STAR-Dundee

SpaceWire User's Guide

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GLOSSARY

Data character	– A character containing 8-bits of data
Destination address	– The leading byte or bytes of a packet that are used by routers to determine how to route a packet towards its destination
EEP	– Error End of Packet, which is used to terminate a packet when an error has occurred
EOP	– End of Packet marker which indicates the end of a packet
FCT	– Flow Control Token which is exchanged for eight N-Chars
Input port	– The part of a SpaceWire interface in a router that receives packets
Link	– A connection between two SpaceWire interfaces
N-Char	– A data character, EOP, or EEP
Node	– A source or destination of SpaceWire packets
Null	– A symbol that is sent when there is no other information to send to keep the link active
Output port	– The part of a SpaceWire interface in a router that sends packets
Packet	– A sequence of data characters followed by an EOP or EEP, the packet is made up of a destination address, cargo, and EOP/EEP
Port	– An input port or output port of a SpaceWire router

Router	– A packet switch that forwards packets towards their destination, selecting a link to forward the packet through based on the destination address of the packet
SpaceWire interface	– An interface used to send SpaceWire packets and time-codes
Time-code	– A symbol comprising an Escape symbol followed by a data character, where the data character contains two reserved bits and six bits of time information

1 Introduction

The SpaceWire User's Guide aims to introduce the reader to SpaceWire.

It begins in chapter 2 with an overview of SpaceWire, providing a brief history of SpaceWire, looking at an example SpaceWire application, examining how SpaceWire works, considering different SpaceWire architectures, and finally looking at some real mission architectures to see how SpaceWire is being used in practice.

Section 3 goes into much more detail about SpaceWire links. It describes each level of the SpaceWire standard in detail, explaining the way each level operates and the reasons SpaceWire is designed the way it is.

Section 4 describes SpaceWire routers and networks. SpaceWire nodes and routers are introduced and the mechanism inside a router explained along with the way in which a router is configured. An example SpaceWire router chip, the Atmel AT7910E SpW-10X router, is then described in some detail.

Section 5 explains how SpaceWire time-codes work and introduces some of the applications they have been used for.

Section 6 introduces some higher level SpaceWire protocols. This chapter is yet to be completed. Please check www.star-dundee.com for the latest version.

The SpaceWire User's Guide is compiled from several papers written by Steve Parkes, the CEO of STAR-Dundee and author of this guide.

2 The SpaceWire Data-Handling Network

SpaceWire is a data-handling network for use on-board spacecraft, which connects together instruments, mass-memory, processors, downlink telemetry, and other on-board sub-systems [1] [2] [3]. SpaceWire is simple to implement and has some specific characteristics that help it support data-handling applications in space: high-speed, low-power, simplicity, relatively low implementation cost, and architectural flexibility making it ideal for many space missions. SpaceWire provides high-speed (2 Mbits/s to 200 Mbits/s), bi-directional, full-duplex data-links, which connect together SpaceWire enabled equipment. Data-handling networks can be built to suit particular applications using point-to-point data-links and routing switches.

Since the SpaceWire standard was published in January 2003, it has been adopted by ESA, NASA, JAXA and RosCosmos for many missions and is being widely used on scientific, Earth observation, commercial and other spacecraft. High-profile missions using SpaceWire include: Gaia, ExoMars rover, BepiColombo, James Webb Space Telescope, GOES-R, Lunar Reconnaissance Orbiter and Astro-H.

2.1 The Rationale for and Brief History of SpaceWire

Before SpaceWire became a standard, many spacecraft primes and equipment manufacturers had their own proprietary communication interface for inter-unit communications, e.g. connecting high data-rate instruments to mass-memory units. This resulted in several different communication links being used on a spacecraft, increasing the cost and extending the time required for spacecraft integration and test. There was a clear need for a standard on-board communication link that would simplify spacecraft development.

Back in 1992, when work on what became SpaceWire started, there was also substantial interest in high performance digital signal processing systems which were beyond the capability of the single-chip devices

available at that time. The use of parallel processing was investigated and this required some form of network to interconnect the individual processing elements [4]. The Inmos Transputer [5], a microprocessor designed for parallel processing was studied, and the serial communication links being developed for the T9000 Transputer [6] were identified as being an attractive solution for spacecraft on-board networking. This serial link technology was subsequently published as IEEE 1355-1995 [7].

Several radiation tolerant devices were developed using the IEEE 1355-1995 standard and it was used on some space missions. However, there were many problems with this standard, which had to be resolved if this technology was to continue to be used for ESA spacecraft. University of Dundee received a contract from ESA [8] to examine and solve these problems which eventually resulted in the SpaceWire standard.

SpaceWire aims to:

- facilitate the construction of high-performance on-board data-handling systems,
- help reduce system integration costs,
- promote compatibility between data-handling equipment and subsystems, and
- encourage re-use of data-handling equipment across several different missions.

Use of the SpaceWire standard ensures that equipment is compatible at both the component and sub-system levels. Instruments, processing units, mass-memory devices and down-link telemetry systems using SpaceWire interfaces developed for one mission can be readily used on another mission. This:

- reduces the cost of development (Cheaper),
- reduces development timescales (Faster),
- improves reliability (Better),
- increases the amount of scientific work that can be achieved within a limited budget (More).

2.2 An Example SpaceWire Application

SpaceWire is able to support many different payload processing architectures using point-to-point links and SpaceWire routing switches. The data-handling architecture can be constructed to suit the requirements of a specific mission, rather than having to force the application onto a restricted bus or network with restricted topology.

An example SpaceWire architecture is shown in Figure 1. It uses two SpaceWire routers to provide the interconnectivity between instruments, memory and processing modules.

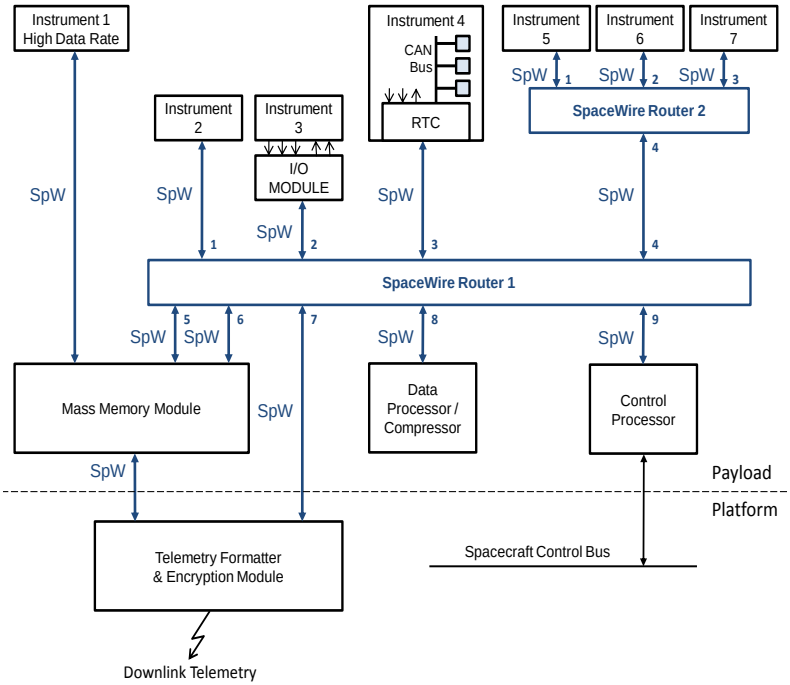


Figure 1 Example SpaceWire Architecture

Instrument 1 in the top left-hand corner is a high data-rate instrument. A SpaceWire point-to-point link is used to stream data from this instrument directly into the Mass Memory Module. If a single SpaceWire link is

insufficient to handle the data-rate from this instrument then two or more links may be used in parallel.

Instrument 2 is of lower data-rate than instrument 1. Its data is passed though SpaceWire Router 1 to the Mass Memory Module.

Instrument 3 does not have a SpaceWire interface so an input/output (I/O) module is used to connect the instrument to the SpaceWire router. Its data may then be sent over the SpaceWire network to the Mass Memory Module.

Instrument 4 is a complex instrument containing a number of sub-modules which are interconnected using the CAN bus. A Remote Terminal Controller (RTC) is used to bridge between the CAN bus and SpaceWire. Other signals from the instrument are also connected to the RTC, which contains a processor for performing the bridging and local instrument control functions.

Instruments 5, 6 and 7 are located in a remote part of the spacecraft. To avoid having three SpaceWire cables running to this remote location a second router (SpaceWire Router 2) is used to concentrate the information from these three instruments and send it over a single SpaceWire link to Router 1 and then on to the Mass Memory Module.

This Mass Memory Module can receive data from any of the instruments either directly, as is the case for Instrument 1, or indirectly via Router 1. Data stored in the Mass Memory Module can be sent to the Telemetry Formatter/Encryption Module for sending to Earth, or it may first be sent to a Data Processing or Data Compression Unit. This unit may return the processed/compressed data to the Mass Memory Module or send it straight to the Telemetry Module via Router 1.

The Control Processor is responsible for controlling all the Instruments, Mass Memory Module and Telemetry unit. Via the SpaceWire Network it has access to all these modules: it can configure, control and read housekeeping and status information from them. The Control Processor is also attached to the spacecraft control bus over which it can receive telecommands and forward housekeeping information.

With several instruments and the Data Processor/Compressor sending data to the Mass Memory Module via Router 1, a single link from that Router to the Mass Memory Module may be insufficient to handle all the data, so a second link has been added to provide more bandwidth. In a SpaceWire network links can be added to provide additional bandwidth or to add fault tolerance to the system. In Figure 1 no redundancy has been included for clarity. In a spaceflight application, an additional pair of routers would be included with duplicate links to the modules to provide redundancy. It is straightforward to support traditional cross-strapped, redundant modules using SpaceWire.

2.3 How SpaceWire Works

Having looked at the way in which SpaceWire can be used to provide a spacecraft data-handling system, we will now examine SpaceWire in a little more detail to provide some understanding of how SpaceWire works.

2.3.1 SpaceWire Links

SpaceWire links are point-to-point data links that connect together a SpaceWire node (e.g. instrument, processor, mass-memory unit) to another node or to a router. Information can be transferred over both directions of the link at the same time. Each link is a full-duplex, bi-directional, serial data link which can operate at data-rates of between 2 Mbits/s and 200 Mbits/s. It sends information as a serial bit stream using two signals in each direction (data and strobe). These signals are driven across the link using Low Voltage Differential Signalling (LVDS) [9] [10] which requires two wires for each signal, resulting in a SpaceWire cable containing four screened twisted pairs.

Bit synchronisation in SpaceWire is achieved by sending a clock signal along with the serial data. To reduce the maximum clock to data skew requirements the clock signal is encoded into a strobe signal in such a way that XORing the data and strobe signal recovers the clock signal.

Character synchronisation is performed once only, when the link is started. If character synchronisation is ever lost it will be detected as a parity error and the link restarted to recover character synchronisation.

SpaceWire provides a simple mechanism for starting a link, keeping the link running, sending data over the link, ensuring that data is not sent if the receiver at the other end of the link is not ready for it, and for recovering from any errors on the link. All this is handled by the link state-machine in the SpaceWire interface and is transparent to the user application.

2.3.2 SpaceWire Packets

Information is transferred across a SpaceWire link in distinct packets. Packets can be sent in both directions of the link, provided that there is room in the receiver for more data.

A packet is formatted as illustrated in Figure 2.

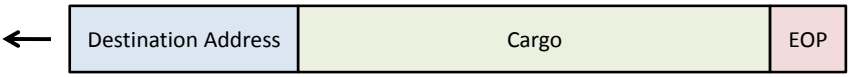


Figure 2 SpaceWire Packet Format

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 SpaceWire network to reach to 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 SpaceWire packet.

The “End of Packet” (EOP) is used to indicate the end of a packet. The data character following an EOP is the start of the next packet. There is no limit on the size of a SpaceWire packet.

As can be seen, the packet format for SpaceWire is very simple. It is, however, also very powerful, allowing SpaceWire to be used to carry a range of user protocols, with minimal overhead.

2.3.2.1 SpaceWire Networks

SpaceWire networks are constructed using SpaceWire point-to-point links and routing switches.

2.3.2.2 SpaceWire Routing Switches

A SpaceWire router [11] connects together many nodes using SpaceWire links, providing a means of routing packets from one node to any of the other nodes or routers attached to the router. A node is simply the source or destination of a SpaceWire packet. A SpaceWire router comprises a number of SpaceWire link interfaces and a switch matrix. The switch matrix enables packets arriving at one link interface to be transferred to and sent out of another link interface on the router.

Each link interface may be considered as comprising an input port (the link interface receiver) and an output port (the link interface transmitter). A SpaceWire router transfers packets from the input port of the switch where the packet arrives, to a particular output port determined by the packet destination address. A router uses the leading data character of a packet (one of the destination address characters) to determine the output port of the router to which the packet is to be routed. If there are two input ports waiting to use a particular output port when the previous packet has finished being sent, an arbitration mechanism decides which input port is to be served.

2.3.2.3 Packet Addressing

The destination address at the front of a SpaceWire packet is used to route the packet through a network from the source node to the destination. There are two forms of addressing used in SpaceWire networks: path addressing and logical addressing.

Path addressing can best be understood using the simple analogy of providing directions to someone driving a car. To reach the destination you might suggest that the driver takes exit 2 at the first roundabout, exit 1 at the next roundabout, and finally exit 3 on the third roundabout. The driver will then have reached the required destination (see Figure 3). There is a direction to follow at each roundabout (take a particular exit). Together these directions describe the path from the initial position to the required destination. There is a list of directions to follow, one for each roundabout. Once a direction has been followed it is crossed off the list and the next direction is followed at the next roundabout.

In a SpaceWire network the roundabouts are routers and the roads connecting the roundabouts are the links connecting the routers (see Figure 3). The list of directions is attached to the front of the SpaceWire packet forming the destination address. The first direction is followed when the first router is encountered. This direction is simply a data character that specifies which port of the router the packet should be forwarded through. A router can have a maximum of 31 external ports (port numbers 1 to 31) and one internal configuration port (port number 0). The leading data character at the front of the packet is used to specify the port that the packet is to be forwarded through: if the leading data character is 3, the packet will be forwarded out port 3 of the router. Once the leading data character has been used to forward a packet, it is discarded as it is no longer needed. This reveals the next data character in the path address for routing the packet at the next router. Figure 3, shows how the path address at the start of the packet is modified as the packet goes through the network. Since a router

can have a maximum of 31 ports along with an internal configuration port, each data character forming a path address is in the range 0 to 31.

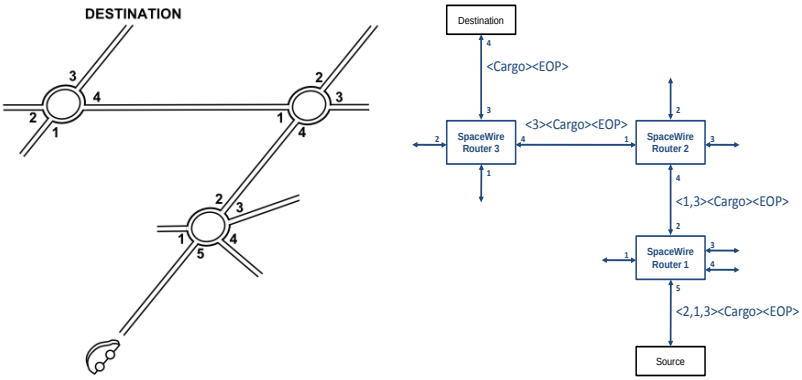


Figure 3 Path Addressing

Logical addressing can also be understood using the analogy of giving directions to a car driver. Logical addressing is like saying to the driver, “follow the signs to Dundee at each of the roundabouts”. This, of course, requires appropriate signs to be placed at each roundabout and each destination has to have a name or identifier so that it can be recognised on the signs. The logical address analogy is illustrated in Figure 4.

In a SpaceWire network using logical addressing, each destination is given an identifier, which is a number in the range 32 to 255. Each router in the network has a routing table (like the sign at a roundabout) which specifies what port the packet should be forwarded through for each possible destination identifier. The leading data character of a packet is set to the required destination identifier (e.g. 44 for Dundee). At each router the leading data character is used to look up the appropriate directions from the routing table and the packet is forwarded accordingly. For logical addressing the leading data character is not discarded at each router, since it will be needed to look up the path to follow at the next router encountered. The use

of logical addressing is illustrated in Figure 4. Logical addressing uses just a single data character to identify the destination which is in the range 32 to 255 so that it does not get confused with path addresses.

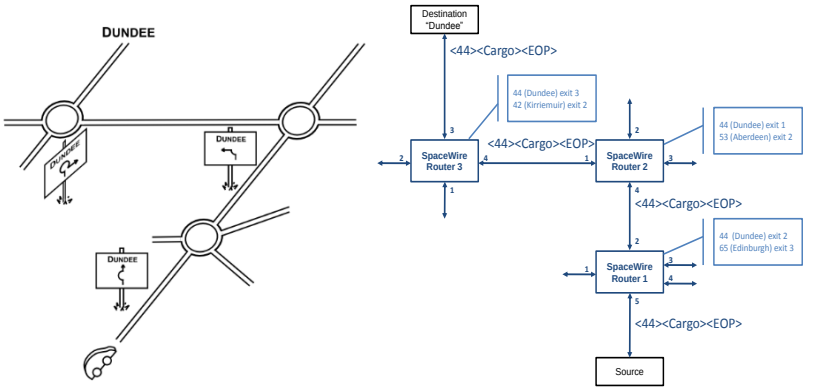


Figure 4 Logical Addressing

Logical addressing has the advantage that only a single address byte is required, but it does require the routing tables to be configured before it can be used. Path addressing requires a byte for each router and does not need routing tables in the routers.

2.4 SpaceWire Architectures

Now the way in which SpaceWire can be used to build data-handling architectures adapted for specific mission requirements is examined.

2.4.1 Point to Point Links

The simplest and most widespread use of SpaceWire is to connect a high data-rate instrument directly to an onboard mass memory. This arrangement is illustrated in Figure 5.

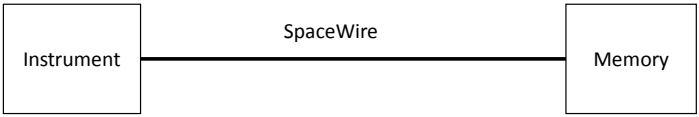


Figure 5 Point to Point Link

The instrument can send SpaceWire packets containing the instrument data directly to the memory over the SpaceWire link. The data can be packaged into SpaceWire packets with a size appropriate to the application. For example if the instrument is some form of push broom imager it may be appropriate to send one line of the image at a time e.g. 34 KByte packets. If the instrument is a camera a complete image could be transferred in one packet e.g. 2 MBytes.

The instrument can simply send data to the memory once it has collected the data or the memory could send a command to the instrument to ask for the next set of data. SpaceWire includes low-level flow control so that if the memory is not ready the instrument is unable to send data until the memory becomes ready. This means that if the memory is not able to accept data from the camera as soon as it is ready, the camera will have to buffer the data.

The advantages of this type of architecture are:

- Simplicity
- Low power per Mbit/s
- Full bandwidth of link available to application

The disadvantages are:

- No redundancy – if the link fails the instrument is lost.
- May be inefficient if link bandwidth not fully utilised

This latter point serves to highlight another capability of SpaceWire. A SpaceWire interface can initialise very rapidly (20 µs). If an instrument provides data in bursts or occasionally on demand, then it is possible to turn off the link when it is not being used. If one end of the link is set to auto-start mode it will start up as soon as some traffic appears on the link. So, for example, if the instrument is to send data to the memory occasionally when it has detected some event, the SpaceWire interface on the memory may be put into auto-start mode. The SpaceWire interface in the memory will stop and wait listening for any traffic on its input. The instrument can then switch off its SpaceWire interface. When an event occurs the SpaceWire interface in the instrument is enabled and started, the initialisation traffic on the link is detected by the SpaceWire interface in the memory unit causing its link to start and a connection to be made. The instrument can then transfer its data. It takes just 20 µs to achieve this connection.

The type of application where the single point to point link is used is for the direct connection of an instrument to memory where no fault tolerance is required i.e. it is acceptable that if the SpaceWire link fails the instrument is lost.

2.4.2 Fault Tolerant Links

The avoidance of possible single point failures is important for most space missions especially for mission critical services. SpaceWire provides a simple means of adding fault tolerance into a system where it is required.

SpaceWire is fairly robust due to the good EMC properties of LVDS and the cable screening used. Rarely are errors seen on a link unless they are injected. If a transient error does occur then the SpaceWire link immediately disconnects itself electrically and goes through the re-initialisation process. In 20 µs the link is up and running again. The packet that was in the process of being transferred is truncated and terminated by a special Error End of Packet (EEP) character to indicate that it was terminated prematurely. The next packet to be sent will be delivered successfully provided that the fault

was temporary. If the packet that was terminated by the fault was important then it is up to the user application to detect the fact that it was not delivered properly and to resend the information. Protocols for providing this type of service which run over SpaceWire have been and are being developed by the SpaceWire working group.

If the fault on a SpaceWire link is permanent, for example the wires may have become disconnected or a SpaceWire interface may have stopped working, then recovery requires a second, redundant SpaceWire link. This is illustrated in Figure 6.

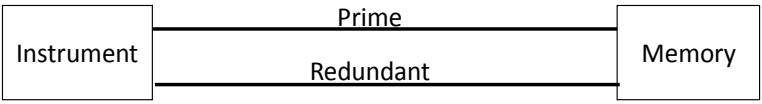


Figure 6 Fault Tolerant Links

If the prime SpaceWire link stops working then the redundant link has to be started and data sent over this link. Simple logic in the instrument can provide this functionality.

A more robust system is illustrated in Figure 7.

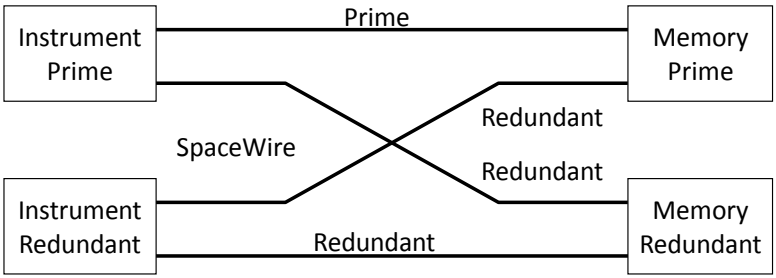


Figure 7 Cross-Strapping

In this example the instrument is crucial to the mission success so two instruments are provided. Each instrument has two SpaceWire interfaces:

one prime and one redundant. Similarly there are two memory units. During normal operation the redundant instrument and memory units are switched off. The prime instrument sends data to the prime memory. If the prime instrument fails then it is switched off and the redundant instrument is switched on. The prime memory then receives instrument data via its redundant SpaceWire interface. This classical cross-strapping is readily supported by SpaceWire – additional links are simply put where redundancy is required.

The advantages of this type of architecture are:

- Simplicity
- Low power per Mbit/s
- Full bandwidth of link available to application
- Fault tolerant

The disadvantages are:

- Mass penalty as several links needed for redundancy
- Inefficient if bandwidth not fully utilised

This architecture is ideal where the direct connection of an instrument to a memory or other unit is required and where a single point failure is not acceptable.

It is important that a failure on the prime link does not propagate and cause a failure on the redundant link.

2.4.3 Router Based Architecture

A SpaceWire router enables more sophisticated architectures to be implemented when required. A basic router-based architecture is illustrated in Figure 8.

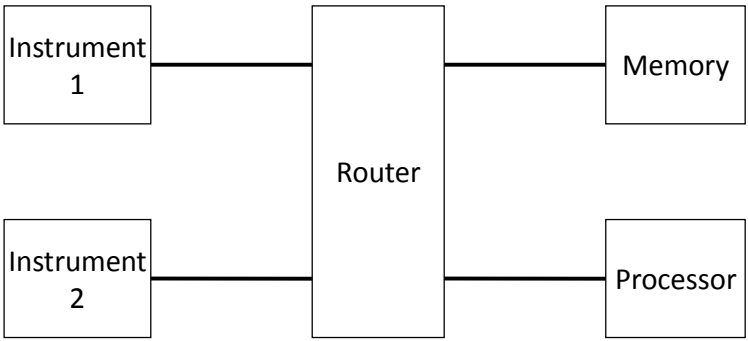


Figure 8 Basic Router-Based Architecture

The SpaceWire router interconnects all of the SpaceWire units. It is then possible for any unit to send data or receive data from another unit. The two instruments can send data to the memory unit, the processor unit can read data from the memory unit for checking or processing, and the processor can control the two instruments and memory unit.

The advantages of this type of architecture are:

- Versatile architecture
- All units can talk to one another through router
- Control and data can be sent over network
- Control flow is generally opposite direction to data flow

The disadvantages are:

- Have to be aware of potential blocking in router - need to consider traffic on network
- Router is potential single point failure
- Additional power consumption of router

The possible blocking of a router can occur if, for example, the two instruments both decide to send data to the memory unit at the same time. Since the router only has one link to the memory unit, only one instrument can send a packet down this link at a time. If the packet from instrument 1 gets there first it will be sent, but the packet from instrument 2 will be blocked until the packet from instrument 1 has been sent. If the packet from instrument 1 is large then instrument 2 may have to wait for a long time. This is illustrated in Figure 9.

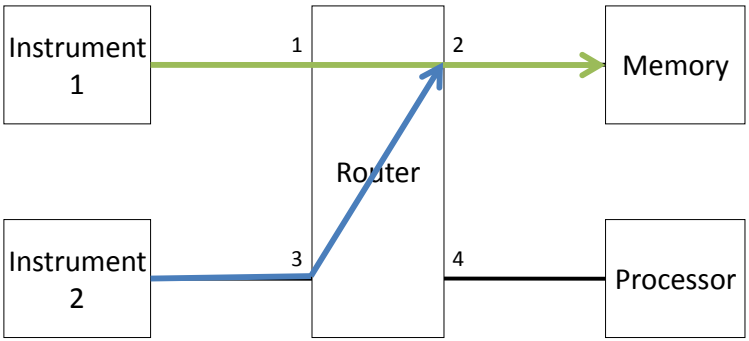


Figure 9 Blocking in a Router

Instrument 1 is sending a packet (shown in green) to the memory unit. Instrument 2 also wants to send a packet (blue) to the memory unit, but since the link from the router to the memory unit is already being used this packet is blocked within the router. Only when the packet from instrument 1 has finished being sent, will the packet from instrument 2 be able to proceed on its way to the memory unit. This characteristic of a SpaceWire network is known as “blocking” and is an important characteristic to understand.

There are several ways to avoid this situation. If the required total data rate from the two instruments is larger than can be provided by a single SpaceWire link then a second link is required between the router and memory, possibly using group adaptive routing, which will provide graceful degradation in the event of a failure of one link. If the total data rate from the

two instruments is less than the data rate of a single SpaceWire link then the router can act as a concentrator permitting a packet from say instrument 1 first, followed by a packet from instrument 2. In this case the amount of data buffering in the instruments will depend upon the size of the packets being sent. Hence, it makes sense to use short packets rather than long ones to reduce the amount of buffer memory required. Another alternative is for the memory (or processor) to control when an instrument is allowed to send data. For example, the memory could request data from instrument 1 and once this has been received it could request data from instrument 2. There are many possibilities: SpaceWire is flexible enough to support the requirements of different types of mission.

It should be noted that since the router uses wormhole routing and does not support packet buffering in the router, the speed of all the SpaceWire links attached to a router should normally all be set to the same rate.

Typical applications for this type of architecture include payload data-handling systems with more than one instrument or multiple possible destinations for data from an instrument. The potential single point failure of the router can be avoided by including a second router connected to all the units.

Figure 10 shows a prime and redundant pair of routers which have been included in prime and redundant data handling units together with the mass memory and processing units. This provides router redundancy while reducing the lengths (and hence mass) of the SpaceWire links.

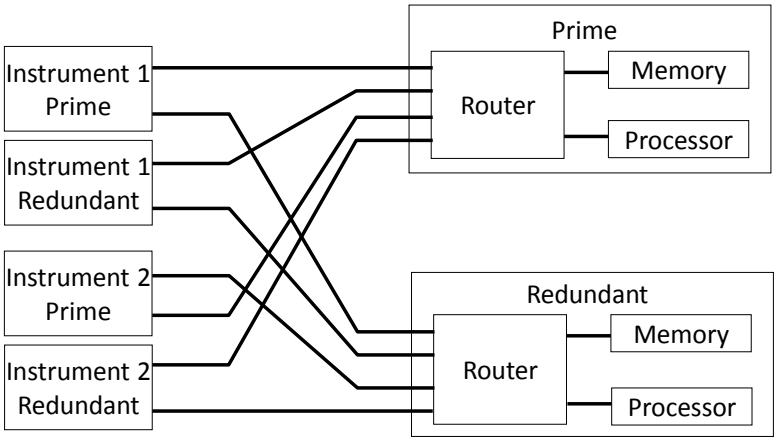


Figure 10 Router in Data-Handling Unit

The advantages of this type of architecture are:

- Supports multiplexing of several instruments
- Supports prime/redundant instruments
- No single point failures
- Lower mass penalty of links since several links embedded in data-handling units

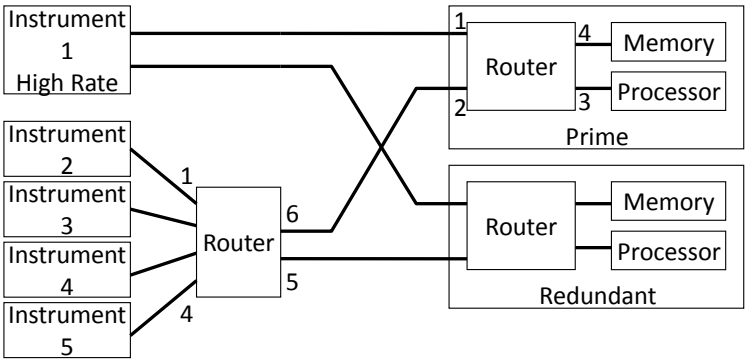
The disadvantages are:

- Have to be aware of potential blocking in router - need to consider traffic on network
- Additional power consumption of router.

This type of architecture is ideal when a redundant data handling system is required.

2.4.4 Instrument Data Concentrator

It has already been mentioned that a SpaceWire router can act as a data concentrator. Another example of this is shown in Figure 11.



Note: numbers by router ports are example port numbers

Figure 11 Router as Data Concentrator

Instrument 1 is a high data rate instrument and is connected by direct links to the routers in the prime and redundant data-handling systems. Instruments 2-5 are lower data rate instruments which are, for example, all situated in one area of the spacecraft. To reduce the size of the cable harness the data from Instruments 2-5 are concentrated by a SpaceWire router and sent to the prime or redundant data-handling units over single SpaceWire links.

The advantages of this architecture are:

- Reduced cable mass
- High rate instrument(s) have direct connection to data-handling unit
- Low to moderate rate instruments are connected via concentrating router

The disadvantages of the particular architecture shown in Figure 11 are:

- Have to be aware of potential blocking in router - need to consider traffic on network
- Concentrating router is not redundant

The concentrating router can be made redundant if required by adding redundant SpaceWire links and interfaces.

This type of architecture is suitable for payload data-handling systems with distributed clusters of instruments which are being served by centralised data-handling unit.

2.4.5 Bridge to Low Data Rate Sensor Bus

Some sensors, like thermocouples, are very low data rate and a low data rate sensor bus (e.g. CAN bus) may be more suitable for gathering data from them. The data gathered may still be sent to the data-handling system via a SpaceWire link if a bridge between the low data rate sensor bus and SpaceWire is used. This is illustrated in Figure 12.

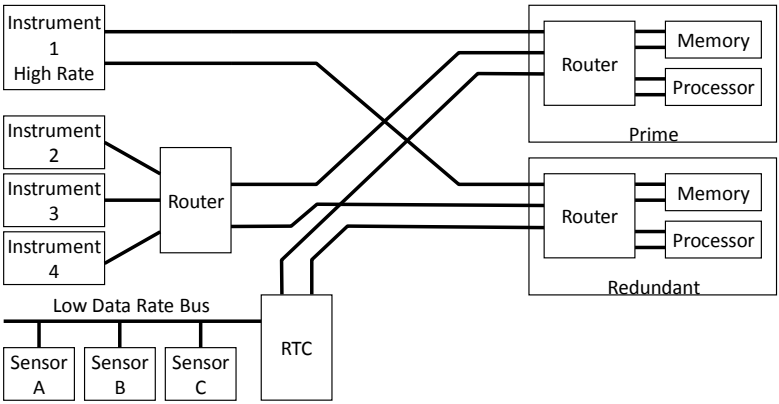


Figure 12 Bridge to Low Data Rate Bus

The Remote Terminal Computer (RTC) provides a bridge between the SpaceWire network and the low data rate sensor bus. The RTC gathers data from the low data rate sensors, puts it in a SpaceWire packet and sends it to the data handling system. Commands for the low data rate sensors (or actuators) can be passed from the data-handling processor to the RTC for distribution to the low data rate sensors.

The advantages of this type of network are:

- Multiple low data rate sensors attached to low speed bus - sensor data packed and sent to data-handling unit over SpaceWire
- Legacy devices can be supported – e.g. Mil-Std 1553

The disadvantages are:

- Two types of bus/network used

The applications for this type of architecture are data handling systems that include several low data rate sensors or that require to support legacy devices.

Other units like the downlink telemetry and uplink telecommand system can be readily included in a SpaceWire system. SpaceWire architectures can be adapted to the mission requirements including links to serve one or more instruments, routers to provide architectural flexibility, and interfaces to electronic ground support equipment.

2.5 Example SpaceWire Mission Architectures

Some of the major space missions currently using SpaceWire are listed in this section and then the data-handling architectures of five of them (two from ESA, one from NASA, and two from JAXA) are examined in more detail.

2.5.1 Missions Using SpaceWire

The European Space Agency (ESA) is using SpaceWire on:

- GAIA a very high resolution star-mapper [16];
- ExoMars a semi-autonomous Mars surface rover [17];
- BepiColombo Mercury Polar Orbiter [17];
- Sentinel 1 [19], a pair of imaging radar satellites that will provide an all-weather, day-and-night imaging capability for a range of services including sea-ice mapping, oil-spill monitoring, ship detection, land-surface movement, and disaster management.
- Sentinel 2 [20], a high-resolution, multi-spectral imaging mission which will support operation land monitoring and the emergency services.
- Sentinel 3 [21], a pair of satellites that will provide operational marine and land Earth Observation services using optical and microwave instruments.
- Sentinel 5 [22], series of Earth observation satellites.

NASA is using SpaceWire on:

- SWIFT a gamma-ray burst observatory, in orbit and making scientific discoveries since 2004 [23];
- Lunar Reconnaissance Orbiter, currently in orbit around the moon taking very high resolution images of the surface (these images all travel over SpaceWire twice on-board the spacecraft) [24];
- LCROSS the mission that was deliberately crashed into the south pole of the moon and discovered ice there [25];
- James Webb Space Telescope (JWST) an infra-red telescope which will be the biggest satellite ever launched with the exception of the international space station, when specifying a data-handling network for JWST NASA did an extensive survey of suitable technologies and chose SpaceWire [26];

- Magnetospheric Multi-Scale mission which is a multi-satellite mission that will explore the Earth's magnetosphere [27];
- GOES-R, a series of geostationary Earth Observation spacecraft, due to replace the USA's current weather satellites [28].
- Plug and Play Sat (PnPSat), which is pioneering rapid assembly, integration and deployment technology for tactical and disaster monitoring applications [29].
- TacSat, which is part of the USA operationally responsive space (ORS) programme. Both TacSat and PnPSat chose SpaceWire for their on-board data-handling networks, in competition with other space and terrestrial technologies [30].

Japan Aerospace eXploration Agency (JAXA) has adopted SpaceWire for all of their spacecraft that require moderate or high data rates, including:

- BepiColombo Mercury Magnetospheric Orbiter, which is a companion to the ESA BepiColombo spacecraft and will measure the magnetosphere of Mercury [31];
- ASTRO-H, an X-ray telescope being designed to explore the structure and evolution of the Universe [32];
- SPRINT-A, which is a small satellite that will observe the atmosphere of Venus, Mars and Jupiter in extreme ultraviolet (EUV) from Earth orbit, at an altitude of about 1,000 kilometers [33];
- ASNARO is a Japanese optical high-resolution Earth imaging mission [34];
- NEXTAR, which is the one of the first spacecraft to be designed to use SpaceWire for all of its on-board communications and is being built by NEC [35].

RosCosmos the Space Agency of the Russian Federation have recently approved SpaceWire for use on their spacecraft, regarding SpaceWire as a key technology for their future space missions [36].

SpaceWire is also being used in countries including Argentina, Brazil, Canada, China, India, Korea, Taiwan, Thailand, and many other countries, and by the space agencies of individual European member states. A number of commercial spacecraft, including Inmarsat [37], are also using SpaceWire.

2.5.2 ESA ExoMars

ExoMars is an ESA mission to Mars that incorporates a versatile rover. The ExoMars rover will carry a comprehensive array of scientific instruments dedicated to exobiology and geology research. The Rover will travel several kilometres searching for traces of past and present signs of life, collecting and analysing samples from within surface rocks and from the subsurface, down to a depth of 2 metres [17].

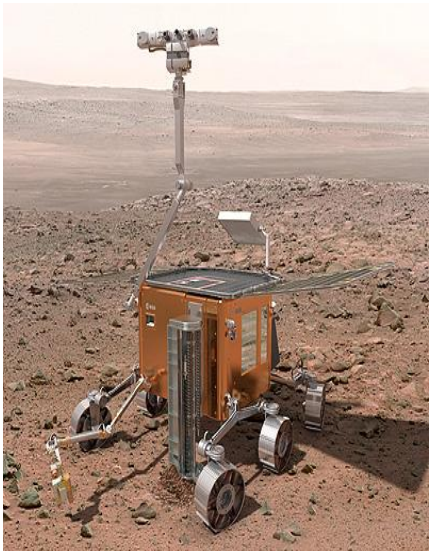


Figure 13 ExoMars Rover (Courtesy ESA)

The SpaceWire data-handling architecture used on ExoMars is illustrated in Figure 14. It follows closely the example architecture of Figure 1.

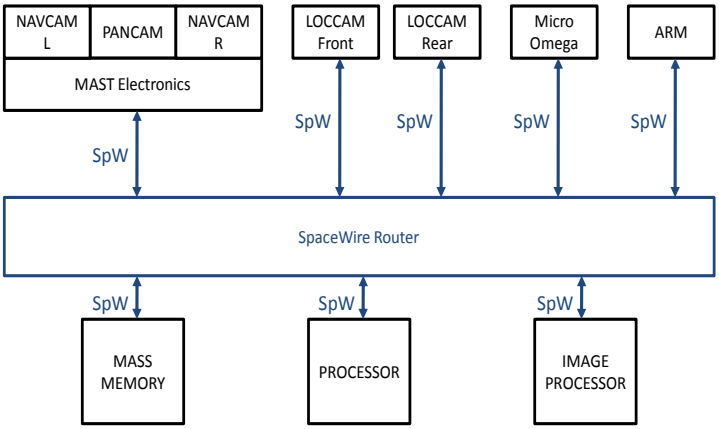


Figure 14 ExoMars SpaceWire Data-Handling Architecture

ExoMars carries several cameras to support navigation: PanCam providing a panoramic view around the rover, NavCams used to provide stereoscopic images from which DEMs can be derived and used for navigation purposes, and LocCams used to measure the motion of the rover relative to the surface. The processing of this image data is quite intensive so a dedicated image processing chip is used to support the processing. SpaceWire is used to transfer images from the cameras to mass memory and from there to the processor and image processing chip. A SpaceWire router is used to interconnect the various SpaceWire units [38]. The instrument arm and the Pasteur instrument are also connected to the data-handling system using SpaceWire.

ExoMars makes extensive use of the RMAP protocol [14] for passing data from cameras, to mass memory and to/from the processor and image processing chip.

2.5.3 NASA Lunar Reconnaissance Orbiter

The Lunar Reconnaissance Orbiter (LRO) [24] is a NASA mission currently in orbit around the moon returning images and other scientific data about the lunar surface, see Figure 15.

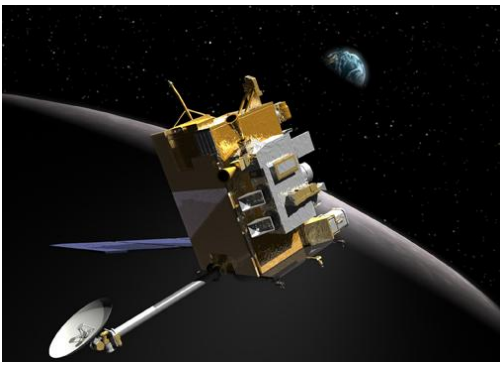


Figure 15 LRO In Lunar Orbit (courtesy NASA)

The data-handling architecture of LRO [39] is illustrated in Figure 16. Once again this is similar to the example architecture of Figure 1.

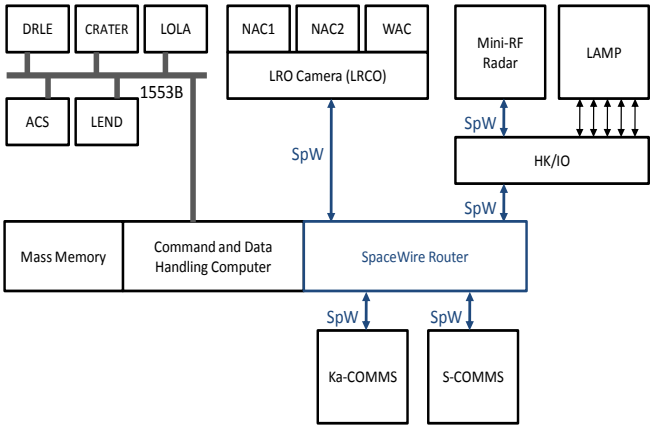


Figure 16 Lunar Reconnaissance Orbiter Data-Handling Architecture

SpaceWire is used to connect the LRO Cameras (Narrow angle Cameras, NAC1 and NAC2, and Wide Angle Camera, WAC), and Mini-RF radar instrument, to the Command and Data-handling (C&DH) system. SpaceWire is also used to pass data from the Command and Data-handling system to the Ka and S-Band communications systems. Information from the Lyman-Alpha Mapping Project (LAMP) instrument is passed into an I/O board in the C&DH system (HK/IO) and then sent over SpaceWire to the C&DH computer/mass memory. The C&DH computer includes a 4-port SpaceWire router for handling the SpaceWire communications.

An example image from LRO is given in Figure 17. It shows the Apollo 12 landing site. The Apollo 12 (Intrepid) descent stage is clearly visible in the image as is the earlier Surveyor 3 spacecraft. The black lines radiating out from Intrepid and pointed to by arrows in other parts of this image are the footsteps of the Apollo 12 astronauts. This image travelled over SpaceWire twice: from the NAC to the mass memory and from the mass memory to the downlink communication system.

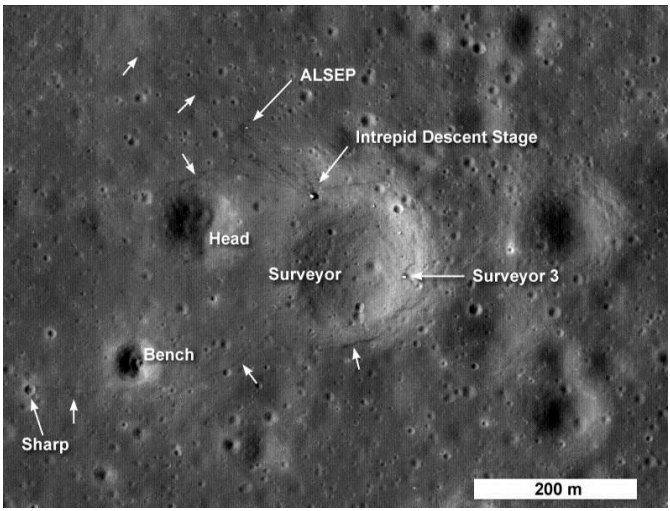


Figure 17 Image from LRO Showing Apollo 12 Landing Site (courtesy NASA)

2.5.4 BepiColombo

BepiColombo is a joint ESA/JAXA mission to Mercury which aims to explore Mercury, to attempt to understand the planet, and to provide clues to the formation of the solar system. BepiColombo is a particularly challenging mission because of Mercury's proximity to the Sun and the harsh environment this entails.

BepiColombo is made of three spacecraft: the Mercury Polar Orbiter (MPO) which will study the planet's surface and internal composition, the Mercury Magnetospheric Orbiter (MMO) which will study Mercury's magnetosphere, and the Mercury Transfer Module (MTM) which carries the other two spacecraft to Mercury. MMO and MPO will separate from the MTM when it reaches Mercury. MMO is being developed by Jaxa and the other two components are being developed by ESA.

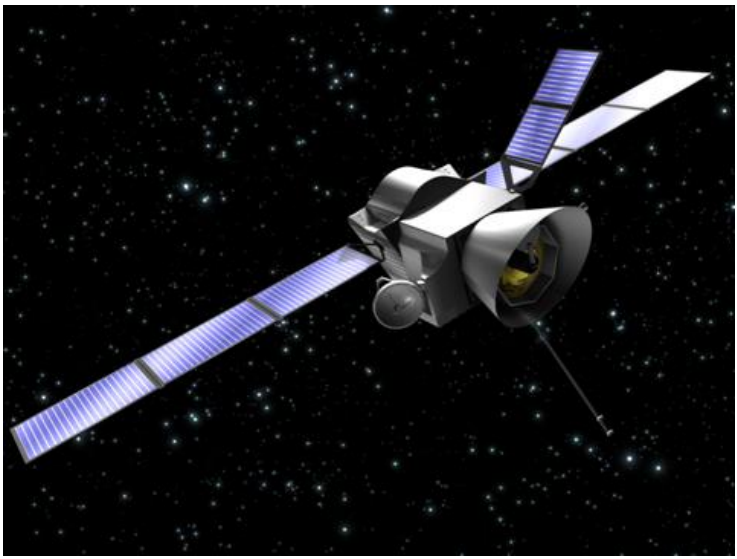


Figure 18 BepiColombo MPO and MMO (Courtesy ESA)

The SpaceWire data-handling architecture used on MPO is shown in Figure 19.

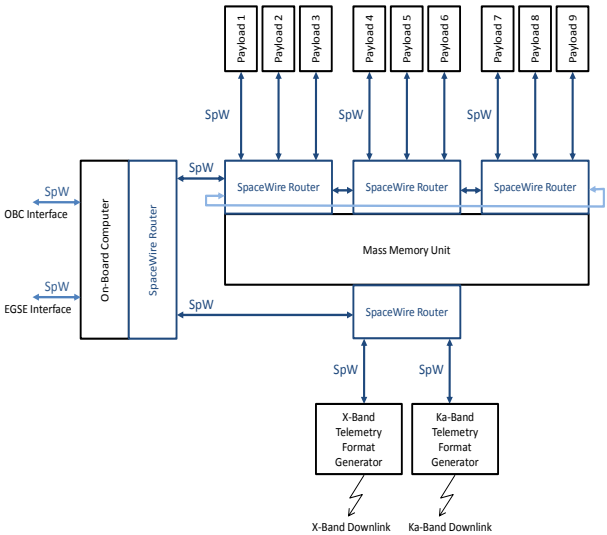


Figure 19 Mercury Polar Orbiter Data-Handling Architecture

MPO uses SpaceWire for the data-handling from its nine science payloads. These payload instruments are connected to the on-board mass memory unit via point-to-point links and three SpaceWire routers that are integrated within the mass memory unit. These routers are also connected to the on-board computer and to each other in a daisy chain. This enables the on-board computer to access each of the routers and payload instruments for configuration and control purposes. Another router is used to connect the mass memory unit to the X-band and Ka-band downlink telemetry format generators, which format the payload data before sending it back to Earth. This SpaceWire router is also attached to the on-board computer to allow the router and downlink telemetry format generators to be configured and controlled. SpaceWire links are also used to connect the on-board computer to the spacecraft platform and electronic ground support equipment (EGSE).

The SpaceWire routing devices used are the ESA SpW-10X routers (Atmel AT7910E).

Figure 19 has been simplified for clarity. For redundancy purposes the data-handling units are duplicated with cross-strapping between units to enhance overall reliability and avoid possible single-point failures.

MMO is illustrated in Figure 20 and its data-handling architecture is shown in Figure 21.

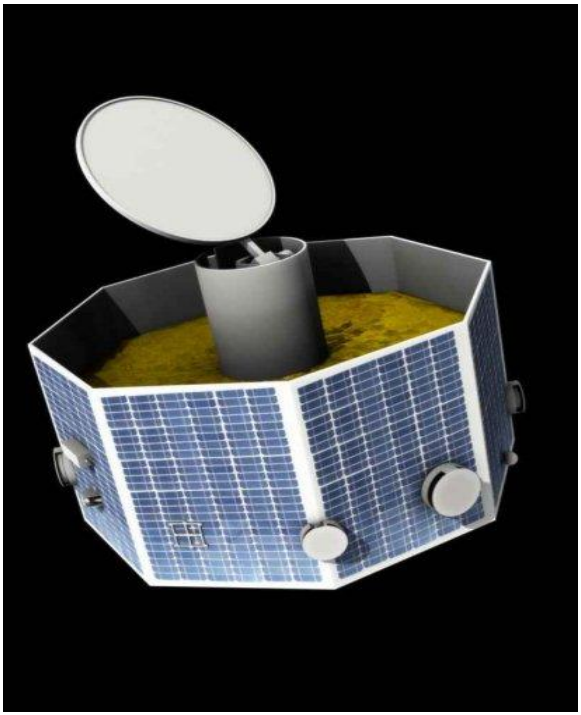


Figure 20 BepiColombo MMO (Courtesy ESA)

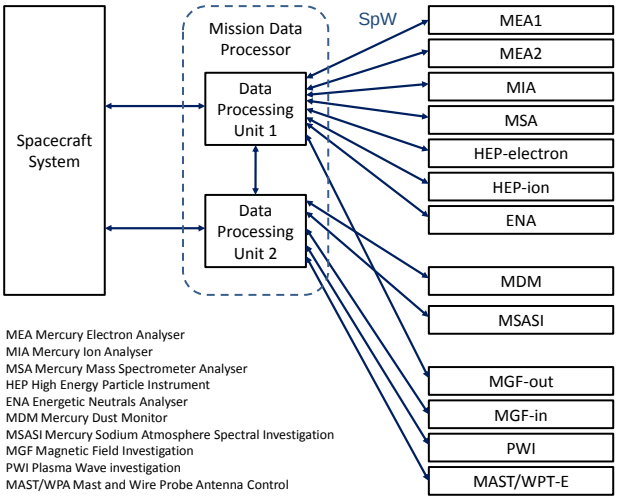


Figure 21 Mercury Magnetospheric Orbiter Data-Handling Architecture

Each instrument is connected using a point-to-point link to the mission data processor, which contains two data-handling units, each of which contains a central processing unit and a SpaceWire router. SpaceWire is used to configure, control, gather housekeeping information and collect data from all the instruments on MMO. It is also used to pass telecommands from the spacecraft system and pass housekeeping and science data to the spacecraft system for telemetering back to Earth. Because of the low power and mass requirements of MMO a special version of the SpaceWire interface was implemented which can start up and continue operation at 2 Mbits/s.

2.5.5 ASNARO

ASNARO is a Japanese optical high-resolution Earth imaging mission with ground sampling distances of 0.5m pan-chromatic and 2m multispectral, and a swath width of 10km. ASNARO is being developed by the NEC Corporation and USEF (Institute for Unmanned Space Experiment Free

Flyer) with funding from the Japanese Ministry of Economy, Trade and Industry. The overall objective of the ASNARO project is to develop a next-generation high-performance mini-satellite bus system based on open architecture techniques and manufacturing methodologies to drastically reduce the cost and the development period with adoption of up-to-date electronics technologies [34].

SpaceWire is used on-board ASNARO for all the data-handling. The SpaceWire architecture is illustrated in Figure 22.

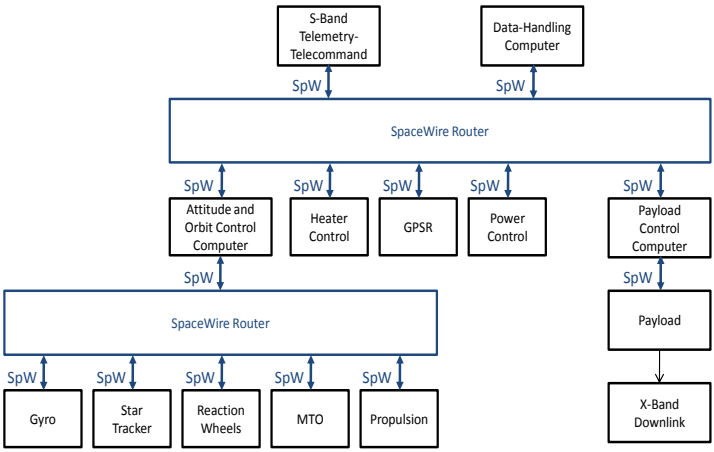


Figure 22 ASNARO SpaceWire Networks

ASNARO uses SpaceWire for platform and attitude and orbit control (AOCS) as well as for payload data-handling. The payload control computer is attached to the payload using SpaceWire. The platform electronics including the data-handling computer, payload computer, attitude and orbit control computer, heater control, GPS receiver, power control and S-Band telecommand-telemetry unit, are interconnected using a SpaceWire router. A separate SpaceWire network connects the AOCS sensors and actuators to the AOCS computer.

3 SpaceWire Links

In this section the operation of a SpaceWire link is considered in more detail. SpaceWire is based on two previous standards IEEE 1355-1995 [2] and ANSI/TIA/EIA-644 [3].

The SpaceWire standard covers the physical connectors and cables, electrical properties, and logical protocols that comprise SpaceWire data links and networks which are defined in the following normative protocol levels

- **Physical Level** – SpaceWire connectors, cables, cable assemblies and printed circuit board tracks.
- **Signal Level** – signal encoding, voltage levels, noise margins, and data signalling rates used in SpaceWire.
- **Character Level** – data and control characters used to manage the flow of data across a SpaceWire link.
- **Exchange Level** – protocols for link initialisation, flow control, link error detection and link error recovery.
- **Packet Level** – definition of how data for transmission over a SpaceWire link is split up into packets
- **Network Level** – structure of a SpaceWire network and the way in which packets are transferred from a source node to a destination node across a network. The network level also defines how link errors and network level errors are handled.

In the following subsections each of these protocol levels will be considered in turn up to and including the packet level.

3.1 Physical Level

The physical level of the SpaceWire standard covers cables, connectors, cable assemblies and printed circuit board tracks. SpaceWire was developed to meet the EMC specifications of typical spacecraft.

3.1.1 Cables

The SpaceWire cable comprises four twisted pair wires with a separate shield around each twisted pair and an overall shield. To achieve a high data signalling rate with SpaceWire over distances up to 10 m a cable with the following characteristics is used:

- Characteristic impedance of 100 ohms differential impedance, which is matched to the line termination impedance.
- Low signal-signal skew between each signal in a differential pair and between Data and Strobe pairs.
- Low signal attenuation.
- Low cross-talk.
- Good EMC performance.

The structure of a SpaceWire cable is illustrated in Figure 23.

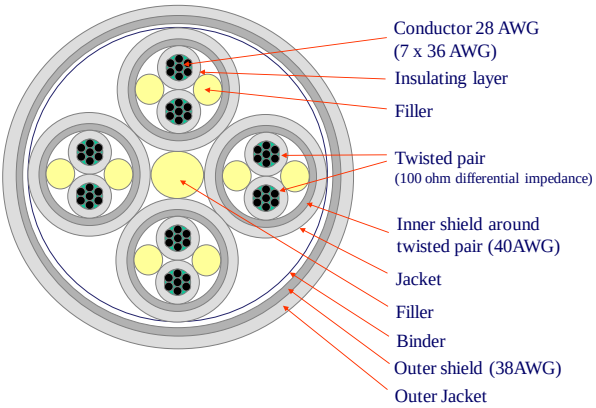


Figure 23 SpaceWire Cable Structure

One of the drawbacks of SpaceWire is the mass of the cable which is around 87 g/m. A new form of SpaceWire cable is currently being developed by ESA which is of significantly lower mass. This cable only uses one level of shielding.

SpaceWire is able to operate at 200 Mbits/s over 10m cable. For longer distances it is possible to increase the wire gauge of the conductors to reduce cable attenuation.

3.1.2 Connectors

The SpaceWire connector has eight signal contacts plus a screen termination contact. A nine pin micro-miniature D-type is specified as the SpaceWire connector. This type of connector is available qualified for space use. The pin-out of the connector is illustrated in Figure 24.

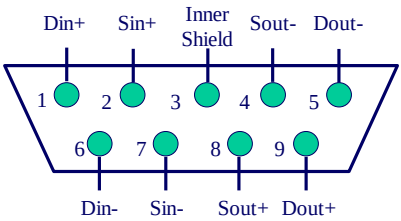


Figure 24 SpaceWire Connector Pin-Out

3.1.3 Cable Assemblies

SpaceWire cable assemblies are made from a length of SpaceWire cable of up to 10 m length terminated at each end by nine-pin micro-miniature D-type plugs.

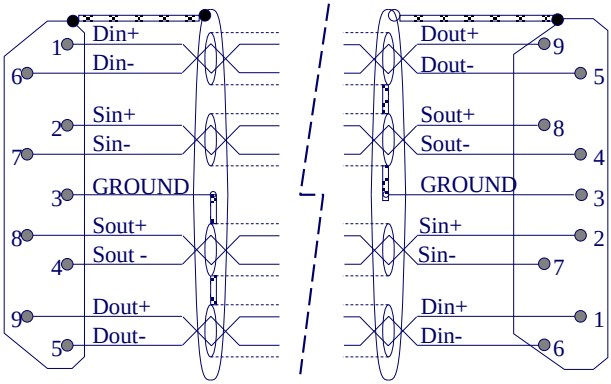


Figure 25 SpaceWire Cable Assembly

The SpaceWire cable assembly includes an outer-shield which is 360º terminated to the connector backshell at each end of the cable. Each twisted pair also has a shield (inner-shields) which are connected to pin 3 of the connector (signal ground) at one end of the cable only, the end driving the twisted pairs.

This arrangement is far from ideal and in future it is recommended that all shields are terminated to the backshell and pin 3 at both ends of the connector.

A photograph of a SpaceWire cable assembly is shown in **Figure 26**.

Figure 26 Photograph of SpaceWire Cable Assembly

3.1.4 Printed Circuit Board Tracks

SpaceWire can also be run over printed circuit boards (PCBs) including backplanes. Because of the high-speed of SpaceWire signals which have a bandwidth of over 1 GHz (at 200 Mbps the signal frequency is 100 MHz and that of the signal edges around ten times this, giving 1 GHz) care has to be taken with the PCB layout. The following guidelines should be adhered to:

- The PCB tracks must have 100 ohm differential impedance
- Track pairs well separated from other tracks
- No right-angle turns
- Minimal use of vias
- Each signal of the differential pair to be tracked identically and kept to the same length (< 5 mm)
- Data and strobe signal pairs to be of the same length (< 5 mm)

3.2 Signal Level

The signal level part of the SpaceWire standard covers signal voltage levels, noise margins and signal encoding.

3.2.1 Signal Level and Noise Margins

Low Voltage Differential Signalling (LVDS) as defined in ANSI/TIA/EIA-644 [9] is specified as the signalling technique for SpaceWire. LVDS uses balanced signals to provide very high-speed interconnection using a low voltage swing (350 mV typical). The balanced or differential signalling provides adequate noise margin to enable the use of low voltages in practical systems. The low voltage swing results in relatively low power consumption at high speed. LVDS is appropriate for connections between chips on a board, boards in a unit, and unit to unit interconnections over distances of 10 m or more. The LVDS signalling levels are illustrated in Figure 27.

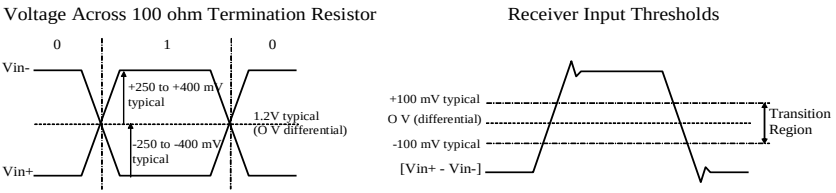


Figure 27 LVDS Signalling Levels

A typical LVDS driver and receiver are shown in Figure 28, connected by a media (cable or PCB traces) of 100 ohm differential impedance. The LVDS driver uses current mode logic. A constant current source of around 3.5 mA provides the current that flows out of the driver, along the transmission medium, through the 100 ohm termination resistance and back to the driver via the transmission medium. Two pairs of transistor switches in the driver control the direction of the current flow through the termination resistor. When the driver transistors marked "+" in Figure 28 are turned on and those marked "-" are turned off, current flows as indicated by the arrows on the diagram creating a positive voltage across the termination resistor. When the two driver transistors, marked "-", are turned on and those marked "+" are turned off, current flows in the opposite direction producing a negative voltage across the termination resistor. LVDS receivers are specified to have high input impedance so that most of the current flows through the termination resistor to generate around ±350 mV with the nominal 3.5 mA current source.

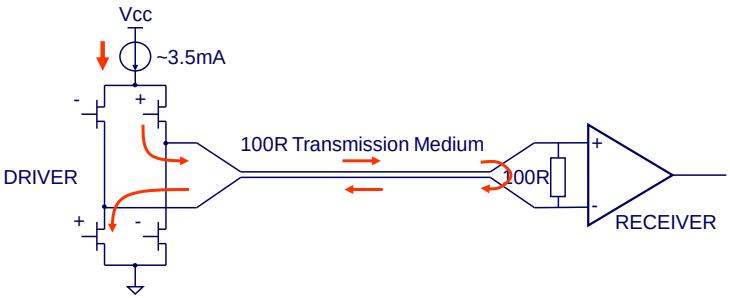


Figure 28 LVDS Operation

LVDS has several features that make it very attractive for data signalling [6]:

- Near constant total drive current (+3.5 mA for logic 1 and -3.5 mA for logic 0) which decreases switching noise on power supplies.
- High immunity to ground potential difference between driver and receiver, LVDS can tolerate at least ±1 V ground difference.
- High immunity to induced noise because of differential signalling, normally using twisted-pair cable.
- Low EM emission because small equal and opposite currents create small electromagnetic fields which tend to cancel one another out.
- Not dependent upon particular device supply voltage(s).
- Simple 100 ohm termination at receiver.
- Failsafe operation - the receiver output goes to the high state (inactive) whenever
    - the receiver is powered and the driver is not powered,
    - the inputs short together,
    - input wires are disconnected.
- Power consumption is typically 50 mW per driver/receiver pair for LVDS compared to 120 mW for ECL/PECL.

The signal levels and noise margins for SpaceWire are derived from ANSI/TIA/EIA-644 [3] which defines the driver output characteristics and the receiver input characteristics. The eye diagram for SpaceWire signals sent over 10 m of cable at 200 Mbits/s baud rate is shown in Figure 29.

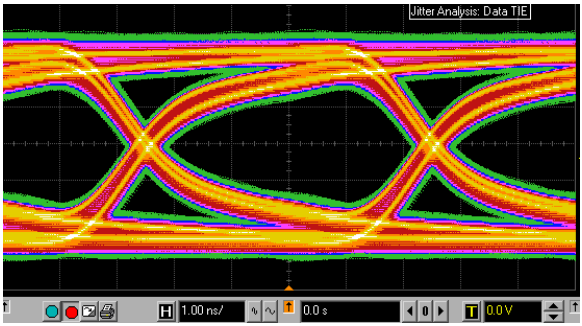


Figure 29 SpaceWire Eye Diagram (200 MHz, 10 m cable)

3.2.2 Data encoding

SpaceWire uses Data-Strobe (DS) encoding. This is a coding scheme which encodes the transmission clock with the data into Data and Strobe so that the clock can be recovered by simply XORing the Data and Strobe lines together. The data values are transmitted directly and the strobe signal changes state whenever the data remains constant from one data bit interval to the next. This coding scheme is illustrated in **Figure 30**. The DS encoding scheme is also used in the IEEE 1355-1995 [7] and IEEE 1394-1995 (Firewire) standard [41].

The reason for using DS encoding is to improve the skew tolerance to almost 1-bit time, compared to 0.5 bit time for simple data and clock encoding.

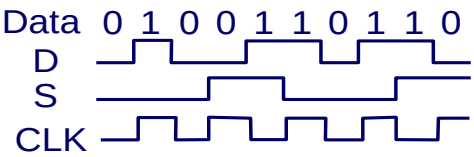


Figure 30 Data-Strobe (DS) Encoding

A SpaceWire link comprises two pairs of differential signals, one pair transmitting the D and S signals in one direction and the other pair transmitting D and S in the opposite direction. That is a total of eight wires for each bi-directional link.

A bit trace from a SpaceWire link analyser is shown in Figure 31. The yellow lines are the data and strobe signals (DIN and SIN). At each transition of the strobe line a dotted white line has been drawn vertically from the strobe signal over the data signal. The value of the data line between these vertical lines or the transitions of the data line is the decoded data value, shown as white 0 or 1 on the trace. Bit synchronisation on SpaceWire is therefore quite straightforward, but determining the boundaries between SpaceWire characters is more difficult in a bit trace.

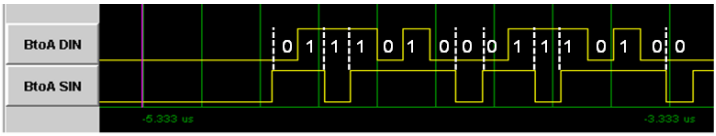


Figure 31 Decoding SpaceWire Data

SpaceWire performs bit synchronisation by XORing the data and strobe signals to form a clock signal, both edges of which are then used to read in the values on the data line.

3.3 Character Level

In this section the character level of SpaceWire is described.

3.3.1 SpaceWire Characters

SpaceWire has two types of characters: data and control characters which are illustrated in

Figure **32**.

- Data characters which hold an eight-bit data value transmitted least-significant bit first. Each data character contains a parity-bit, a data-control flag and the eight-bits of data. The parity-bit covers the previous eight-bits of data or two-bits of control code, the current parity-bit and the current data-control flag. It is set to produce odd parity so that the total number of 1's in the field covered is an odd number. The data-control flag is set to zero to indicate that the current character is a data character.

- Control characters which hold a two-bit control code. Each control character is formed from a parity-bit, a data-control flag and the two-bit control code. The data-control flag is set to one to indicate that the current character is a control character. Parity coverage is similar to that for a data character. One of the four possible control characters is the escape code (ESC). This can be used to form longer control codes. Two longer control codes are specified and valid which are the NULL code and the Time-Code.

In addition to the data and control characters there are two control codes: NULL and time-codes.

- NULL is formed from ESC followed by the flow control token (FCT). NULL is transmitted, whenever a link is not sending data or control tokens, to keep the link active and to support link disconnect detection.

- The Time-Code is used to support the distribution of system time across a network. A Time-Code is formed by ESC followed by a single data-character.

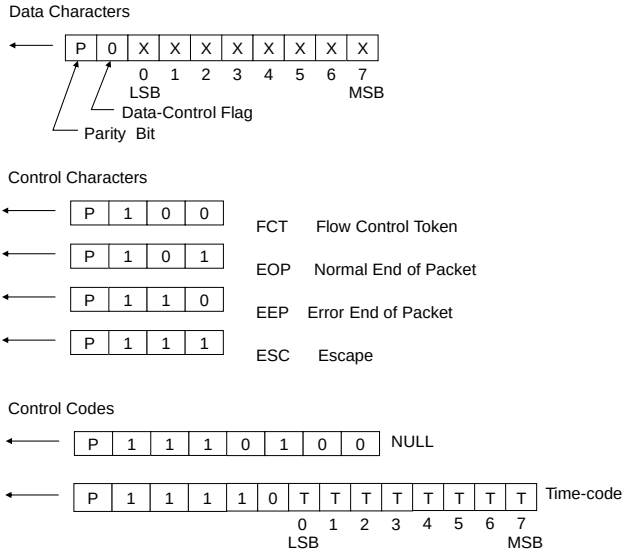


Figure 32 Data and Control Characters and Control Codes

3.3.2 Parity Coverage

The parity coverage for SpaceWire is a bit unusual, as it follows that of IEEE1355-1995. Because of the different lengths of control and data character, the parity field of the previous character includes the data/control flag of the next character. This is so that the length of the following character is validated by the parity bit before that character is decoded. This avoids incorrect decoding of a character when its data/control flag is in error.

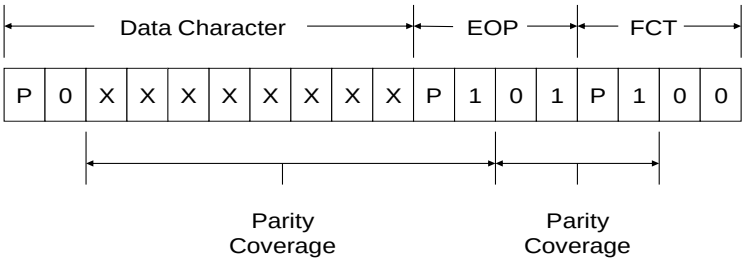


Figure 33 Data and Control Characters Parity Coverage

3.3.3 Character Priority

Character transmission is prioritised as follows:

- Time-codes - highest priority
- FCTs
- N-Chars
- NULLs - lowest priority

Time-codes are highest priority because they are used to transfer time or synchronisation information and have to be delivered with low jitter. FCTs are higher priority than N-Chars, so that a large amount of data being sent in one direction does not stop FCTs being sent, thus causing the other end of the link to stop sending data because it has run out of flow control. NULLs are the lowest priority as they are only sent to keep the link running and synchronised when there is nothing else to send.

3.3.4 Character Functions

Characters in SpaceWire are used for three different functions: link control, sending packets and sending time-codes.

The characters and control codes used for link control are the NULL and FCT, which are known as L-Chars or Link characters. They are used in the Exchange level and not passed up to any higher level.

The characters and control codes used for sending packets are the data characters and end of packet markers (EOP and EEP), which are known as N-Chars or Normal characters. These characters are passed up to the packet layer.

The time-codes are used for sending time and synchronization information and are passed to the time-code handler of a node or router.

A SpaceWire link interface interleaves L-Chars, N-Chars and time-codes. N-Chars from one packet are not interleaved with N-Chars from another

packet. A received character should have its parity checked before it is acted upon.

3.3.5 Character Synchronisation

Character synchronisation is performed only once when a link is started or re-started following a link disconnection. This is illustrated in **Figure 34**.

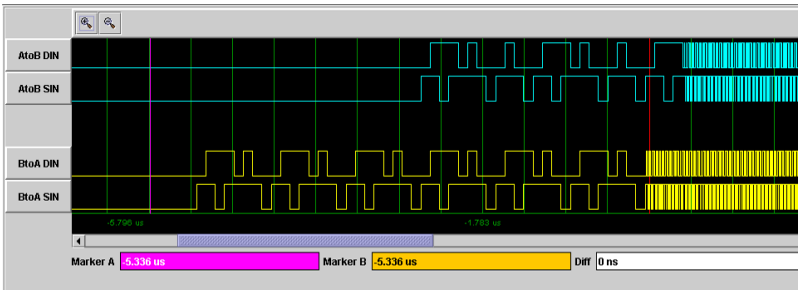


Figure 34 SpaceWire Link Start-up and Character Synchronisation

One end of the link (bottom trace, End B) starts to send Nulls, a specific sequence of 8 data bits. The other end detects this sequence, synchronises its receiver and starts to send Nulls back (top trace, End A). When End B receives these Nulls it synchronises its receiver. Further handshaking is done between the two ends of the link which is described later in section 3.4. The SpaceWire interfaces initially start operating at a line data signalling rate of 10 Mbits/s. Once the connection has been made the two ends of the link can switch to higher speed operation if required. This is clearly visible in Figure 34.

Before a link sends its first Null both data and strobe lines are set low as shown in Figure 35.

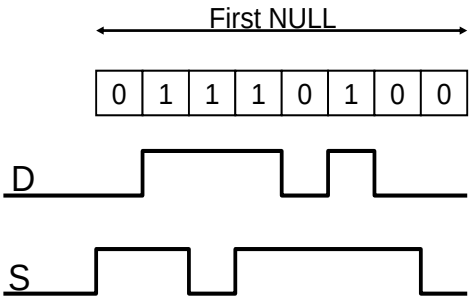


Figure 35 SpaceWire Link Start-Up Bit Sequence

Unfortunately the bit sequence for a Null is not unique in a SpaceWire bit sequence so it cannot be reliably used for resynchronisation of the signals without first stopping the SpaceWire link and then restarting and re-synchronising it.

3.4 Exchange Level

The SpaceWire exchange level is responsible for exchanging information between the two ends of a link. It provides the following functions: link initialisation, flow-control and error-handling.

3.4.1 SpaceWire Link Interface

At each end of a SpaceWire link is a SpaceWire link interface. A block diagram of a link interface is illustrated in Figure 36.

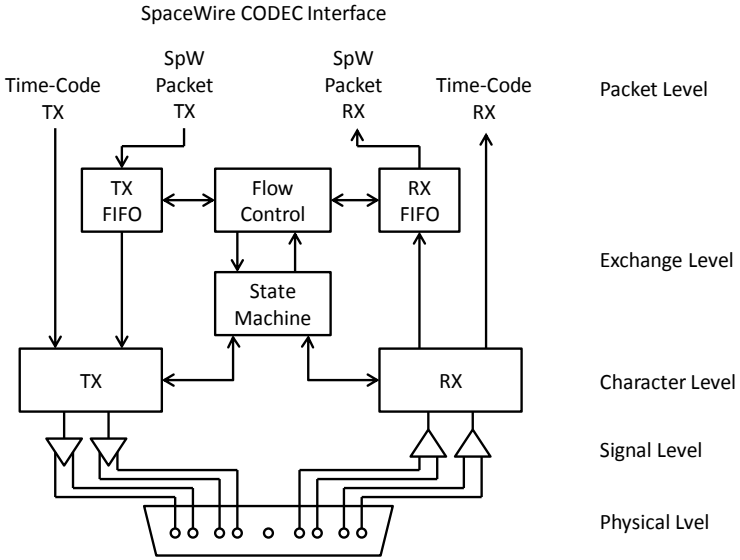


Figure 36 SpaceWire Link Interface Block Diagram

The SpaceWire link can send and receive SpaceWire packets and time-codes once it has been initialised and is running. As described in section 2.3.2 a SpaceWire packet comprises a destination address, cargo and end of packet marker. To send a SpaceWire packet over a SpaceWire link it is passed character by character to the transmit FIFO starting with the first character of the destination address. SpaceWire packets are received into the RX FIFO and can be read out by the application. To send a time-code, it is presented to the SpaceWire interface and will be transmitted as soon as the current character has finished being transmitted. When time-codes are received they are made available via the time-code interface. Time-codes need to be validated before they are used, see section 5.

Before a SpaceWire link can send and receive SpaceWire packets and time-codes, it needs to be initialised. This is done under control of the link

state machine. This state machine also manages recovery from any errors detected on the link, by re-initialising the link.

To prevent overflow of the receive FIFO the SpaceWire interface includes circuitry to monitor the amount of space available in the receive FIFO and to regulate the data being sent from the other end using flow-control tokens.

3.4.2 Link Initialisation

Link initialisation is necessary to get both ends of the link fully synchronised and ready to receive data and EOP characters and time-codes. Bit synchronisation is performed by decoding the data-strobe signals to produce the bit clock and data stream. Character synchronisation is performed once during link initialisation. Both ends of the link have to be character synchronised or the link will automatically reset and attempt to resynchronise.

Following reset the SpaceWire interface is held in the reset state until it is instructed to start and attempt to make a connection with the SpaceWire interface at the other end of the link. A connection is made following a handshake that ensures both ends of the link are able to send and receive characters successfully. Each end of the link sends NULLs, waits to receive a NULL, then sends FCTs and waits to receive an FCT. Since a SpaceWire interface is not allowed to send FCTs until it has received a NULL, receipt of one or more NULLs followed by receipt of an FCT means that the other end of the link has received NULLs successfully and that full connection has been achieved. This exchange of Nulls and FCTs is known as the Null/FCT handshake.

Link initialisation is handled by a state machine in each of the SpaceWire interfaces at either end of the SpaceWire link. The basic state machine is illustrated in Figure 37. This diagram is simplified to highlight the link initialisation procedure.

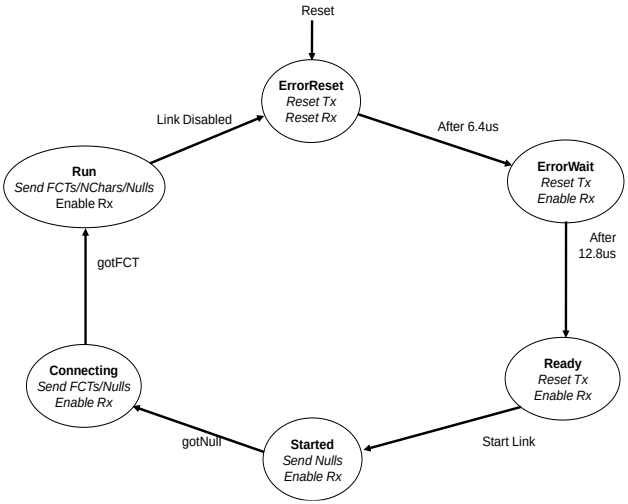


Figure 37 SpaceWire Interface State Machine

On reset the SpaceWire interface state machine enters the ErrorReset state where both the transmitter and receiver in the SpaceWire interface are reset. The state machine remains in this state for 6.4 µs to ensure that the interface is properly reset, and then moves to the ErrorWait state where it keeps the transmitter reset but enables the receiver. The reason for this will become clear later. After waiting 12.8 µs in the ErrorWait state the SpaceWire interface moves to the Ready state, where it waits for a command to start the link. When the SpaceWire interface is instructed to start the link (by the local application logic using the SpaceWire interface) it moves to the Started state where it begins to send out Nulls. If the other end (End B) of the link is also sending Nulls then End A will receive the Null (gotNull) and move to the Connecting state. In the Connecting state the transmitter is allowed to send Nulls and FCTs. It will send out an initial burst of FCTs (see flow control section later on) as part of the initialisation handshake. The other end of the link (End B) will have received Nulls and with therefore also be in the Connecting state sending out FCTs and Nulls. The FCTs will be received at End A and the state machine will move to the

Run state. In the Run state both ends of the link have made a connection (or are just about to) and the SpaceWire interface is ready to start transferring data. The link will now remain in the Run state until one of the SpaceWire interfaces is disabled by the local application logic asserting the Link Disabled control bit.

If the other end of the link (End B) is not ready and does not send Nulls and FCTs when expected, End A will wait in the Started or Connecting state for 12.8 µs and then give up waiting, move back to the ErrorReset state and try again to make a connection. This is illustrated in Figure 38.

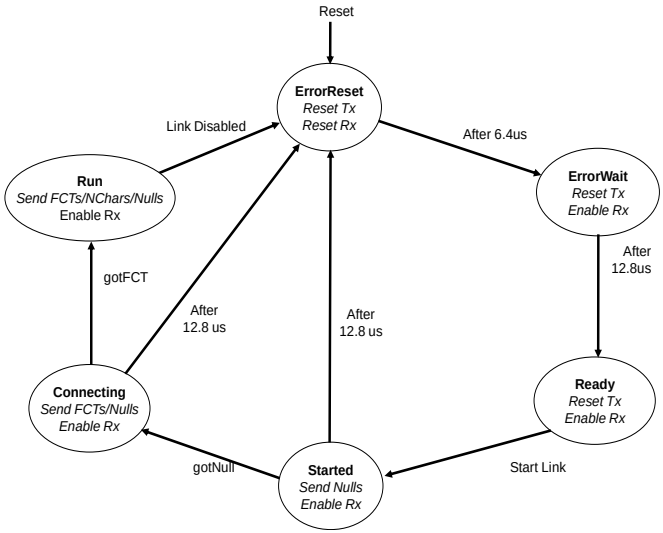


Figure 38 SpaceWire Interface State Machine moves to ErrorReset when no Nulls or FCTs received

To avoid having to set both the Start Link bit in both ends of the link to start a link, an Auto-Start mode is included in the SpaceWire state-machine. A SpaceWire interface in the Auto-Start mode will automatically start up when it receives a bit (gotBit) on its receiver. This functionality is achieved by

adding an extra condition on the transition between the Ready and Started states. This addition is illustrated in Figure 39.

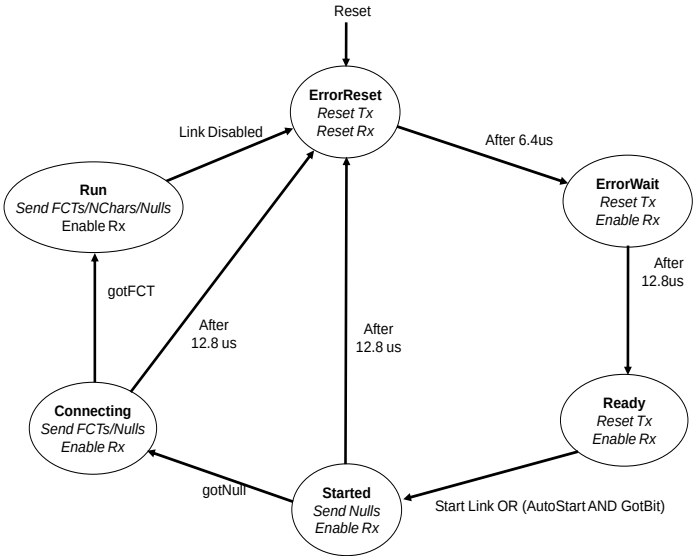


Figure 39 SpaceWire Interface State Machine with Auto-Start

One end of the link (End B) has its AutoStart control bit set and has reset, moved through ErrorReset and ErrorWait, and is now sitting in the Ready state. The other end of the link (End A) has also reset and is waiting in the Ready state. When End A gets the command to Start Link, it moves to the Started state and begins sending Nulls. End B receives the start of the Null and gotBit is asserted causing it to also move to the Started state. The Null/FCT handshake now takes place with both ends moving through Started and Connecting to Run.

When one end of the link is trying to make a connection, i.e. Start Link is asserted, and the other end of the link (End B) is not ready to make a connection for whatever reason, End A will send Nulls for 12.8 µs and then go silent for 19.2 µs (6.4 µs + 12.8 µs) repeatedly. Observing bursts of Nulls

from one end of a link while nothing is being sent in the other direction is a clear indication that one end is trying to send and the other end is not responding. This could be because that end of the link does not have its Auto-Start control bit asserted, or alternatively its Disable bit is asserted.

The link initialisation sequence is shown in Figure 40. The sequence of characters under A->B Event is for one direction of the link (characters being sent from End A to End B) while that under B->A Event is the other direction.

1. The link is disconnected causing both ends of the link to reset, moving through the ErrorReset and ErrorWait states to the Ready state.

2. End B of the link has Start Link asserted and so moves to the Started state and begins sending Nulls, which are received at End A initially causing GOT-BIT to be asserted and then a series of Nulls to be received.

3. End A has AutoStart asserted, so as soon as it has received the first bit (GOT-BIT) it moves to the Started state and sends at least one Null, which is received at End B.

4. When End A receives a Null, and after it has sent at least one Null in response, it moves to the Connecting state and is able to send one or more FCTs.

5. The Null from End A is received at End B, so End B moves to the Connecting state, and is able to send one or more FCTs.

6. The FCT from End A is received at End B, so End B moves to the Run state and switches to the required link operating speed (note the change in character timing).

7. The FCT sent from End B is received at End A, so End A moves to the Run state and switches to the required link operating speed. The link is now running in both directions.

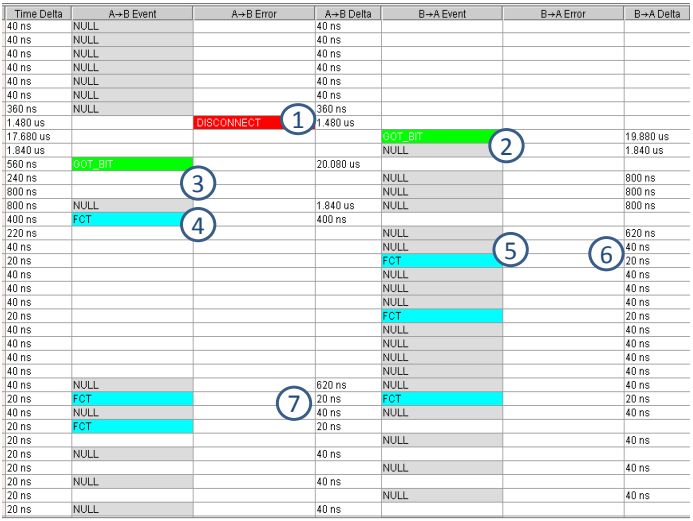


Figure 40 Link Initialisation

Note that during initialisation at least one Null must be sent before FCTs are sent, although this is not clearly stated in the SpaceWire standard.

If there is noise on the input to a receiver, possibly caused by the cable being disconnected, the random noise might occasionally correspond to a Null followed by an FCT. If the receiver is in auto-start mode, this will cause the receiver to start up and begin sending Nulls and FCTs. Eventually the noise will cause a parity error and a disconnect. If a SpaceWire interface is observed to periodically send short bursts of characters, it is likely that the cause is noise on its receiver inputs. To some extent unwanted noise can be overcome using biasing resistors on the receiver inputs.

3.4.3 Link Flow Control

A transmitter is only allowed to transmit N-Chars (normal characters, which are data characters, EOP or EEP), if there is space for them in the receive FIFO at the other end of the link. The receive FIFO indicates that there is space for eight more N-Chars by requesting the link transmitter to send a

flow control token (FCT). The FCT is received at the other end of the link (end B) enabling the transmitter at end B to send up to eight more N-Chars. If there is more room in the receive FIFO, multiple FCTs can be sent, one for every eight spaces in the receive buffer. Correspondingly, if multiple FCTs are received then it means that there is a corresponding amount of space available in the receive FIFO e.g. four FCTs means that there is room for 32 N-Chars. Each FCT is exchanged in this way for 8 N-Chars. The operation of flow control is illustrated in Figure 41.

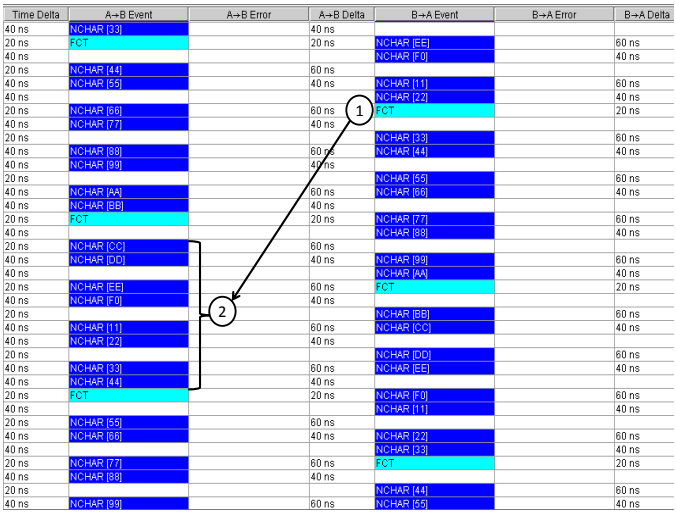


Figure 41 Flow Control With FCTs

The FCT sent by End B and received by End A (1), permits End A to send eight more N-Chars (2). The FCT goes in the opposite direction to the data that it is exchanged for. The SpaceWire link in Figure 41, is sending data in both directions of the link so FCTs are also being sent in both directions.

A SpaceWire interface is permitted to have a maximum of seven outstanding FCTs, corresponding to 56 N-Chars. Buffers larger than this can be used if required, but seven FCTs are more than enough to support

continuous data transfer across a link. Smaller FIFOs may also be used, in which case fewer than the maximum of seven FCTs will ever be outstanding.

3.4.4 Link Error Handling

There are several types of error that can occur in a SpaceWire link:

- Disconnect error – the link is disconnected in one or both directions, so data or Nulls are not received.
- Parity error – a received character contains a parity error.
- Escape error – an Escape character is received which is followed by another Escape, an EOP, or EEP, which are character sequences that are not allowed.
- Credit error – an N-Char arrives when there is no room for it in the receive FIFO.

Link disconnection is detected when following reception of a data bit no new data bit is received within a link disconnect timeout window (850 ns). Once a disconnection error has been detected, the link attempts to recover from the error.

Parity errors occurring within a data or control character are detected when the next character is sent, since the parity bit for a data or control character is contained in the next character. Once a parity error has been detected, the link attempts to recover from the error.

Following an error or reset the link attempts to re-synchronise and restart using an “exchange of silence” protocol (see Figure 42). The end of the link that is either reset or that finds an error, ceases transmission. This is detected at the other end of the link as a link disconnect and that end stops transmitting too. The first link resets its input and output for 6.4 μs to ensure that the other end detects the disconnect. The other end also waits for 6.4 μs after ceasing transmission. Each link then waits a further 12.8 μs before

starting to transmit. These periods of time are sufficient to ensure that the receivers at both ends of the link are ready to receive characters before either end starts transmission. The two ends of the link go through the NULL/FCT handshake (see Figure 40) to re-establish a connection and ensure proper character synchronisation.

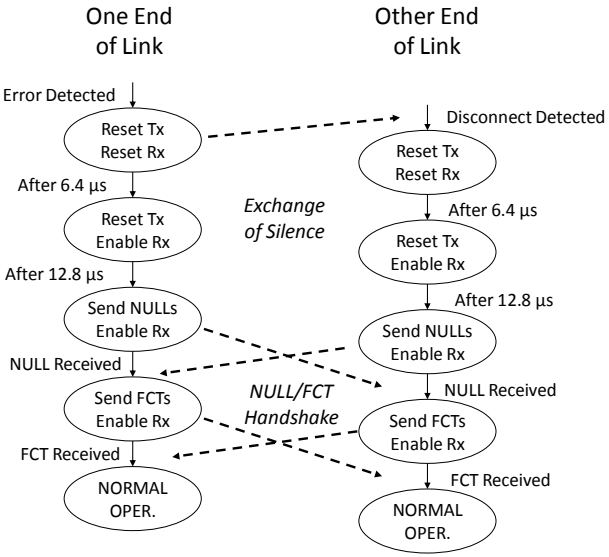


Figure 42 Link Restart

Recovery from errors is controlled by the state machine in the SpaceWire interface. The complete state machine is shown in Figure 43.

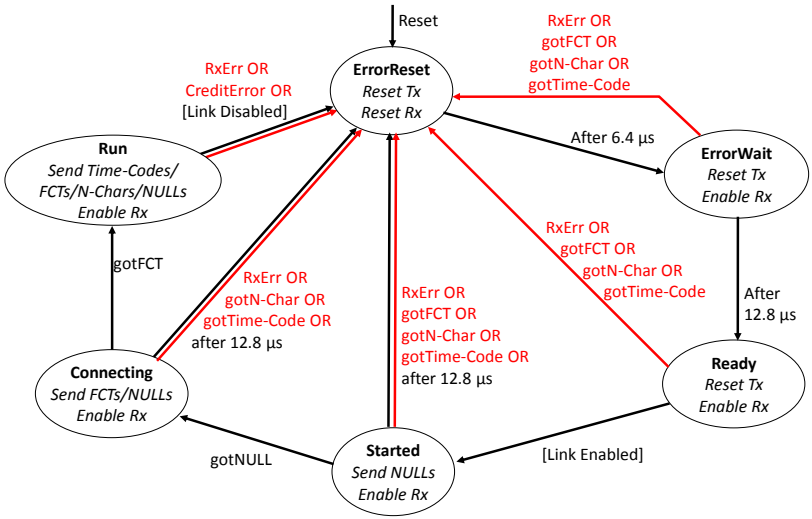


Figure 43 SpaceWire Interface State Machine Error Recovery

The error conditions that can occur are shown in red. Any error that is detected results in a transition to the ErrorReset which starts the error recovery cycle.

RxErr is a Disconnect Error, Parity Error, or Escape Error.

Disconnect Error detection is enabled following link reset, only after the first bit has been received.

An RxErr can be detected in any state, except ErrorReset, and will result in a transition to ErrorReset.

In the ErrorWait, Ready and Started states it should not be possible to receive an FCT, N-Char or time-code, because the link has not yet been fully initialised. If any of these characters are received it is an error and results in a transition to the ErrorReset state.

In the Connecting state it should not be possible to receive N-Chars or time-codes as the link is only partially connected, an FCT must be received before any of these other characters, finishing link initialisation and causing a transition to the Run state. If any N-Chars or time-codes are received in the Connecting state, it is an error and the state machine moves to the ErrorReset state.

Detection of Parity Error, Escape Error, gotFCT, gotN-Char, and gotTime-Code are only enabled after the first Null has been received, i.e. gotNULL asserted.

Thus

RxErr OR gotFCT OR gotN-Char OR gotTime-Code

is really

RxErr OR (gotNULL AND (gotFCT OR gotN-Char OR gotTime-Code)).

3.4.5 Auto-Start

The Auto-Start facility in a SpaceWire link interface is provided to permit the far end of the link to initiate starting of the link. One end of the link is set to Auto-Start. Sometime later the other end of the link is started and begins sending Nulls. These are received by the end of the link set to Auto-Start, which responds to the reception of Nulls by starting and sending Nulls. Initialisation of the link takes place and data can then be sent over the link.

Both ends of a SpaceWire link can be set to Auto-Start, in which case either end can be started and cause link initialisation.

Without the Auto-Start facility both ends of the link would have to be started specifically. One end could be started, sending Nulls for a long time before the other end is also started. This wastes power.

The condition for enabling a link to begin initialisation is:

[Link Enabled] = (NOT [Link Disabled]) AND ([LinkStart] OR ([AutoStart] AND gotNULL))

Where:

- LinkDisabled is a flag set by software or hardware to indicate that the link is disabled,
- LinkStart is a flag set by software or hardware to start a link,
- AutoStart is a flag set by software or hardware to request the link to start automatically on receipt of a NULL,
- gotNULL is a flag indicating that the link interface has received a NULL.

If the link is disabled, LinkDisabled asserted, the other flags are ignored and the link will not attempt to start initialisation, until LinkDisabled is de-asserted.

3.5 Packet Level

The packet level of SpaceWire simply defines the fields in a SpaceWire packet: destination address, cargo and end of packet marker, as illustrated in Figure 44.

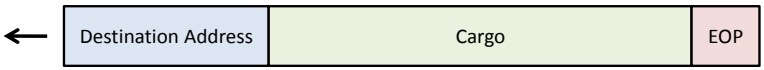


Figure 44 SpaceWire Packet Format

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 SpaceWire network to reach to 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 SpaceWire 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 SpaceWire packet.

In addition to the normal end of packet marker (EOP), there is another end of packet marker, the Error End of Packet marker (EEP), which indicates that the packet has been terminated prematurely because of an error that occurred as the packet traversed a SpaceWire link or network. A packet terminated by an EEP is illustrated in Figure 45.

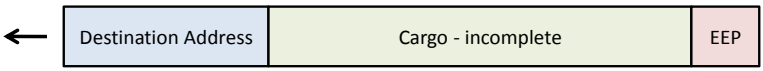


Figure 45 SpaceWire Packet Terminated by EEP

When a packet is terminated by an EEP it is likely that the Cargo is incomplete and may contain some erroneous data characters. It is also possible for an error to occur at the start of the packet, while sending the destination address. In this case, there is no cargo, just an incomplete destination address followed by an EEP. If this incomplete destination address is a path address, as the packet terminated by the EEP moves across the SpaceWire network, each router will forward the packet and delete the leading character of the packet. Eventually all the destination address characters will be deleted before the packet arrives at its destination, since it was an incomplete destination address. All that is left is an EEP. Since a router cannot know where to forward an EEP on its own it will simply delete the EEP. The prematurely terminated packet will then have disappeared completely.

3.6 Link error Recovery

The handling of link errors by the link state machine is described in section 3.4.4. This section considers what happens to a packet that is travelling across a link when an error occurs.

If an error is detected by a link interface, the following sequence of events takes place to recover from the error:

1. Detect Error

A Disconnect, Parity, Escape, or Credit error is detected.

Figure 46 shows the two directions of the link transferring packets, from an end user buffer passing data to the SpaceWire transmitter, via the SpaceWire interface transmit FIFO, across the link, into the SpaceWire interface receive FIFO at the other end of the link, and on into the end user buffer taking data from the receiver. In the left to right direction of the link the head of a packet is in the receive user buffer and the tail of the packet with the EOP is in the transmit end user buffer. An error has just occurred in this direction of the link.

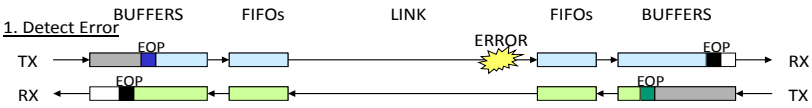


Figure 46 Link error recovery: error detection

2. Disconnect Link

The error detected in the receiver on the right hand side of Figure 46, causes the transmitter at that end to disconnect, resulting in a disconnect error occurring at the other end of the link. Both ends of the link are now disconnected as illustrated in Figure 47.

Figure 47 Link error recovery: link disconnection

3. Terminate Packets with EEPs

The information in the receive FIFOs has an EEP appended to it, as soon as there is room in each FIFO to add one. This terminates the received part of the packet, so that it can continue on its way through the SpaceWire network. This is illustrated in Figure 48.

Figure 48 Link error recovery: terminate packets with EEPs

4. Spill Rest of Packet

The remainder of the packet which has not yet been transferred across the link has to be discarded, since one or more N-Chars will have been lost or corrupted due to the error on the link. The tail end of the packet that has not yet been sent across the link contains valid data, but its destination is not clear: for example, it could have been an EOP that was lost when the error occurred on the link. Since the destination is unknown all that can be done with the tail end of the packet is to discard it. Data is read by the transmitter and spilt until the EOP (or EEP) is reached. The character following the EOP will be the destination address at the start of the next packet. The result after spilling the packet is shown in Figure 49.

Figure 49 Link error recovery: spill rest of packet

5. Reconnect

Now the SpaceWire link has tidied up after the error, the link can be re-initialised and the connection re-established. This is shown in Figure 50.

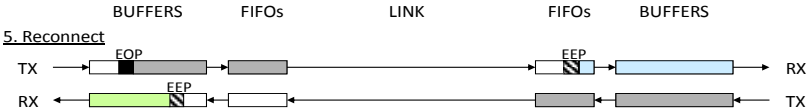


Figure 50 Link error recovery: reconnect

6. Continue Packet Transfer

With the link restarted the next packet, whose head and destination address is waiting in the transmit FIFO, can be sent. Normal operation has resumed. This is shown in Figure 51.

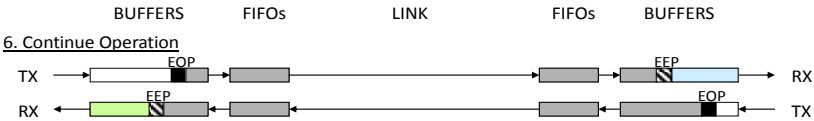


Figure 51 Link error recovery: continue operation

The error recovery mechanism works across networks comprised of a number of routing switches. Only the link on which the error occurs is reset (disconnect/reconnect). All the other links continue operation. Normally only the packet in which the error occurred is partly lost and all other packets remain valid. In some cases more than one packet can be lost due to the time taken for link disconnection.

If the header byte (i.e. first byte after an EOP or EEP) is corrupted, the entire packet is lost and the data is not propagated across a network. The routing switch simply disposes of the packet.

If the error occurs in a EOP (or EEP), two packets are affected: the one before the EOP where all the data is sent but no EOP is received, and the following one because the link transmitter “spills” the packet until the next EOP (or EEP).

If the error occurs in a NULL or FCT inserted in the data stream for a packet, the packet being sent is discarded from that point on. This is because it is not known what the character was before it was corrupted.

The time taken for complete recovery from the error on the link will depend upon how long it takes to spill the tail end of the packet being transferred when the link error occurred, which depends on the size of that packet. The tail may have to be pulled out from the packet source, through one or more routers making up a SpaceWire network as it is being split.

The decision about what to do with the packet that terminates with the EEP is up to the user application.

4 SpaceWire Networks

SpaceWire networks are built from SpaceWire links, nodes and routers. The links and routers are there to connect together nodes so that they can exchange information and work together to perform some required function.

4.1 SpaceWire Nodes

A node is a piece of equipment that is using the services of a SpaceWire link or network. It is a source or destination of SpaceWire packets, an end-point on a SpaceWire network. For example, an instrument, mass-memory unit or processor attached to a SpaceWire network is a SpaceWire node.

A node can have more than one SpaceWire interface and may have more than one logical address.

4.2 SpaceWire Routing Switch

A SpaceWire router connects together many nodes and provides a means of routing packets from one node to one of many other possible nodes. A SpaceWire router comprises a number of SpaceWire link interfaces and a switch matrix. The switch matrix enables packets arriving at one link interface to be transferred to and sent out of another link interface on the router. Each link interface may be considered as comprising an input port (the link interface receiver) and an output port (the link interface transmitter) as illustrated in Figure 52.

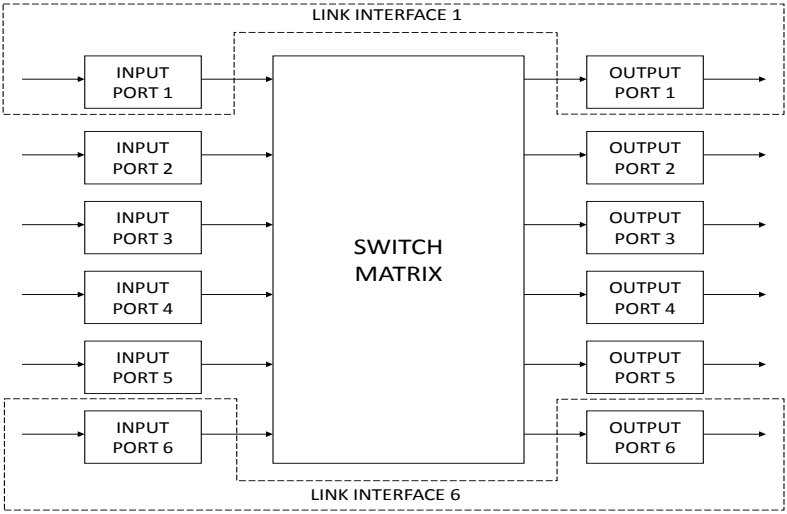


Figure 52 Router Switch Matrix

A SpaceWire router transfers packets from the input port of the switch where the packet arrives, to a particular output port determined by the packet destination address. A router uses the leading data character of a packet (one of the destination identifier characters) to determine the output port of the router to which the packet is to be routed. If there are two input ports waiting to use a particular output port when the previous packet has finished being sent then an arbitration mechanism in the output port decides which input port is to be served.

4.3 Routing Tables

A routing table within the router is used to translate from the destination address at the front of a packet to the port number through which the packet will be sent. The router addresses are assigned as shown in Table 1.

Table 1 Router Addresses	
Address Range	**Function**
0	Internal Configuration Port
1-31 (01-1F hex)	Physical Output Ports
32-254 (20-FE hex)	Logical Addresses, which are mapped on to the physical output ports
255 (FF hex)	Reserved

The internal configuration port is used to access configuration and status information of the router. A SpaceWire packet arriving at any port of the router with a leading destination address value of 0 will be routed to the configuration port. Configuration information that can be accessed via the configuration port includes the routing table, enabling the routing information to be programmed over the SpaceWire network. All SpaceWire routers have a configuration port. Since the configuration port is both the source and destination of SpaceWire packets, that makes the configuration and status circuitry of a router a node.

The physical output ports are the actual SpaceWire ports on the router. For connecting to equipment local to the router it is not always necessary to use a SpaceWire link. In this case, a FIFO port can be used instead. The FIFO port is bi-directional and behaves like a SpaceWire port as far as the router, but there is no SpaceWire link attached to it. Instead, some user application connects directly to the FIFO port. The physical output ports of a router include both the SpaceWire ports and the FIFO ports. The physical output ports are always numbered from one upwards and normally the SpaceWire ports are first. So a router with four SpaceWire ports and two FIFO ports would number the SpaceWire ports 1 to 4 and the FIFO ports 5 and 6. FIFO ports are also called external or parallel ports, meaning external to the

SpaceWire network, and parallel as opposed to the serial SpaceWire link. A router is allowed to have a maximum of 31 physical ports, hence the physical output ports are numbered 1 to 31 maximum.

Logical addresses are mapped by the routing table to physical output ports. It is necessary to be able to distinguish between path and logical addresses so that the router can handle them appropriately. This is done in a simple way: the value of the leading address character of a packet determines whether it is a path or logical address, if it is in the range 0 to 31 it is a path address, if it is in the range 32 to 255 it is a logical address. A path address is used directly to determine the output port that the packet is to be forwarded through. A logical address is used as an index into the routing table from which the physical port number is determined. The packet is then forwarded through the specific output port.

Logical address 255 is reserved for future applications and should not be used.

An example routing table for a router with four SpaceWire ports and the configuration port is illustrated in Figure 53. A ‘1’ in the table maps an address to an output port number. The configuration port (port 0) is accessed only via path addressing with the address 0. Ports 1 to 4 are accessed using path addresses 1 to 4 respectively. Path addresses beyond address 4 have no meaning in a 4-port router and give rise to a routing error. Logical addresses can be used to access any of the four output ports depending on how the routing table is programmed. For example in Figure 53, logical address 33 has been programmed to port 4. Any packets arriving with address 33 will be routed to output port 4.

	Address	Port 0	Port 1	Port 2	Port 3	Port 4
Configuration	0	1	0	0	0	0
Path Addressing	1	0	1	0	0	0
	2	0	0	1	0	0
	…					
Logical Addressing	32	0	0	1	0	0
	33	0	0	0	0	1
	34	0	1	0	0	0
	…					
	255	0	0	0	0	0

Figure 53 Routing Table for 4-Port Router

4.4 Group Adaptive Routing

SpaceWire routers can implement group adaptive routing. When two or more output ports lead, either directly or indirectly, to the same destination, these output ports may be configured as a group. When a packet arrives at an input port for routing out of an output port that is busy, any other output port in the same group as the addressed output port may be used to forward the packet.

A routing table in a router that implements group adaptive routing is illustrated in

Figure 54. Logical address 33 has two output ports assigned to it. When a packet with this logical address is received the router has the choice of routing the packet out of port 3 or port 4.

	Address	Port 0	Port 1	Port 2	Port 3	Port 4
Configuration	0	1	0	0	0	0
Path Addressing	1	0	1	0	0	0
	2	0	0	1	0	0
	…					
Logical Addressing	32	0	1	1	0	0
	33	0	0	0	1	1
	34	0	1	1	0	0
	…					
	255	0	0	0	0	0

Figure 54 Routing Table with Group Adaptive Routing

4.5 Wormhole Routing

SpaceWire routing switches employ wormhole routing. When a packet starts to arrive at an input port of a router, its destination address is looked at immediately. If the output port that is to be used to forward the packet towards its destination is not currently being used, the head of the packet is sent to that output port straightaway, with the rest of the packet following as it is received at the input port. There is no buffering of complete packets in the router, neither before, nor after switching.

Wormhole routing has a number of advantages over other approaches like store and forward:

- No packet buffering
- Little buffer memory
- Can support packets of arbitrary size
- Rapid switching

Wormhole routing suffers from one main problem, that of blocking. If the output port that the packet is to be forwarded through is not ready or is currently being used, the packet has to wait until it is ready or the packet currently flowing through it has finished. Since the tail of a packet can be spread out through the network, not only is the waiting packet halted, but that packet blocks any other packet in the network that is waiting to use the links that it is currently occupying. This is illustrated in Figure 55.

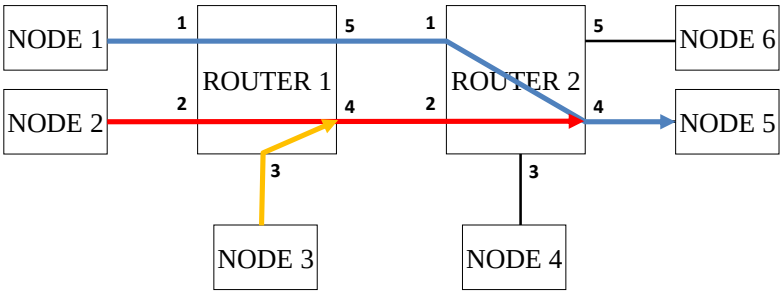


Figure 55 Packet Blocking

A long packet it being transferred from node 1 to node 5, shown in blue. Another packet, shown in red, wants to go from node 2 to node 5, but since the link from router 2 to node 5 is already in use, the red packet is blocked in router 2. A third packet, shown in yellow, wants to go from node 3 to node 6. This does not use any of the links being occupied by the first packet (blue), but it is blocked by the waiting packet (red) in router 1 since it has to travel over a link from router 1 to router 2. Once there is a blockage its effect can multiply, causing further blockage throughout a network.

Blocking can occur for several reasons:

- A large packet is being sent;
- The destination of the packet is not ready to receive it;
- Something has gone wrong on the network, e.g. a link failure, so that a packet cannot move forward across the failed link.

There are some strategies that help to avoid blocking a network:

- Split large packets up into many smaller ones, e.g. an image could be sent as a series of image lines;
- Make sure that the destination is ready before sending the packet, which can be done using an end-to-end flow control mechanism;
- If the destination is not ready to receive a packet it can simply throw the packet away, this can be combined with a retry mechanism to implement flow control, although it might result in inefficient use of network bandwidth if the destination is often not ready.
- If a packet does get blocked for longer than might be expected, indicating that a fault has occurred, detect this using a watchdog timer and discard the blocked packet.

4.6 Header Deletion

Header deletion is the removal of the first data character of a packet after it has been used to perform its routing function. Header deletion is always employed in a router for path addressing. Once a path address has been used it is no longer needed and is discarded, exposing the next path address character to be used by the next router encountered on the network.

Header deletion is not normally applied to logical addresses as the logical address gives the identity of the destination node. The one logical address character is used by each router encountered by the packet as an index into the router's routing table, so that the router can forward the packet towards its intended destination. This does limit the number of nodes to 223, which is considered plenty for most spacecraft applications.

There is, however, a means of extending the number of logical addresses. Regional logical addressing uses a logical address in one region of a

network, but if a packet crosses the boundary of one region into another region, its leading logical address is deleted, exposing another logical address character that is used in the next region. This is illustrated in Figure 58.

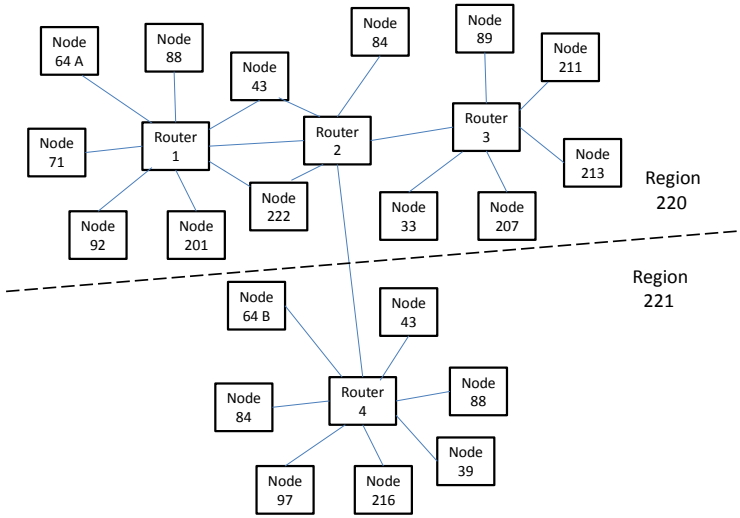


Figure 56 Regional Logical Addressing

Figure 56 shows a large network. Above the dashed line all the node logical addresses are unique, but below the dashed line some of the logical addresses are repeats of those above the line. Node 71 wants to send one packet to node 64 above the line (node 64 A) and another packet to node 64 below the line (node 64 B). How can this be done? If the routers above the line are configured to route to node 64 A, a packet sent from node 71 with destination address 64 will end up at node 64 A.

To reach node 64 B the network is split into two regions: above the line and below the line. In each region the node logical addresses must all be unique. Each region is then given a logical address, which should not be assigned to any of the nodes. The region above the line is given logical address 220 and that below is given 221. Now to route from node 71 to

node 64 B, the packet is given two cascaded logical addresses, the first of which is the logical address of the destination region (where the target node lies) and the second of which is the logical address of the destination node in that region. So for node 64 B this is 221, 64. The packet sent is then:

221, 64, cargo, EOP

The routers in region 220 are all configured to route any packet with logical address 221 first to router 2 and then on to router 4. Router 2 is programmed so that when the packet is forwarded from router 2 to router 4, its leading address character is stripped off, revealing the second address character:

64, cargo, EOP

The routers in region 221 are configured to route packets with logical address 64 to the local node with that logical address, i.e. to node 64 B.

To use regional logical addressing it is necessary to:

1. Split the network into regions which are each given a logical address
2. Within a region nodes must have unique logical addresses
3. Nodes in two different regions can have the same logical address
4. When routing a packet from one region to another the router must strip off the leading destination address character. This has to be specifically configured in the router.
5. It is possible to cross regions to reach a destination, provided there is one logical address for each region.

For most spacecraft applications regional logical addressing is not necessary as there is normally far fewer than 223 nodes.

4.7 Time-code Broadcast

As well as forwarding SpaceWire packets towards their destinations, a SpaceWire router also broadcasts time-codes. Time-codes and the way in which they are broadcast by a SpaceWire router are described in section 5.

Each router contains a time-code register (also called a time-code counter). When a time-code arrives on a port its value (6-bits carried in the data character of the time-code, see section 3.3.1) is compared to that of the time-code register. If it is one more than the time-code register, the time-code is valid and is forwarded out of all of the physical ports of the router, except the configuration port and the port that the time-code arrived on. This broadcasts the time-code over the network. The time-code register is then updated with the value of the received time-code. If the time-code is not one more than the time-code register, the value of the time-code is loaded into the time-code register, but the time-code is not forwarded. This prevents time-codes repeatedly circulating around a network that contains a loop via one or more routers. It also provides a method for recovering from time-codes that go missing, for whatever reason. Note that some routers can be configure to broadcast time-code on specific ports only. This facility was included to permit operation with legacy IEEE-1355 devices which could accept SpaceWire packets, but did not understand time-codes.

There is normally one time-code register in a router. Some implementations have, however, provided four time-code registers in the router with the top two-bits of the time-code data character being used to determine which of the four time-code registers to use. This permits up to four sets of time-codes to be broadcast simultaneously across the network. Strictly this violates the SpaceWire standard as the standard reserves the top two-bits of the time-code. These two-bits are likely to be used for other purposes in future, including interrupt signalling.

4.8 Router Configuration

A router is configured via its configuration port. The SpaceWire standard does not specify how a router should be configured, but it is common practice for this to be done using the SpaceWire remote memory access protocol (see section 6.2). This provides a standard means of reading and writing to registers in the configuration port, but it does not specify the arrangement and function of registers in the configuration port. Work is currently being done on a SpaceWire plug and play standard, which aims to standardise SpaceWire network configuration. In the meantime each router configuration space has a proprietary arrangement of registers.

4.9 Packet Distribution

The SpaceWire standard specifies a means of using a router to copy and distribute a SpaceWire packet to several nodes attached to different ports of the router. This was included for the specific purpose of distributing the same data to several processors in a parallel processing system. It can cause significant problems when used in a SpaceWire network and its use is not recommended. For example, if a packet is arriving at one port of the router and being distributed out of several other ports and a node attached to one of these ports cannot accept any more data, for whatever reason, the data going to all of the processors will halt. Any fault is effectively multiplied.

4.10 Example SpaceWire Router

In this section the architecture of the ESA SpW-10X SpaceWire router ASIC is described and then some specific features added into this router to enhance its capabilities are explained.

4.10.1 SpW-10X Architecture

The architecture of the SpaceWire router ASIC is illustrated in Figure 57.

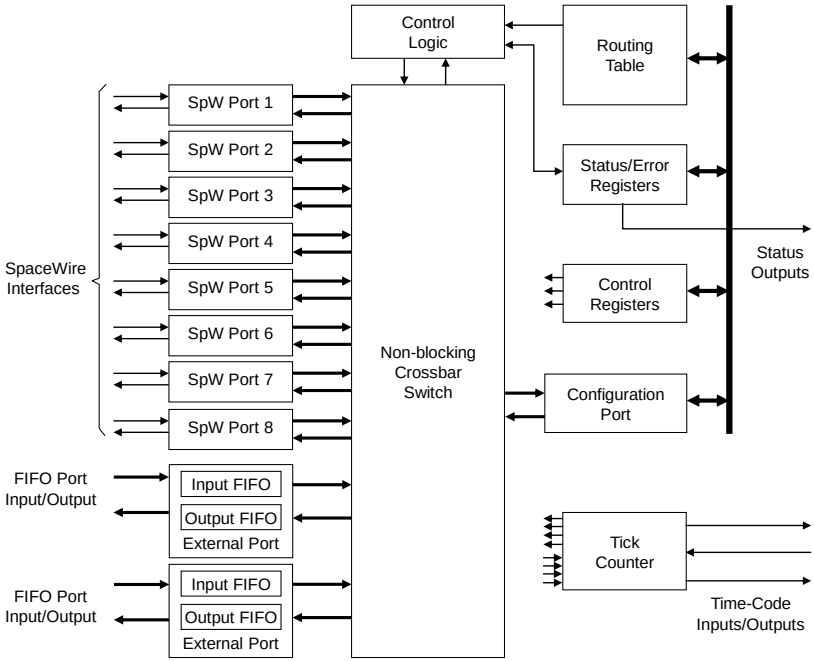


Figure 57 ESA SpW-10X SpaceWire Router ASIC Architecture

There are eight SpaceWire ports, two external ports and an internal configuration port in the SpaceWire router. A low latency, worm-hole routing, non-blocking, crossbar switch enables packets arriving at any SpaceWire port, external port or generated in the configuration port to be directed out of any other SpaceWire or external port or to be routed to the configuration port.

The SpaceWire ports are compliant with the SpaceWire standard [2] providing high-speed, bi-directional communications. The FIFO ports each comprise an input FIFO and an output FIFO and can receive and send data characters and end of packet markers. A time-code port is also provided along with a time-counter to facilitate the propagation of time-codes, see section 5. When a valid time-code arrives at a router port it is sent out of all the other SpaceWire ports and a TICK_OUT signal is generated at the time-

code port. The router can operate as a time-code master using the TICK_IN provided in the time-code port.

The configuration port is accessible via any of the SpaceWire or external ports. It contains registers which control the operation of the SpaceWire ports, external ports and the crossbar switch. The configuration port holds status registers for the various ports and the switch. These registers can be read using a configuration read command to determine the status of the router and to access error information. Status and error information can also be selected for output on several status pins. The routing table is accessed via the configuration port. The logical address port mappings and priority bits can be set in the routing table. The routing table is used to control group adaptive routing and priority arbitration in the crossbar switch. In the SpW-10X Router configuration is done using the SpaceWire Remote Memory Access Protocol (RMAP), see chapter 6.

The SpW-10X was designed by the University of Dundee, transferred to radiation hard technology by Austrian Aerospace, and is manufactured by Atmel and sold as the AT7910E device. It is packaged in a space qualified 256 pin QFP package, see Figure 58.

Figure 58 Photograph of SpW-10X Router ASIC

4.10.2 Watchdog Timers

Watchdog timers are provided in the SpW-10X on each port to detect blocking (see section 4.5). If a SpaceWire packet becomes blocked for any reason the SpW-10X will detect this blockage, append an EEP to the end of data already sent, and spill the tail end of the packet. A range of time-out values are provided from 0.1ms to over 1s. The watchdog timers can be disabled.

4.10.3 Routing to a Not-Connected Port

It is possible that a packet does not have a correct address, or a routing table is not correctly configured and it ends up being routed to a port that is not connected to anything. In this situation, if watchdog timers are enabled, the router will wait for the link to start until the end of the time-out period and then spill the packet. No EEP is appended since no data from the packet will have been transferred. If watchdog timers are not enabled, the packet will be spilt immediately.

4.10.4 Routing to a Non-Existent Port

Similarly a packet could be routed to a port that does not actually exist on the router, e.g. port 12 on an 8 port router. In this case the router immediately spills the packet and logs this error in its status registers.

4.10.5 Routing to a Busy Port

If a packet is routed to a port that is already busy on a router, the router will wait to send the packet for the watchdog timer period. If it times out it will spill the packet, but not append an EEP to the end of the packet since no data from the packet has been sent. This is different from the case in section 4.10.2, as there the packet is in the process of being sent through a router output port when it becomes blocked. Here the packet has not yet been switched to the output port, as that port is busy. If the time out occurs and the waiting packet is spilt, this error is logged in a status register.

4.10.6 Start On Request, Disable On Silence

The SpW-10X has some facilities to support power saving. It can be set to “disable on silence” and to “start on request”.

Disable on silence will switch off a link when there is no packet to send, after the watchdog timer interval.

Start on request will start a disabled link when a packet that arrives on another port wants to be routed across the disabled link. It will attempt to do this for the watchdog interval and then give up spilling the waiting packet.

These features, together with auto-start, allow automatic enabling and disabling of a link when only sporadic data transfers are required. This is illustrated in Figure 59 to Figure 64.

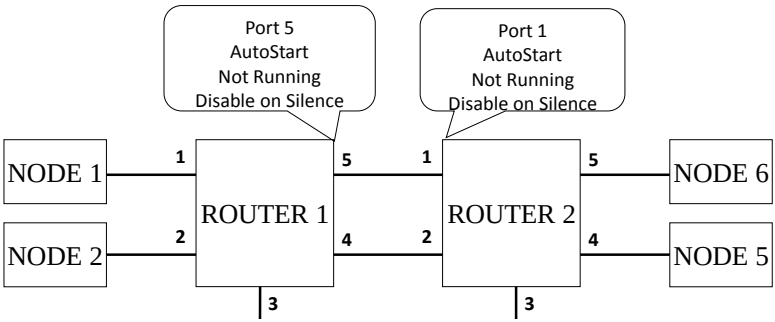


Figure 59 Start On Request, Disable On Silence: Initial State

Router 1 and Router 2 are set to auto-start, to start on request and to disable on silence. No traffic is flowing.

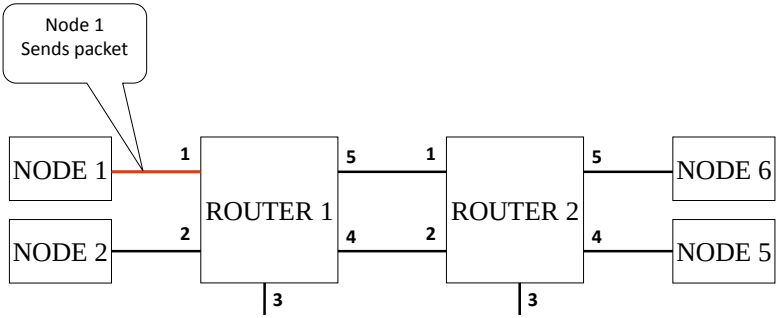


Figure 60 Start On Request, Disable On Silence: Node Starts to Send Packet

Node 1 sends a packet to Router 1 which is destined for node 5 and is to be forwarded out of port 5 of Router 1. This port is disabled at present.

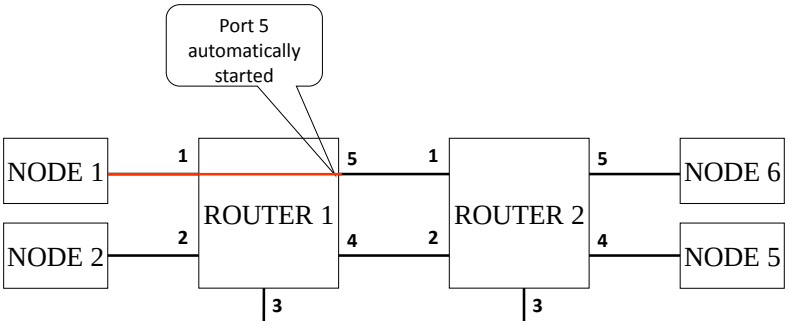


Figure 61 Start On Request, Disable On Silence: Output Port Started

Port 5 of Router 1 is started automatically and attempts to initialise the link to port 1 of Router 2.

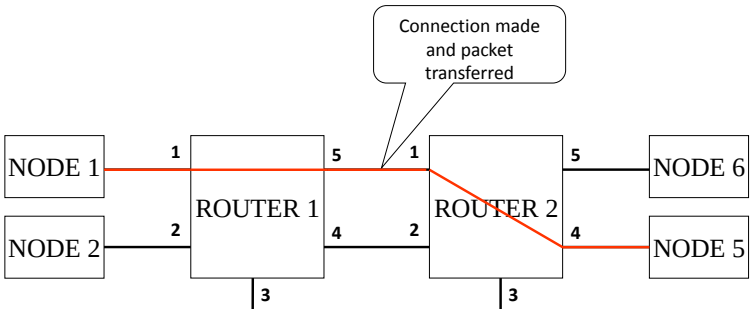


Figure 62 Start On Request, Disable On Silence: Connection Made and Packet Forwarded

Port 1 of Router 2 is set to auto-start, so when Router 1 tries to initialise the link it succeeds and the packet is forwarded through Router 2 to reach node 5.

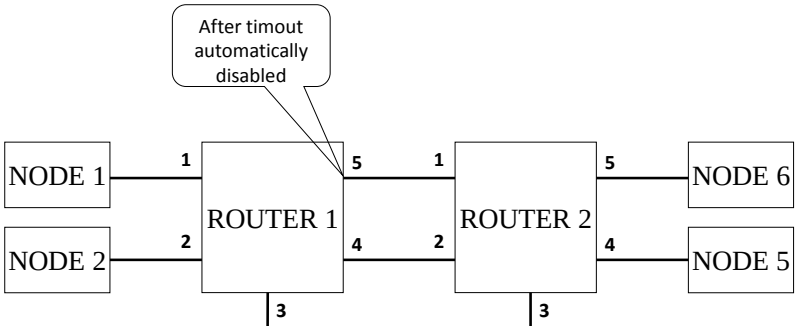


Figure 63 Start On Request, Disable On Silence: Time-out When Silent

There are no more packets to be sent so the link between Router 1 port 5 and Router 2 port 1 falls silent. After the time-out period. Router 1 detects that there is no more traffic being sent over this link and since it is set to disable on silence, it disables output port 5.

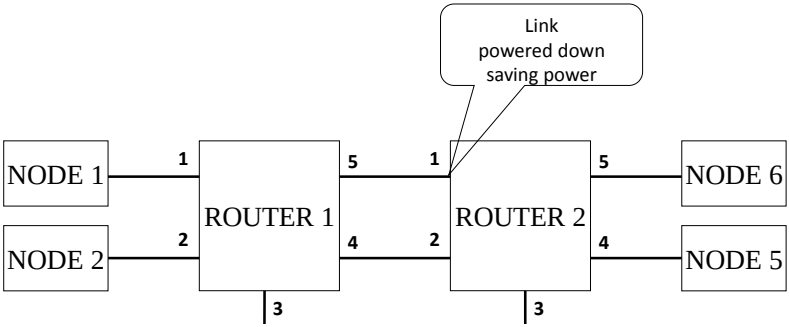


Figure 64 Start On Request, Disable On Silence: Link Disconnected

Once Router 1 port 5 is disabled, it forces a disconnect to be detected at the other end of the link. Router 2 port 1 is then disabled. If tri-stating of links is enabled, power can be saved.

4.10.7 Tristate

The output ports can be put in a state similar to tri-state to save some power when they are not being used. Remember that an LVDS driver is always sourcing current. Tri-stating it turns off this current and stops power being wasted. Tri-state can be used with the power saving techniques mentioned in section 4.10.6.

4.10.8 Disable Transmit Clocks

The SpW-10X router has eight SpaceWire ports. In some systems not all of these ports are required. It is then possible to turn off the clock tree to a port to save power. The front end receive part of the port has its clock derived from the receive signal so there will be no dynamic power consumed in the receiver if it is not connected. Configuration registers are used to disable the transmit clocks to unused ports.

4.10.9 Priority Packet Delivery

Some SpaceWire routers have implemented a priority scheme, although this is not specified in the SpaceWire standard.

If there are two input ports in a router waiting to use a particular output port, an arbitration mechanism is used to select which input port is to be served. The arbitration mechanism can include a priority scheme. There is no priority flag available within the header of a SpaceWire packet to specify its priority level. The SpaceWire header only contains address information, so packet priority must be associated with a logical address (or with the input port number). In the routing tables logical addresses may be assigned high or low priority. High priority logical addresses have preferential access to an output port when arbitration takes place. A logical address that has been assigned high priority, acts as a high priority channel across the network from many possible sources to the one destination. If high and low priority access to a particular destination is required, two logical addresses are required for a particular destination, one assigned high priority and the other low priority. A source can then decide which logical address to use when sending a packet to a destination, depending on the required priority of the packet. There is a compromise between the number of destinations that can be addressed and the number of priority levels. With two priority levels it is possible to have, say 128 low priority destinations and 96 high priority destinations within the 224 logical addresses available.

5 Time-Codes

SpaceWire time-codes [12] provide a means of synchronising units across a SpaceWire system with reasonably low jitter. This time information can be provided as “ticks”, an incrementing value which may be synchronized to spacecraft time. The time-codes are broadcast rapidly over the SpaceWire network, alleviating the possible need for a separate time distribution network.

5.1 Time-code Structure

A SpaceWire time-code comprises the SpaceWire ESC character followed by a single 8-bit data character. The data character contains two control-flags and a six-bit time-count. The time-code is illustrated in Figure 65. The six-bit time-count is held in the least-significant six-bits of the Time-Code (T0-T5) while the two most-significant bits (T6, T7) contain the two control-flags. The parity bit (P) in the middle of the time-code is set to one to give the correct parity.

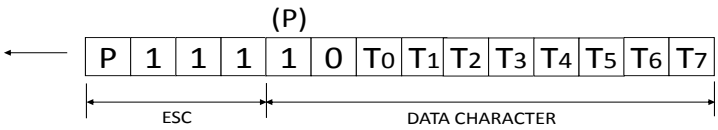


Figure 65 SpaceWire Time-Code

The two control-flags are for general use, they do not have a specific function for time-code distribution. The only permitted value for the flags is 0b00. The other possible values are reserved.

5.2 Time-code Interface

In order to be able to transmit and receive time-codes a SpaceWire CODEC has a time-code interface. The time-code interface comprises two signals, TICK_IN and TICK_OUT, together with an eight-bit time-code input-port and

an eight-bit time-code output-port. The eight-bit input and output are split into two fields: a six-bit time field and two-bit control-flag field.

The TICK_IN signal is used to request the transmission of a time-code and the eight-bit input port provides the time-code value to be sent. Whenever TICK_IN is asserted the SpaceWire CODEC will send a time-code immediately after the character currently being transmitted has finished. Note that a SpaceWire CODEC can only send time-codes when it is up and running sending Nulls, FCTs and/or data (i.e. is in the *Run* state).

The TICK_OUT is used to indicate that a time-code has arrived at a SpaceWire interface. TICK_OUT is asserted whenever the link interface is in the *Run* state and the receiver receives a valid time-code. The eight-bit time-code output-port is set to reflect the contents of the time-code.

5.3 Time-counter

Each node and router contains a time-counter which is used to hold the current 6-bit time value from the time-code time. This counter is also used to validate an incoming time-code and to decide whether the time-code should be propagated. In a node, time-code propagation is up to the application (hardware or software). In a router it is to all the output ports of the router, or at least all port that have been configured to forward time-codes.

During normal operation the time value in a time-code increments from one time-code to the next, rolling round from 63 to 0 when it reaches the maximum possible time value. When a time-code arrives at a SpaceWire node or router its value should be one more than the current value of the time-counter at this node or router. The time value of an incoming time-code is compared to the value of the time-counter. If the time-code is one more than the current value of the time-counter then the time-code is deemed valid. The time-counter is then incremented to the value of the time-code and the arrival of a valid time-code is indicated.

If the time value of the time-code is not one more than the time-counter then the time-code is not valid. In this case the time-counter is set to the value of the newly arrived time-code but the arrival of the time-code is not flagged.

5.4 Time Master

A single SpaceWire node or router in a system is responsible for generating time-codes. This “time-master” has an active TICK_IN signal which is asserted periodically (e.g. every millisecond) by its host system. Only the time-master should assert its TICK_IN signal, all other nodes must keep their TICK_IN signals de-asserted. To send out a time-code the time-master has to increment the time value on the SpaceWire CODEC time input-port and then assert the TICK_IN signal. The SpaceWire CODEC will then read in the new time-code value and transmit the requested time-code as soon as the current character has finished being sent.

The time-counter in the node or router acting as the time-master, may be used to generate the correct sequence of time-codes for transmission. The six-bit time-counter output is fed to the time-code input-port. When the next time-code is to be transmitted, the time-counter is incremented and the TICK_IN signal asserted. This causes the SpaceWire CODEC to send the required time-code. The values of the two control-flags sent in the time-code are application dependent. Their values should be updated when the time-counter is incremented.

Time-codes are normally generated periodically by the time-master to provide a regular timing tick for the SpaceWire system. The frequency of time-code is called the tick rate and the period between time-codes is called the tick interval.

5.5 Time-codes across a Link

When one end of a SpaceWire link is periodically sending out valid time-codes, the SpaceWire interface at the other end of the link receives the

time-codes, checks their validity, updates the time-counter with the new time value and asserts the TICK_OUT signal. The host system attached to this end of the SpaceWire link, receives periodic TICK-OUT signals together with the six-bit time value and the two control-flags. The TICK-OUT signal can be used to raise an interrupt or event in a software-driven node.

If a SpaceWire interface receives a time-code that is not one more than the current value of its time-counter then the time-code is not valid and the interface does not emit a TICK_OUT signal.

5.6 Router Action on Receiving a Time-code

A router contains a single time-counter. When a link interface on a router receives a time-code it checks that it is one more than the current value of the router's time-counter. It then increments the router's time-count and emits a TICK_OUT signal. This TICK_OUT signal propagates to the TICK_IN interfaces of all the router output ports so that they all emit the time-code. This time-code is the same value as that received by the router, since the router time-counter has been incremented. The time-code is not emitted by the link that first received the time-code.

If there is a circular connection then the router will receive a time-code with the same time value as the router time-counter. When this happens the time-code is ignored. In this way time flows forward through a network reaching all nodes but is suppressed if it flows back due to a circular connection.

5.7 Time-code Distribution across a Network

In this section the distribution of time-codes across a SpaceWire network is described.

The initial state of a network is shown in Figure 66. N1 and N2 are nodes. R1 and R2 are routers. The dotted lines represent the SpaceWire links between the nodes and routers. N1 is time-master and sends out a time-

code whenever its TICK_IN signal is asserted. The numbers in the node and router boxes represent the current values of their time-counters.

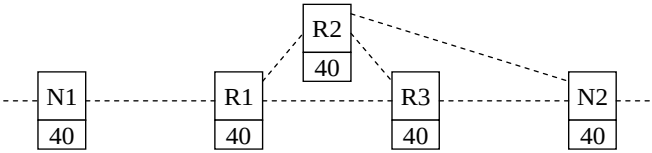


Figure 66 Initial State of Network

When TICK_IN is asserted in node N1, its time-counter is incremented from 40 to 41 and a time-code with time value 41 is transmitted. This is shown in Figure 67.

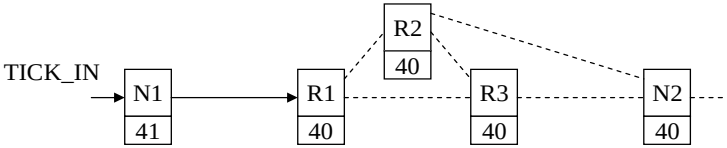


Figure 67 TICK_IN Asserted

The transmitted time-code is received by router R1 which checks that the time value is one more than the current time counter value, and then increments its time-counter and sends out time-code on all its other links. See Figure 68.

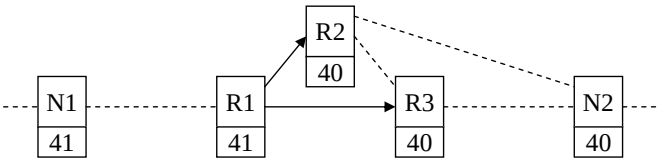


Figure 68 Router R1 Forwards Time-codes

Routers R2 and R3 both receive time-codes sent from R1 and both of these routers send out a time-code on all other links as shown in Figure 69.

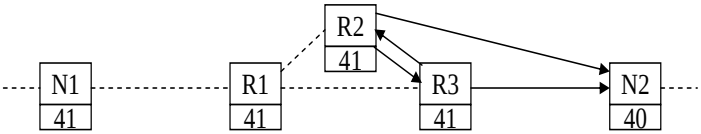


Figure 69 Routers R2 and R3 Forward Time-codes

Node N2 receives the time-code from R3 and validates that the incoming time-code has a time value of one more than the node's time-counter. It then increments the time-counter and asserts TICK-OUT. See Figure 70.

Time in N2 is updated.

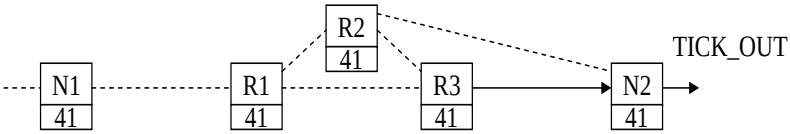


Figure 70 N2 Receives Time-code and Asserts TICK_OUT

R3 will also receive a time-code from R2, which is now not one more than R3's time-counter value, so is ignored as shown in Figure 71. This prevents time-codes from going back through the network. Time-codes move forward through the network even when there are loops in the network.

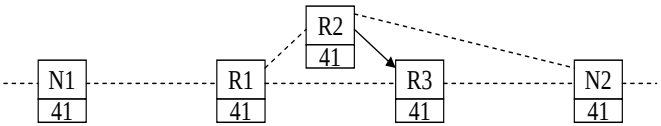


Figure 71 Time-codes Cannot Go Backwards

Node N2 will also receive a time-code from R2 which is not one more than N2's time-counter value, so is ignored. This prevents multiple triggering of the TICK_OUT signal as duplicate copies of the time-code which have taken

different paths through the SpaceWire network arrive at the node. See Figure 72.

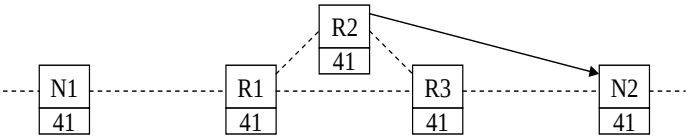


Figure 72 Other Time-codes Received at N2 are Not Valid

5.8 Lost Time-Codes

If a received time-code is not one more than (modulo 64) the current time-count at the receiving link-interface, then either the time-code or the time-count shall be considered invalid. This can happen if a time-code is lost, or if a link is reset or restarted after a disconnect.

If the time-code is invalid then the time-count is updated to the new value but the time-code is not propagated in a router and TICK_OUT is not asserted in a node. This prevents propagation of invalid time-codes across a network. When the next time-code is received it is expected that the time-counter matches the time-code and normal operation resumes. Recovery from missing or invalid time-codes will now be considered.

Figure 73 shows a SpaceWire network in which a time-code with a time-value of 20 is lost between R1 and R2.

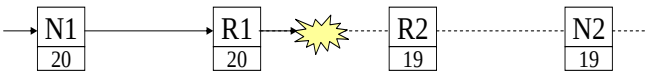


Figure 73 Lost Time-Code

On the next tick N1 sends out the time-code 21. R1 then forwards this time-code to R2. This is not same as, nor one more than time-counter of R2 so

R2 updates its time-counter but does not emit the time-code, as shown in Figure 74.

Figure 74 R2 Time-counter Updated

On the next tick the time-code 22 is sent from N1 to R1, which forwards it on to R2. At R2 the time-count is now 21, so the incoming time-code is one more than the time-count hence the time-code is now valid and is propagated by the router and reaches N2. See Figure 75. When the time-code reaches N2 it is not one more than N2's time-count (value 19) so the time-code is deemed invalid. N2 updates its time count to 22 but does not give a TICK_OUT.

Figure 75 N2 Time-counter Updated

The next tick will result in the time-code 23 propagating across the network and N2 will produce a TICK_OUT, as shown in Figure 76.

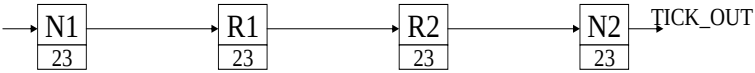


Figure 76 N2 gets Valid Time-code

It takes several ticks to recover from initial error, depending upon the size of the network.

Note that if there is an alternative path from R1 to R2 the time-code may propagate successfully through the alternative path so that R2 gets a valid

time-code even though one of the time-codes on its way to R2 gets lost. This provides a first level of fault tolerance for time-code distribution.

Nodes using the time-code distribution function can either use the TICK_OUT signal as a periodic timing signal or use the value of the time-count as an indication of the least-significant 6-bits of system time.

As a missing tick results in a timing discrepancy, the TICK_OUT signal should not be used to increment a counter with the expectation that this counter always corresponds to the system time. Rather a time-lock technique should be used where a free running local time-counter is updated to be an exact multiple of the system tick rate every time the TICK_OUT signal is asserted. The reason for this is that when using the TICK_OUT signal as a periodic timing signal the time-code can be missed so that a TICK_OUT signal is missed. Having said this, SpaceWire signals running over 10m SpaceWire cable have a good eye diagram and are unlikely to give rise to any errors.

5.9 Time-code Latency

The accuracy with which system time can be distributed is dependent upon the number of links over which it is distributed and the operating rate of each of those links. A delay of at least 14 bit-periods (ESC + data character = 4 + 10 bits) is encountered for each link that the time-code traverses, due to the time taken for each link-interface on the way to receive a Time-Code. This gives rise to a time-skew across a network of T_{skew} = 14.S/A where S is the number of SpaceWire links traversed and A is the average link operating-rate. Jitter is also introduced at each link interface due to the variation in time spent waiting for the transmitter to finish transmitting the current character or control code. At each link interface a delay of 0 to 10 bit-periods can be encountered. Across a network, this gives rise to a total jitter of T_{jitter} = 10.S/A. For an average rate of 100 Mbit/s and 10 links traversed, the time skew is 1.4 μs and the jitter 1.0 μs. The skew and jitter may be higher than indicated above depending on the implementation of the link-interface. A

time accuracy across a network of significantly better than 10 μs may be difficult to achieve, using the standard time-code mechanism.

5.10 Time-code Applications

5.10.1 Synchronisation

Time-codes sent periodically may be used to synchronise the operation of a SpaceWire network, separating time into discrete time-slots during which scheduled transactions take place.

5.10.2 Time Distribution

With the provision of this basic time distribution function, application level protocols can be used to distribute specific time values at full resolution (not just 6-bits) and to issue time dependent commands etc. The two control flags that are distributed with the 6-bit time code can be used to broadcast information to all nodes and routers on the network. However, these two control flags are reserved in the SpaceWire standard, so they should be both set to zero, to be compliant with the standard.

Nodes using the system time distribution function can either use the TICK_OUT signal as a periodic timing signal or use the value of the time-count as an indication of the least-significant 6-bits of system time.

5.10.3 Event Signalling Across A Point-To-Point Link

Time-codes can also be used to signal events or to pass a high-priority byte of information across a point-to-point link. The time-code is sent transparently in the middle of the packet currently being transmitted. There is no need to terminate the current packet or to wait for its transmission to complete before sending the time-code. This technique should not be used when there are routers in the SpaceWire network.

5.10.4 Multiple Time-codes

NASA Goddard Space Flight Centre used four independent time-code counters in their routers and interfaces to provide four independent sets of time-codes indicted by the four possible values of the two flags in the time-code character. The value of these two flags determined which of the four time-code counters was used to validate the time-code before it was forwarded.

This approach allowed four different time signals to be provided over the SpaceWire network.

5.10.5 Interrupt scheme

Professor Yuriy Sheynin of St Petersburg University of Aerospace Instrumentation (SUAI) devised a scheme for sending interrupts over SpaceWire using a time-code like mechanism. Using one of the reserved values of the time-codes it permitted 32 interrupt signals to be transferred over the SpaceWire network. This mechanism operates in parallel with the time-code mechanism.

6 SpaceWire Protocols

"SPACEWIRE PROTOCOLS" and other chapters will be added to the SpaceWire User's Guide.

Please check www.star-dundee.com for latest updates.

Here is a brief indication of what the SpaceWire Protocols chapter will contain.

6.1 Protocol Identifier

The protocol identification scheme enables many different protocols to operate concurrently over a SpaceWire network without them interfering with each other. Each protocol is given a unique identifier. Units receiving packets process and respond to them according to the protocol specified by the protocol identifier in the packet. If a packet arrives with a particular protocol identifier that is not supported by a node, then it is ignored.

The protocol identification scheme is specified in ECSS standard ECSS-E-ST-50-51C.

6.2 Remote Memory Access Protocol

The flexibility of SpaceWire means that it can be used in many different ways to solve an on-board communication need, e.g. configuring and controlling an instrument. To avoid unnecessary duplication of effort the SpaceWire Working Group [13] examined these common applications of SpaceWire and specified some additional protocols, enabling further standardisation of the on-board data-handing system. The SpaceWire

Remote Memory Access Protocol (RMAP) [14] [15], is a particularly successful example of one of these protocols that operate over SpaceWire.

RMAP provides a common mechanism for reading and writing to registers and memory in a remote device over a SpaceWire network. It can be used to configure devices, read housekeeping information, read data from an instrument or mass-memory, and write data into a mass-memory from an instrument. Together RMAP and SpaceWire provide a powerful combination for spacecraft instrument data-handling. A central payload processing computer is able to configure the instruments using RMAP. When data is available it can be read from the instrument using an RMAP read command. A uniform memory space can be provided for each instrument with pages for instrument data, configuration registers and housekeeping status registers, simplifying and standardising instrument control operations.

6.3 CCSDS Packet Transfer Protocol

The Consultative Committee for Space Data Systems (CCSDS) Packet Transfer Protocol (PTP) is designed to transfer CCSDS Space Packets from one SpaceWire device to another. It encapsulates a CCSDS Space Packet into a SpaceWire packet, transfers it from the unit initiating the data transfer to a target device across a SpaceWire network. At the target device the CCSDS Space Packet is extracted from the SpaceWire packet and passed to a target user application. This protocol does not provide any means for ensuring delivery of the packet nor is it responsible for the contents of the packet being a CCSDS Space Packet.

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