frame level
 - Frame level multiplexing is preferred for a higher level of flexibility



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SpaceFibre Prototyping Activities

- Prototyping performed by two teams
- Covering complementary areas:
 - SpaceFibre physical layer
 - SpaceFibre Codec
- Two parallel development contracts

- "Optical Links for the Space Wire Intra Satellite Network Standard"

Objective: The development of a high speed point to point fibre optic link for space applications.

Contractors: Patria (Prime), VTT, INO, Fibre Pulse, W.L. Gore

- "Space Fibre" The TOPNET Call Off No. 2

Objective: Codec development and SpaceFibre integration into the Space Wire network through the development of a high speed router.

Contractor: University of Dundee



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PC with PC with **SpaceWire** SpaceWire Interfaces Interfaces Serial Serial Electrical Electrical Interface Interface **Optical Fibres** CML CML **SpaceWire SpaceWire** ТΧ ТΧ SpaceFibre **SpaceFibre** RX RX Router Router ΤХ ТΧ RX RX Codec **Fibre Optical Fibre Optical** Codec Serialiser/ Transceiver Transceiver Serialiser/ Deserialiser Deserialiser • ٠

SpaceFibre Demonstrator

- University of Dundee:
 - SpaceWire-SpaceFibre Routers
 - CODEC
 - Serialiser / Deserialiser
 - **Copper Version**

- Patria et.al.:
 - Fibre Optical Transceiver
 - **Optical Fibres**
 - **Optical Cable Assembly**
 - **Fibre Connectors**
 - Environmental test program
- Simple serial digital data electrical interface CML between the two parts ٠

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SpaceWire 101



SpaceFibre CODEC

- A number of high speed serial link standards have been reviewed
 - Fibre Channel,
 - Serial ATA,
 - PCI Express,
 - Infiniband,
 - Gigabit Ethernet,
 - Hypertransport
- Proposed solution must ensure compliance with SpaceWire protocols and routing mechanisms



SpaceFibre CODEC Trade-off 1/5

- 8B/10B Encoding
 - Gigabit Ethernet, Fibre Channel, PCI Express, Serial ATA and Infiniband all use 8B/10B encoding
 - Zero DC bias: same number of ones and zeros
 - 1024 possibilities to encode 8-bit data characters + 16 control characters
 - Uses only codes with: 5 ones + 5 zeros, 4 ones + 6 zeros, 6 ones + 4 zeros
 - Characters with uneven number of ones and zeros have two possible encodings to preserve DC bias
 - Running disparity determines which of two possible codes is used
 - Control codes with unique seven bit comma sequence are used for character alignment
 - Ensures sufficient bit transitions enabling for clock recovery with PLL
 - No more than 5 consecutive ones or zeros
 - Constant bit and character rate is simplifying decoding



SpaceFibre CODEC Trade-off 2/5

- Ordered Sets
 - Ordered Set concept of Fibre Channel, PCI Express, and Serial ATA
 - Ordered Set is Comma Control Code followed by 3 bytes information
 - Very attractive and powerful concept
 - Enables transfer of link control information and other e.g. time-codes
- Scrambler
 - Use of data scrambler to provide a spread spectrum signal
 - Within PCI Express and Serial ATA
 - To reduce the EM emissions from the copper version of SpaceFibre.
- Receive Elastic Buffer
 - Required to compensate slight clock differences between transmitter and receiver
 - Skip characters are inserted or removed to avoid congestion
 - Reduces size of receive clock domain
 - Simplifies circuitry and improves speed



SpaceFibre CODEC Trade-off 3/5

- Byte Striping and Lanes
 - PCI Express and Infiniband use byte striping across one or more lanes
 - Extra lanes are added to increase the available bandwidth
 - The group adaptive routing approach of SpaceWire is preferred
- Link Control
 - Link initialisation
 - Flow control
 - Error detection and recovery
- Speed Negotiation Philosophy
 - Link speed negotiation philosophy used by Serial ATA,
 - Starting with the highest link speed first avoiding limitations with legacy systems
 - Is worth adopting for SpaceFibre



SpaceFibre CODEC Trade-off 4/5

• Fine Grained Power Management

- Serial ATA provides for fine control of the power state of the interface
- Two standby power states
- Specified in terms of the time that they take to recover
- Should be adopted for SpaceFibre.
- Soft Reset
 - Serial ATA uses unexpected arrival of the SYNC character to reset the interface.
 - Effective mechanism for signalling severe error conditions
 - A similar mechanism should be included in SpaceFibre



SpaceFibre CODEC Trade-off 5/5

- Frames
 - Nearly all of the standards examined use some sort of frame to transfer data across a link
 - Important if several channels are to be multiplexed over a single link
 - Especially when different quality of service provided
 - Frames should be used in SpaceFibre
- Virtual Channels and Traffic Classes
 - Virtual channels and traffic classes are powerful concepts defined in the PCI Express standard
 - Can be used to introduce quality of service at link layer
 - The use of these concepts should be explored for SpaceFibre.



SpaceFibre CODEC Trade Summary

- Use the lower level of Fibre Channel as the basis for SpaceFibre
 - Bit and word synchronisation,
 - 8B/10B encoding
 - Ordered Sets.
- Elastic receive buffering compensates slight differences in clock speed between units
- Scrambling of data and control codes should be included
- Link speed negotiation protocol should follow the highest-speed first approach of Serial ATA
- Frame concept used in Fibre Channel, PCI Express and Serial ATA should be adopted
- Fine grained power management of the link interfaces should be supported
- Virtual channel and traffic class concepts similar to PCI Express should be adopted.



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SpaceFibre CODEC Implementation

- CODEC state machine and 8B/10B en/decoder are implemented in VHDL
- SerDes contains PLL to recover the clock from the signal
- Analogue function that can not be implemented in VHDL
- Implementation possibilities
 - SerDes part of Rocket-IO interface available in Virtex-2/-4 for development
 - Dedicated SerDes device like TLK2711 from Texas Instrument available in QML V
 - Supports up to 2.5 Gbps
 - SerDes IP-core for ASIC integration



SerDes: TLK2711HFGQMLV



SpaceWire-SpaceFibre Router Implementation

- Specific board based on Xilinx Virtex 4 has been designed
- Makes use of Rocket-IO interface and dedicated SerDes chips
- Supports SpaceFibre Optical Link interface and SpaceFibre copper version via SMA connector
- Copper version will only bridge a limited distance due to cable losses



Block Diagram of SpaceWire-SpaceFibre Router with optical and electrical interfaces



SpaceFibre Optical Link Overview







Transceiver Module Design 1/4

Selection of optoelectronic components:

- 850-nm vertical cavity surface emitting lasers (VCSELs)
 - low drive current and small power consumption
 - VCSELs are also easier to drive without optical power monitoring due to their smaller temperature sensitivity of emission characteristics
 - VCSELs have demonstrated good radiation tolerance
- GaAs PIN diodes
 - PIN diodes are the most common photodetectors in short-reach fibre-based data transmission
 - Si photodiodes are more sensitive to SEUs than GaAs detectors



GsAs VCSEL - ULM Photonics 850nm Operating Wavelength Bandwidth 6GHz



GaAs PIN Diode – Ulm Photonics 850nm Operating Wavelength Bandwidth 5GHz



Transceiver Module Design 2/4

Optical design:

- Low temperature co-fired ceramic (LTCC) substrate technology
- The VCSEL laser chip is aligned with the substrate hole and attached using solder bumps
- The multimode fibre is passively aligned and supported using a precision hole in the five-layer LTCC substrate
- The fibre-to-detector coupling is realized using the same principle







Transceiver Module Design 3/4

Electrical design:

- Transceiver is divided into the main module and two submodules
- The transmitter sub-module contains the VCSEL, its driver chip and few passive components
- The receiver sub-module contains the detector, transimpedance amplifier (TIA) chip and few passives
- Typical power dissipation of 420 mW



Block diagram of the transceiver electronics

CML

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Transceiver Module Design 4/4

Packaging design:

- Kovar package with a laserwelded lid
- LTCC substrates are inherently airtight
- dimensions of 8 · 22 · 25 mm³ (thickness · length · width).
- The weight without pigtails is 5 g
- Pigtails are terminated with Diamond AVIM connectors that weigh 6 g each



SpaceFibre transceiver module with Diamond AVIM connectors





SpaceFibre Environmental Requirements

- Several different missions were reviewed for identifying typical requirements to be used as the baseline for the SpaceFibre link specifications:
 - Random vibration \leq 25 g_{rms}
 - Mechanical shock \leq 3000 g @ 10 kHz
 - Total radiation dose \leq 100 krad
 - Operational temperature –40 ... + 85 °C
 - Storage temperature –50 ... + 95 °C
 - Mission lifetime up to 15 years
 - Non-outgassing materials



Transceiver Module Testing 1/3

Functional testing:

- The eye diagram at the receiver output was found to remain acceptable up to 6 Gbps
- BER testing at 2.5 Gbps showed that with 99% confidence BER is better than 1.3 · 10⁻¹⁴. - No errors were detected during the measurement period, so the BER result is expected to improve in measurements with longer duration
- The SpaceFibre link was proved to have an optical power budget margin of at least 15 dB



Eye diagram of the 3.125 Gbps PRBS at the receiver output



Transceiver Module Testing 2/3

Vibration testing:

- Four modules were tested to all three axis
- Two different test levels:
 - Intermediate level test
 - Four sinusoidal vibration sweeps up and down with a maximum acceleration of 20 g.
 Followed by a 10-min period of random vibrations from 20 to 2000 Hz with a total level of 15.7 g_{rms}.
 - Evaluation level test
 - Two sinusoidal vibration sweeps with a maximum acceleration of 30 g, which was followed by a 6-min. period of random vibrations of 22.3 g_{rms}.
- No performance degradation was detected for any of the four transceivers after vibration testing



Vibration test setup for two modules on a test board (y-direction).



Transceiver Module Testing 3/3

Shock testing:

- Three modules were tested to all three axis
- Impacts with peaks from 2900 to 3900 g were used
- All modules were found to be operational after the shock impacts.
- One module showed slight degradation in performance

Thermal cycling:

- Two modules were subjected to a test campaign of 2 x 40 cycles in air circulating chamber from -40 ℃ to +85 ℃.
- The average duration of min. and max. temperature levels for each cycle was 15 minutes
- Modules were operational throughout the testing, transmitting BER test data at 2.0 Gbps to both directions
- The maximum degradation of module power budget was in the order of -4 dB at + 85 ℃.
- At -40 ℃ the performance degradation was negligible

Radiation testing is ongoing but looks very promising

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Optical Fibre Selection

- The selected optical fibre needs to be radiation hardened and capable of 10 Gbps transmission capacity over a length of 100 meters
- Phosphorous doping must be avoided as it is very sensitive to radiation
- Single-mode fibres must be avoided due to tight laser to fibre alignment tolerances
- Step-index multimode fibre must be avoided due to bandwidth limitations
- → With its **50-micron core diameter** and large NA, the laser-optimized **graded-index multimode fibre** is the only option that can meet the bandwidth and light coupling requirements of the SpaceFibre link



Optical Fibre Examples





Cumulative Distribution Function

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Optical Fibre Testing

- Radiation can introduce darkening of the fibre
- Radiation hardness of several COTS laser-optimized graded-index multimode fibres were determined
- Measurements of the radiation-induced attenuation show losses varying from 7 to 16 dB when the 100 m long fibres are exposed to a dose rate of 45 krad/h and for a total irradiation dose of 100 krad
- When considering the typical dose rates in space, radiationinduced attenuation losses can be as low as 0.05 to 1 dB
- Draka MaxCap 300 radhard-optimized fibre, the best performing fibre was selected for the SpaceFibre link



Connectors

- Diamond AVIM connector was selected for the SpaceFibre link
- This connector has already been used successfully in several space missions
- The AVIM connector has been selected for several reasons:
 - Compact, low profile and lightweight
 - Excellent performance (typical insertion loss 0.2 dB)
 - Works for both single-mode and multimode
 - Return loss (typical < 45 dB)
 - Environmentally robust
 - No outgassing materials
 - Includes a unique ratchet style Anti-Vibration Mechanism



AVIM connector from Diamond



Cable Design

- Cables from W. L. Gore were selected for the SpaceFibre link
- Due to the wide operational temperature ranges in space, thermally-induced microbending is a real phenomenon to be managed
- An expanded polytetrafluoethylene (ePTFE) buffering system can minimize microbendinduced attenuation changes
- W. L. Gore design incorporates a layer of ePTFE directly over the coated fibre
- This layer significantly mitigates the variation of coefficient of thermal expansion (CTE) effects between the fibre and the other layers



SpaceFibre cable schematics



Conclusions

- SpaceFibre was investigated as the fibre optical extension to the SpaceWire standard
- SpaceFibre will be able to cover the very high data rate applications while being in line with the SpaceWire developments
- The copper version of SpaceFibre is intended to cover shorter distances in particular application areas
- System requirements together with CODEC and optical technology trades-offs were presented
- CODEC and optical transceiver design where shown
- Environmental testing results for the optical technology where reported
- A demonstrator has been developed within the SpaceFibre activity to show a mixed SpaceWire – SpaceFibre network
- The demonstrator can serve as test bed for a standardisation to be initiated in the SpaceWire Working Group