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Next-Generation High-Speed Satellite Interconnect

Disclosing the SpaceFibre Protocol – A System Perspective

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ISBN 978-3-030-77043-3 ISBN 978-3-030-77044-0 (eBook)
https://doi.org/10.1007/978-3-030-77044-0

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Foreword

Today, many spacecraft incorporate SpaceWire for the communication between on-board equipment such as scientific payloads, mass memories, and on-board computers. The protocol was standardized in an open European Cooperation for Space Standardization (ECSS) standard in 2003, with support from all major space agencies (ESA, NASA, JAXA, and Roscosmos).

Already around that time the idea of a successor protocol was born with the overall objective of increasing the capabilities of SpaceWire by an order of magnitude due to higher data rates, improved Quality-of-Service (QoS), better Fault Detection, Isolation and Recovery (FDIR) capabilities, and the possibility of utilizing also optical fibres as communication links. This protocol, dubbed SpaceFibre, is the result of more than 15 years of research and development leading to an open ECSS standard finally released in 2019. The rather long development time is not untypical for the space industry, which often conservatively adapts new technologies due to the stringent reliability requirements of space missions. Because of this long development time, SpaceFibre represents a very robust and well-tested protocol today, with many interesting features particularly suited for space-borne equipment.

The ECSS standard and the first reference designs were developed by the University of Dundee and STAR-Dundee UK for ESA, with many valuable contributions from international space agencies, large system integrators, and research institutes. One of the European academic institutions particularly worth mentioning in this context is the University of Pisa. Several researchers contributed to the ECSS standard working group and have been researching SpaceFibre-related topics for several years now, with many interesting outcomes such as the development of end-point and routing switch IP cores, an Electrical Ground Support Equipment (EGSE) system, and a simulator for SpaceFibre networks.

This book, which is to our knowledge the first of its kind, gives an excellent overview of the SpaceFibre technology and is therefore well suited for anyone who wants to quickly understand the workings of the protocol. In addition, it also delves into implementation details of the different building blocks developed by the research group in Pisa over the previous years, revealing a wealth of practical information that should prove useful and inspirational to anyone working and researching on this topic.

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Preface

Earth observation services are vital to our society: all major and minor space agencies are massively investing resources to have better performance in monitoring Earth with satellites. Moreover, in the last few years, a wide range of private companies is also entering the business. Thanks to higher resolution instruments, Earth observation satellites' capabilities are consistently enhanced. However, to fully support the increasing demand for high-performance and high-bandwidth instruments onboard, an unprecedented requirement for faster and faster communication between instruments and mass memory is arising. For this reason, ESA recently proposed the SpaceFibre protocol (several Gbps bandwidth) for satellite onboard communication, as the successor of SpaceWire (hundreds of Mbps bandwidth). This book aims at giving a complete vision of the SpaceFibre protocol, together with an analysis of all the necessary hardware and software components to integrate this technology onboard a satellite. This book is addressed to all players involved in onboard satellite communication, from researcher to industry. The text provides a system perspective for the end user willing to adopt this technology for a future space mission, guiding potential system adopter in the understanding of the protocol, analysing strengths, weaknesses and performances. Also, practical design examples and prototype performance measurements in reference scenarios are included. The goal of the book is to introduce all space community members, both from academia and industry to this novel protocol. Indeed, SpaceFibre is expected to follow the success of its predecessor SpaceWire protocol (Mbps), which has been adopted by all significant space agencies (e.g. ESA, NASA and JAXA).

First, in Chap. 1, an introduction to satellite data-handling will be given, focusing on the anatomy of a generic spacecraft, paying attention to the internal communication system and its requirement. State-of-the-art solutions will be presented, including an analysis of the already available and future high-speed technological solutions. In Chap. 2, we will present in detail the SpaceFibre standard itself. The relevant ECSS standard will be taken as a reference point. However, the different protocol layers will be presented with a system user perspective, describing protocol mechanism but also available features, points of strength and weaknesses. In Chap. 3, all the different hardware building blocks that can be found in a

SpaceFibre network will be presented, taking as reference example real devices already used by the space community. In particular, the following devices will be presented: a SpaceFibre CoDec, a SpaceFibre router and a SpaceFibre electrical ground segment equipment. Once that the protocol has been introduced and the potential building block of a network has been presented and analysed, the next step in SpaceFibre network development is to check for interoperability of available devices. Although being compatible with the standard already ensures different implementations to be interoperable, at present no conformance checker is available. Therefore, it is considered a good design practice to assess the interoperability of a device. The interoperability test campaign is fundamental in the case that a new endpoint is developed from scratch to assess standard conformance. In Chap. 5, indications are given on how to interconnect different available devices to create a complex SpaceFibre network. A generic satellite onboard data handling network interconnects at least the payload, a control unit and a mass memory, possibly through a routing switch. Usually, this network can be also connected externally to an electric ground segment equipment, for design and debug purposes. Moreover, this hardware can also be simulated and co-simulated as hardware-in-the-loop thanks to advanced simulators. All these aspects will be analysed in Chap. 5, guiding system developers in the understanding and setup of their own SpaceFibre-based system. In Chap. 6, an overview of the technological progress of the SpaceFibre-based system is carried out, in the form of a detailed analysis of the state of the art. It will indicate to technology users the impact of different SpaceFibre CoDecs & routers on the most essential FPGAs and silicon technology. Also, an analysis of the electrical ground segment equipment available in literature will be carried out, to ease the work of future system adopters. Finally, in Chap. 7, we conclude the work, focusing on the future of the protocol. There are also two appendices available, both focusing on a slightly modified version of the SpaceFibre protocol, which may be used in low-cost space missions. The authors would like to acknowledge all the people that worked in the Electronics System Laboratory at the University of Pisa and in the IngeniArs S.r.l. company, especially Alessandro Leoni and Daniele Davalle, who contributed actively to the development of the work presented in this book. We would also like to acknowledge the entire SpaceFibre community, which under the wise guidance of the European Space Agency, has been able to cooperate in the development of this technology.

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Contents

Acronyms

ACK	ACKnowledge
API	Application Programming Interface
ARINC	Aeronautical Radio INCorporated
ASIC	Application-Specific Integrated Circuit
BC	BroadCast
BE	Best Effort
BER	Bit Error Rate
BFM	Bus Functional Model
BRAM	Block RAM
CAN	Controller Area Network
CDR	Clock Data Recovery
CMOS	Complementary Metal-Oxide-Semiconductor
CoDec	Coder-Decoder
cPCIe	compact Peripheral Component Interconnect express
CRC	Cyclic Redundancy Check
CRD	Current Running Disparity
CSA	Canadian Space Agency
CT	Continuous Traffic
DICE	Dual Interlocked storage Cell
DSP	Digital Signal Processor
DUT	Device Under Test
EBF	End Broadcast Frame
ECSS	European Cooperation for Space Standardization
EDAC	Error Detection and Correction
EDF	End of Data Frame
EEP	End Error Packet
EGSE	Electrical Ground Support Equipment
EO	Earth Observation
EOP	End of Packet
ESA	European Space Agency
FC FSM	Flux-Control FSM

FCT	Flow Control Token
FDIR	Fault Detection Isolation and Recovery
FF	Flip-Flop
FIFO	First-In-First-Out
FPGA	Field Programmable Gate Array
FSM	Finite State Machine
GAR	Group Adaptive Routing
GUI	Graphical User Interfaces
HIL	Hardware-In-the-Loop
ICU	Instrument Control Unit
iLLCW	Inverse Lane Layer Control Word
IN VC	INput Virtual Channel
IP	Intellectual Property
ISO	International Organization for Standardization
JAXA	Japan Aerospace Exploration Agency
LCROSS	Lunar CRater Observation and Sensing Satellite
LET	Linear Energy Transfer
LLCW	Lane Layer Control Word
LSS	Lowest Significant Symbol
LUT	Look Up Tables
MAC	Medium Access Controller
MCU	Main Control Unit
MIB	Management Information Base
ML-FSM	Multi-Lane FSM
MMFU	Mass Memory and Formatting Unit
MSS	Most Significant Symbol
NASA	National Aeronautics and Space Administration
NDCP	Network Discovery and Configuration Protocol
NGSIS	Next Generation Spacecraft Interconnect Standard
OBC	On-Board Computer
OS	Operative System
OSI	Open Systems Interconnection
OUT BC	OUTput Broadcast
OUT VC	OUTput Virtual Channel
PCIe	Peripheral Component Interconnect express
PL	Programmable Logic
PLL	Phase-Locked Loop
QoS	Quality of Service
RAM	Random Access Memory
RC	Rate-Constrained
RefArc	Reference Architecture
RMAP	Remote Memory Access Protocol
RR	Round Robin
RRArbiter	Round Robin Arbiter
R-SpFi	R-SpaceFibre

RT	Reliable Traffic
RTL	Register Transfer Level
SAE	Society of Automotive Engineers
SAR	Synthetic Aperture Radar
SAVOIR	Space AVionics Open Interface aRchitecture
SBF	Start Broadcast Frame
SEE	Single Event Effect
SEL	Single Event Latch-up
SerDes	Serialiser-Deserialiser
SEU	Single Event Upset
SHINe	Simulator for HIgh-speed Network
SOC	System on Chip
SpFi	SpaceFibre
SWIP	Switching Block IP
TB	TestBench
TCP	Transmission Control Protocol
TID	Total Ionization Dose
TMR	Triple Modular Redundancy
TT	Time-Triggered
TTEthernet	Time-Triggered Ethernet
UDP	User Datagram Protocol
UUT	Unit Under Test
UVM	Universal Verification Methodology
VC	Virtual Channel
VHDL	Very high-speed integrated circuits Hardware Description Language
VN	Virtual Network
WISM	Word Identification State Machine

Chapter 1
Introduction to Satellite on-Board Data-Handling

1.1 Anatomy of a Spacecraft and Requirement Analysis

1.1.1 Earth Observation and High-Resolution Payloads

Earth Observation (EO) satellites are an extraordinary tool for collecting information about our planet via remote sensing technologies, helping us to understand how the Earth system responds to natural and human-induced changes. Starting from the '60, EO satellites found applications in several different fields, such as environment monitoring [44], weather prediction [47], land management and cover [61], maritime surveillance [71], agriculture [13], food security [4], disaster monitoring and managing [19] and homeland security [16]. Today, EO is not only a powerful science instrument, but it has also relevant economic, environmental and societal impacts [40]. The United Nation recognised the importance of EO for the achievement of the 17 Sustainable Development Goals program [2] that aims at improving prosperity for people and the planet, building a more sustainable world [80].

The Sputnik 1 can be considered the very first EO satellite because it sent back to Earth the radio signals that Russian scientists used for studying the composition of the Ionosphere [74]. The Landsat mission was the first to downlink a consistent number of images: launched starting from 1972, the Landsat satellites send back to Earth approximately 2 million images [40]. Since then, more and more satellites for EO applications were launched, and Fig. 1.1 shows the number of active EO missions according to the World Metrological Organisation (WMO) [82]. Historically, the United States, Russia, Italy, France and Germany are the leaders in the EO satellite launches, but other states such as China, India, Brazil, Canada, Australia, Nigeria funded their EO missions in the recent past [36]. Approximately 50 countries are now investing in EO programs, and the EO market is expected to continue to grow in the next years [15]. At the same time, EO is rapidly changing as the result of the advances in digital technologies and sensor

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P. Nannipieri et al., *Next-Generation High-Speed Satellite Interconnect*,
https://doi.org/10.1007/978-3-030-77044-0_1

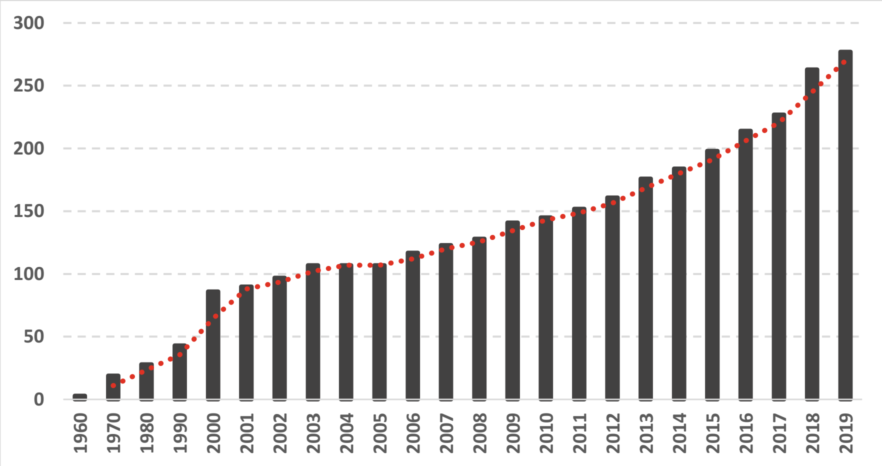

Fig. 1.1 Active EO satellite missions per year according to the WMO

resolution [7, 53]. There is a continuous search for payloads that can offer images with a higher resolution both in the commercial and defence markets [15]. As result, many recently launched and future planned missions mount high-resolution instrumentation, such as Synthetic Aperture Radars (SARs) and hyperspectral images. SARs are commonly mounted on aeroplanes or spacecraft and produce 2-D images or 3-D reconstruction of objects, exploiting the motion of a pulsed radar over the region to be studied [57]. A SAR receives the echoes of the backscattered signal, whose amplitude and phase depend on the physical and electrical features of the object observed. SARs provide high-resolution images independently from daylight, cloud coverage and weather conditions [31, 64], and their applications range from geoscience to climate change research, from 2-D and 3-D mapping to security-related applications [57]. Hyperspectral imagers collect data of hundreds of narrow contiguous spectral bands in order to identify different materials from their spectral signature [54]. For this reason, hyperspectral images are often referred as "cubes". Hyperspectral imagery is exploited for target detection, material mapping and material identification [73]. Figure 1.2a and b show examples of SAR and hyperspectral images, respectively.

Some relevant examples of missions that recently involved this class of payloads are Envisat [51], Sentinel-1 [49], Sentinel-2 [18], Sentinel-3 [17] and PRISMA [50]. CHIME [62], NISAR [43], HyspIRI [8], EnMAP [34] and FLEX [69] are examples of National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) missions mounting SARs that will be launched in the near future.

Besides high-profile missions, small satellites and, in particular, CubeSats are begging to play an important role in EO [10, 72]. CubeSat is a class of nanosatellite (with a mass between 1 and 10 Kg) standardised by the California Polytechnic State University in 1999. They are made up of $10 \times 10 \times 10$ cm units (1U) with a maximum

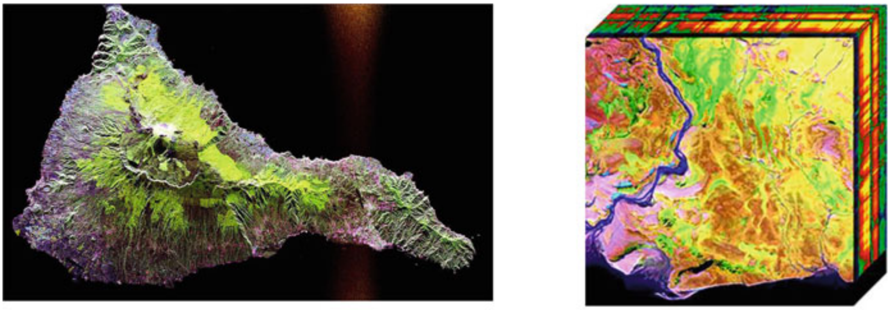

Fig. 1.2 In (**a**), an example of a SAR Image [59]. In (**b**), a hyperspectral cube [60]

weight of 1.33 Kg [14] that could be assembled to compose larger satellites (e.g. 2U, 3U, 6U and 12U). CubeSats, initially developed with educational purposes, despite their limitation in terms of mass and volume are emerging as important technological platforms [81], especially for EO applications, representing a cost-effective and fast-to-launch solution [66].

CubeSats have a limited cost, ranging from few tens of thousands to a few million thousand Euro per unit [15, 81] and can also be part of large constellations with the potential of achieving comparable or even better performances than traditional spacecraft [5, 72]. Currently, several CubeSat missions already plan to mount SAR, such as CIRES [83], Phisat-1 [20], Capella 1 [9] and ICEYE [37], and hyperspectral imagers, such as Intuition-1 [45], HyperCube [46] and Waypoint 1 [75].

1.1.2 Satellites and the On-Board Data-Handling Sub-system

A spacecraft is a machine designed to fly in outer space. It may be used for various purposes, including Earth Observation (EO), space exploration, communication and many others. Spacecraft is often remotely operated, except for few manned missions. They shall be extremely safe to operate, both for ethical (e.g. manned missions) and economic/strategic reasons. The design of a spacecraft requires huge engineering efforts: it is a complex system that has to withstand intense mechanical and thermal stresses, with strict requirements in terms of reliability. This book does not focus at all on the mechanical and thermal requirements involved in the design of a spacecraft; indeed we intend to focus on its electronic system, and in particular, to the mechanisms exploited for collecting and elaborate data: in our preliminary assumption, at least from an electronic point of view, a spacecraft is a system acquiring data through sensors, receiving commands from a remote user (ground) and sending back the acquired data to the remote user. Although in modern spacecraft this is not always the case, we can take it as a solid baseline. The data processing requirements of a satellite are mostly directly related to the electronics of the spacecraft itself, and considering how the world of electronics has evolved in the past decades, we cannot think that the on-board data-handling systems for spacecraft have not changed deeply during history [79]. In the following, we will refer to avionics as the electronic system of a spacecraft. It includes communication, navigation and on-board data-handling. An avionic system is generally composed of the payload, which is the equipment performing mission-specific tasks, and the platform, which performs all satellite operational tasks, including data processing, data storing, navigation and telemetry. It is not our aim to fully detail the complex avionics architecture of a spacecraft, also because different missions have different on-board communication architectures (for detailed analysis on digital avionics architectures please refer to [29]). However, such a complex system shall have several communication links between separate modules, and within the modules as well. In Fig. 1.3 a typical earth observation/scientific spacecraft network topology is systematised. It represents a general high-speed communication architecture for space applications. A spacecraft may mount several instruments, each one producing a significant amount of data that shall be processed: each instrument is usually connected with an electronics system that pre-processes the acquired data and operates the instrument through the Instrument Control Unit (ICU). Data and commands communication lines are then sent to the Mass Memory and Formatting Unit (MMFU), where data is distributed through a routing switch to the other components of the avionics: a mass memory to save data waiting to be transmitted to earth, a Main Control Unit (MCU) operating the entire system and the downlink formatter, for the communication with the ground station (Earth). Redundancy is another important concept displayed in Fig. 1.3: it is common in spacecraft to have redundant components, and this also affects the communication system, or at least its command & control section. Redundancy is introduced to improve reliability: a component may have a failure, a cable may be damaged during the launch of the spacecraft, and this shall not invalidate the entire mission. Of course, this redundancy has disadvantages: the on-board data-handling system gets more complex, there are more cables and components, which means a heavier system and also more expensive.

Now that we had a quick view of a spacecraft avionics block scheme, we are also ready to introduce better the constraints that such systems shall usually withstand. The first requirements for spacecraft come directly from the operative environment: it is known that semiconductors are susceptible to a fault (definitive or not) when exposed to a certain radiation dose [6, 63, 84]; if the circuit is supposed to operate in a harsh environment, such as outer space, where the exposure dose is much higher, an electronic system must be properly designed to operate safely. This means that spacecraft avionics shall be built upon specific silicon technologies, able to cope with the radiation level. Redundancy is a key concept in space avionics design, due to the high cost of spacecraft and the intrinsic difficulty in operating maintenance on them. Therefore, several solutions are usually adopted to strengthen the fault tolerance of the spacecraft avionics system, e.g. each communication link can be doubled. Carrying objects in space has a cost, which is also related to their weight [41]. This is valid also for cables: fewer cables mean lower harnesses, easier

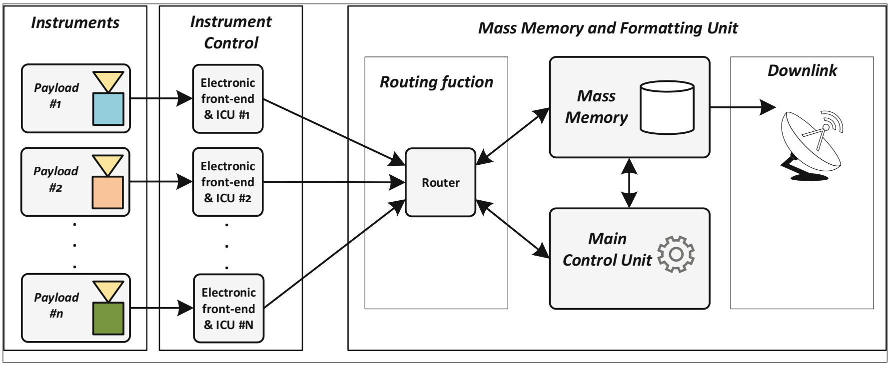

Fig. 1.3 Generic spacecraft network topology

integration and reduced costs. Cable reduction can be achieved by lowering the number of physical communication links and, as a future perspective, by replacing classical copper wires with optical fibre. The need to reduce the weight could also push, in the foreseeable future, towards the use of the same network infrastructure for both science data (not time-critical, high data rate) and command & control data (time-critical, low data rate). Networks will, therefore, need to be able to offer adequate Quality of Service (QoS), to allow different traffic classes to coexist on the same physical medium and protocol infrastructure [58]. It is possible, especially with the use of Synthetic Aperture Radars (SARs) and hyperspectral imagers, e.g. European Space Agency (ESA) upcoming missions (FLEX [69], BIOMASS [11], Sentinel-2 [28], NISAR [43], HyspIRI [8]), that very high data rate is required in spacecraft on-board communications: a large number of instrument can be hosted on the same vehicle, sharing resources and communicating through various sub-system. At present time a data transmission rate in the order of several Gbps is required and the trend is currently growing. The combination of the aforementioned requirements results in several options for data-handling network topology: complex systems may require to include a router, to share and multiplex a single (possibly high-speed) communication medium. All these constraints, combined with the high reliability and efficiency, typically requested in the space field, do not allow designers to adopt general-purpose communication solutions. In particular, the significant growth of data rate requirement led different institutes, agencies and companies to start working on new on-board data-handling communication protocols to meet this request. A set of attributes and features will be used in this book to characterise on-board data-handling systems. In the following, we introduce the key concepts behind these features.

- *Quality of Service*: an on-board data handing protocol providing this service can multiplex and schedule several communication channels on the same physical link, according to specific requirements, e.g. priority and bandwidth allocation.