TCP/IP Router for Space Applications

Jim Joseph and Jennifer Lazbin
Spectrum Astro, Inc.
1440 N. Fiesta Blvd.
Gilbert, AZ 85233

Document # 0000 EF-R61504-000

Abstract- **Advanced science missions are acquiring and processing greater quantities of data from multiple instruments. Data rates from instruments are increasing. Custom interfaces have been developed in the past to address these needs. These interfaces require custom test equipment to verify their operation and add cost and time to spacecraft development schedules. Once the architecture is designed for a spacecraft, it is not easily reconfigured. These are issues that have been resolved in the terrestrial environment by the use of standard data protocols, standard communications interfaces, and the use of data networks. The router is a network device that allows the interface of devices with different data rates and different electrical standards as well as data flow reconfiguration to meet changing needs. Spectrum Astro was awarded a contract by the Earth Science Technology Office to study the requirements for a router qualified for space application and develop a board based on those requirements.**

This router development considers three network configurations: onboard the spacecraft, spacecraft to ground, and spacecraft to spacecraft possibly in a constellation. The requirements consider router protocols, an embedded versus an external routing processor, console port implementation, and appropriate protocols that interface to a router to perform router status and management. Because this is a study and not directed toward a specific mission, derived requirements are being established to guide the design of the router. The concepts are implemented and tested on an existing development board using Ethernet ports that Spectrum Astro developed to evaluate design issues for flight applications. After proving the concepts, Spectrum Astro will build an optimized version of the router and perform thermal and vibration testing to verify the design. This study is planned to close about September of 2005 at a Technology Readiness Level (TRL) of 6~7.

I. Introduction

There is growing interest in the space community in applying the use of open-standard protocols that are used for terrestrial network communications, both Local Area Network (LAN) and Wide Area Network (WAN), for spacecraft architectures. Use of open-standard protocols as opposed to custom protocols for interconnect and interfaces within communication architecture for spacecraft reduces the time to design, test, and integrate a spacecraft and reduces costs over the spacecraft life cycle.

Transport Control Protocol/Internet Protocol (TCP/IP) has long been in use for terrestrial communications. TCP/IP is the key protocol used for Internet communications. Interest in the use of TCP/IP (or IP, for short) for the links from the ground to space has been a concept of research and development for several years, but the idea of using TCP/IP onboard a spacecraft is a newer concept.

Spectrum Astro has developed devices for space that are implemented with open-standard network protocols. As part of the Space Network Devices (SND) Program for the National Aeronautics and Space Administration (NASA) Computing, Information, and Communications Technology (CICT) Program, Spectrum Astro developed two Ethernet devices for space. The hardware is a 10/100 Mbps Network Interface Controller (NIC) and 100 Mbps repeater-based hub interconnect board. These devices were designed for spaceflight from their inception. Spectrum Astro's core area of expertise is in spacecraft manufacturing, including the development of radiation-hardened, flight electronics. Typical mission requirements such as temperature, total dose and Single Event Effects (SEE) radiation, shock, and vibration were taken into consideration in the design of this spacecraft network hardware. The NIC is an enabling technology for support of onboard architectures that utilize TCP/IP.

Spectrum Astro is continuing the work initiated on the SND Program on the Space Network Router (SNR) Program, launched in January 2004, for the NASA Earth Science Technology Office (ESTO), Advanced Information Systems Technology (AIST) Program. As part of the SNR Program, Spectrum Astro is developing a single-board TCP/IP router for space. The SNR router is based on a development board built for the SND Program known as the Ethernet Multipurpose Board (EMB), shown in Fig. 1.

A router is a network device used to interconnect networks of disparate types. Different networks use various media and protocols, each with varying data rates. A router uses specific routing algorithms to determine the best route to send data through a set of interconnected networks. Routers also provide isolation between networks when faults occur to reduce the effects on the set of networks that are connected together. Specific network types of relevance for a single spacecraft include point-to-point links and LANs. WANs have utility for spacecraft constellations.

The SNR space router has four Ethernet interfaces that provide the ability to interconnect various networks that exist on a spacecraft and lays the foundation for seamless interconnectivity in spacecraft communications architectures among spacecraft in a constellation as well as between spacecraft and the ground.

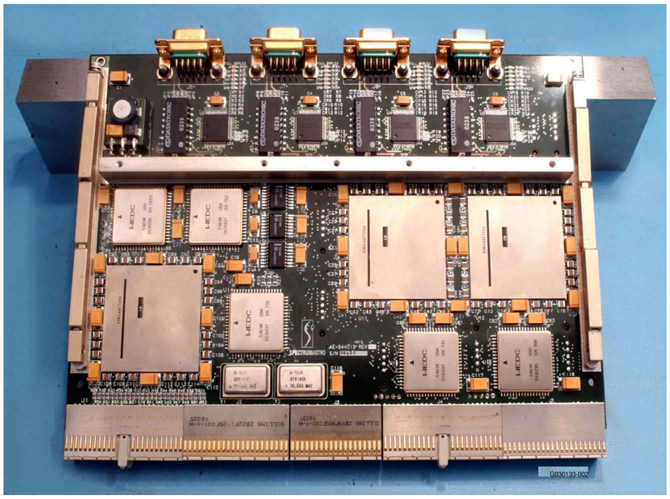

Fig. 1. Ethernet Multipurpose Board

II. WHY USE NETWORK PROTOCOLS IN SPACE?

There are several advantages to using open standards rather than custom implementations in a spacecraft communications architecture. Custom communications interfaces and interconnects require time to develop and extensive test time to verify operation. Significant reductions in cost and schedule can be realized with the utilization of open-standard protocols. Use of open standards facilitates rapid design and development efforts. Testing and integration schedules can be compressed. Plug and play operation with devices from multiple manufacturers is achievable when component interfaces are built to open-system standards.

The use of terrestrial network open standards for space communications architectures also has many advantages. Though rad-hard implementations of devices such as network controllers and routers for space differ internally from their Earth-based cousins, the black-box functionality can remain the same. A huge investment has already been made in the development and testing of hardware and software that is deployed in LANs and WANs all over the world. Protocols such as Ethernet and TCP/IP are well understood by many people. Commercial off the Shelf (COTS) products are readily available to test hardware implemented with these standards.

Use of network standards in space facilitates higher data rates than traditionally used in space. For example, data rates are bounded to 1 Mbps on MIL-STD-1553B busses and interfaces, whereas 10Base-T Institute of Electrical and Electronic Engineers (IEEE) 802.3 Ethernet supports 10 Mbps (20 Mbps in full-duplex mode) and 100Base-T Ethernet supports 100 Mbps (200 Mbps in full-duplex mode). LAN standards can provide a robust, fault-tolerant architecture that is ideal for spacecraft. Seamless interconnectivity between space and ground can be realized using terrestrial network standards such as TCP/IP.

The network standards were designed based on the International Standards Organization (ISO) Open System Interconnection (OSI) 7-Layer Model. In this model, specific functions are assigned to each layer. The advantage to using layered standards is that changing the standard used for one layer does not affect the function of other layers. For example, the IEEE 802.3 Ethernet LAN standard defines functions for Layer 1 (Physical Layer) and Layer 2 (Data Link Layer) of the OSI Model. TCP/IP is defined for Layer 3 (Network Layer) and Layer 4 (Transport Layer). LAN standards other than Ethernet can be used for Layers 1 and 2 while retaining the use of TCP/IP in the architecture.

III. NETWORK-CENTRIC SPACE COMMUNICATIONS ARCHITECTURES

Space communications is comprised of three broad areas. Most mission architectures are a hybrid mix of each of these classes. The first architecture class area is the simplest: communication strictly onboard the spacecraft. The second architecture class area is communication between the spacecraft and the ground. The ground can include the Internet or simply the ground station. The third architecture class area is communication among spacecraft in a constellation. Each class has different requirements. For example, security levels required for each class are different. A more secure network is required in a constellation than would be in a network that is isolated onboard a spacecraft.

Typical spacecraft have many duties they must execute. Some duties are directly correlated to performing their intended functions, while others are required to maintain their ability to function properly. For example, there are payloads and instruments that collect data. The spacecraft must perform the functions of navigating through space and monitoring its condition. The spacecraft must respond to commands that are sent to it and send data regarding the state of the spacecraft in addition to telemetry from the experiment or function that the spacecraft performs. All of this requires a communications architecture that can reliably move data from one point to another in real time. Most of today's spacecraft use a mix of standard protocols such as MIL-STD-1553B, RS-422, and Consultative Committee for Space Data System (CCSDS) as well as custom schemes to transfer data. However, few view onboard communications as a set of networks.

On a spacecraft, instruments and payloads must communicate with the spacecraft electronics bus. These devices are commanded from the ground or flight software resident in the electronics bus. Likewise, telemetry is sent from instruments and payloads to the bus potentially for processing and eventually to the ground for further processing and/or analysis. There may be multiple busses in the spacecraft architecture, such as a Command and Data Handling (C&DH) bus and a payload bus, or a primary bus and a redundant bus. Point-to-point links can be implemented to interconnect a payload or instrument to a bus.

Spacecraft busses can be implemented as LAN networks. This is the first class area architecture. In a large spacecraft, a router can be used to interconnect the busses. Use of a router provides flexibility in the spacecraft architecture, for the second and third class area architectures as well. The appropriate technology can be selected for each bus or link, while the router can provide interface ports that support each standard. This also provides scalability in the design, where various data rates can be implemented based on requirements for a given mission. Router interface ports can be developed for High-Level Data Link Control (HDLC), SpaceWire, FireWire, and MIL-STD-1553B to provide IP support over each of these protocols. HDLC is used for serial links such as crosslinks or uplink/downlinks.

Payloads can be interfaced to the bus with point-to-point links that use network protocols such as full-duplex Ethernet or HDLC for Layers 1 and 2. These LAN protocols enable the use of TCP/IP at Layers 3 and 4, with IP at Layer 3 and then TCP or User Datagram Protocol (UDP) at Layer 4. In this manner, the payload can have its own IP address that enables a Principal Investigator (PI) to access the experiment, with proper security implemented, from the office.

Flexible architecture implementations can also cross the various architecture class areas. For example, onboard communications could be performed with IP while link communications is performed with traditional space protocols. Alternatively, the space-ground link or crosslink to another spacecraft could use IP while the onboard communications could be based on traditional space protocols. In this architecture, the spacecraft is effectively an IP node on the network and thus integrated with the ground network with which it is connected. An architecture with fully-realized TCP/IP could utilize TCP/IP both on the spacecraft and on the links.

IV. Analysis Of LAN Protocols

During the SND Program, Spectrum Astro evaluated Ethernet, SpaceWire, and FireWire for use in space. Of these three LAN protocols, Ethernet has a long history of use with TCP/IP. After carefully considering each protocol, Spectrum Astro recommended development of devices for 10/100 Base-T Ethernet for the SND Program for several reasons, including: data rate support for most mission requirements in the near-term future and growth path to 1 Gbps data rate, support for cable lengths to 100 meters, transformer isolation at cable, existence of a standard for Ethernet across compact Peripheral Connect Interface (cPCI) backplane, its behavior is well understood, and test equipment is readily available. This recommendation is not meant to imply that Ethernet is the ideal solution to meet requirements for every mission. Which LAN protocol or protocols are best for a mission, depends highly on the mission requirements and objectives. In general, however, Ethernet seemed a more worthy candidate for development.

A standard is currently being developed for the use of TCP/IP over FireWire. FireWire was developed to access peripherals to a computer over a serial bus at data rates of 100 Mbps, 200 Mbps, and 400 Mbps. SpaceWire started with a protocol used for transputers and was adapted for space applications at data rates of 100 Mbps, 200 Mbps, and 400 Mbps. SpaceWire uses Low-Voltage Differential Signaling (LVDS) as the electrical interface whereas FireWire uses a modified form of LVDS that requires analog circuitry and Ethernet uses a multi-level signaling technique also requiring analog circuitry. These interfaces limit the length of a physical link for SpaceWire to 10 meters, FireWire to 4.5 meters and Ethernet to 100 meters. Within a spacecraft, this is not much of a restriction but within an integration and test bay, this has a significant impact. As far as use across a backplane, Ethernet is supported in standards for data rates of 10 Mbps, 100 Mbps, and 1000 Mbps while FireWire is supported only at rates of 50 Mbps or less and no standard exists for SpaceWire across a backplane. Backplane implementation has significant utility for space where transitional architectures are likely to include heritage bus standards such as cPCI.

Transformer coupling has benefits with regards to Electro-Static Discharge (ESD) and System Generated Electromagnetic Pulse (SGEMP). In the IEEE 802.3 Ethernet standard, the transformer isolation is located between the cable and the electronics on the board. In FireWire, either transformer or capacitor isolation is provided between the analog and digital portions of the Physical Layer interface but for the purpose of Direct Current (DC) isolation and not for ESD or SGEMP. SpaceWire has no isolation at all. An alternative to transformer isolation is fiber optic coupling. This is available for Ethernet and not for FireWire. SpaceWire could be implemented with fiber optics but no standard exists at this time. Other space programs are using SpaceWire and FireWire.

MIL-STD-1553B is a master-slave architecture. For this reason, it does not map well to a client-server type model. It is not impossible to run a protocol such as TCP/IP over master-slave architecture, although it is not straightforward. Packet sizes are limited and slaves require constant polling to determine when they are waiting for service. MIL-STD-1553B requires an acknowledgment from the slave within microseconds of the end of a transmission by the master so it is only useful within the bounds of the spacecraft and requires careful consideration to how responses to IP packets will be processed.

V. Analysis Of Routing Protocols

Routing protocols are used by routers to route data packets from source nodes to destination nodes. They function at Layer 3, the Network Layer. Fundamentally, their objective is to build and maintain a table of router port addresses that can be used to reach specific networks. Routing tables also contain information about various paths. Routing protocols are based on algorithms that determine optimal routing paths by using one or more metrics. Several different routing algorithms exist for IP. Routers communicate with other routers to update and maintain their routing tables. In this way, the routers establish a database of the network topology. Routers can share their routing tables with other routers or send messages to other routers regarding the state of the sender's links, known as Link-State Advertisement (LSA).

Routing algorithms are designed to achieve several goals including selecting the best route based on the metrics and weights assigned to those metrics, efficiency with low software and hardware utilization, rapid convergence, robustness and stability, and flexibility. Routing algorithms must converge quickly. When a network event occurs, routers must quickly distribute updated routing information to all of the routers on the network and then quickly recalculate optimal routes. A routing algorithm must perform correctly when unusual events occur, such as hardware failures, high traffic loads, or incorrect implementations.

Many dynamic routing protocols exist within the Internet Request For Comments (RFC) standards. Commercial routers typically route via dynamic routing protocols or static routes. The following are dynamic IP routing protocols: Open Shortest Path First (OSPF), Routing Information Protocol (RIP), Exterior Gateway Protocol (EGP), and Border Gateway Protocol (BGP).

Each routing protocol uses a different algorithm to make routing decisions. OSPF is a link state, interior gateway protocol. RIP is a distance-vector protocol, and BGP is a distance-vector protocol used to interconnect autonomous systems. RIP uses hop count as a metric. A custom algorithm such as a predictive one that uses a priori knowledge about link status can also be utilized. The combination of OSPF with a custom algorithm that takes into account scheduled link makes and breaks is very powerful for space applications.

VI. Use Of Routers In Space

Typically, the interface chosen for a particular device onboard a spacecraft has depended on the application and the development of instruments takes place long before the design of a spacecraft architecture is considered. As missions tend to use many different interfaces within the same spacecraft, the router becomes an ideal component to interface multiple networks of different types onboard the spacecraft. How routers are implemented on a particular mission depends on the mission requirements.

The space router should support communication with other nodes in the network using one or both protocols implemented at the Transport Layer (Layer 4), including connection-oriented TCP and connectionless UDP.

Space networks differ from ground networks in that many entities typically share use of a ground network. In the case of the Internet, for example, a particular user has little control over how packets from his message are routed to their destination. Links between routers on the ground usually fail due to congestion and not errors. The algorithms used to detect faults are based on congestion and dealing with congestion issues. In space, links are usually controlled by a single entity. Links in space fail due to poor signal quality and thus errors on the link. Algorithms designed to handle errors are thus more optimal for space links. The Layer 4 algorithms used for links must be selected based on the expected nature of the link.

Security is important, especially when routers are used. Spectrum Astro is looking at standards for security, including Internet Protocol Security (IPsec) and High Assurance IP Equipment (HAIPE) encryption. Different applications have different needs for encryption depending on where the data is to be delivered and for what purpose. Routers often require some level of decryption to enable them to determine the destination for these datagrams. Authentication is the process of verifying that the source of a communication is the legitimate sender they claim to be. If the network is closed on the spacecraft, this is not a problem. When the network extends beyond the bounds of the spacecraft, this is important. Authentication can occur at different levels of the network stack also. For example, the link over which the communications is taking place may be an authenticated link but the datagrams may require authentication to verify that they came from a recognized sender before they arrived at the link.

A requirement of many space missions is redundancy of critical subsystems. In many cases, this requires the backup component to be operating in the fully functional mode that the online component is while staying in the background. Several design approaches are possible. At the Physical Layer, the electrical interface can be made redundant as is commonly implemented with MIL-STD-1553B. If the Physical and Data Link Layer are taken together, then redundancy can be implemented similar to redundant transponders for space-to-ground links. The next level of redundancy is making the entire router redundant similar to block redundancy that is often used for the C&DH subsystem of a spacecraft. Some of these approaches require that parameters be passed between the online component and the backup such that the backup component is able to maintain its parameter tables to match the online component.

OSPF, described earlier, has a facility to allow two routers to determine which is the designated router and which is the backup designated router using the Hello protocol. If the designated router becomes disconnected, the backup router assumes the routing duties. This supports the concept of two fully functional routers operating in hot standby and without the need for a separate device to determine which router should be online.

Important for space routers is network management. Network management is the idea that elements of the network such as routers can be managed, typically from a network control center or ground station. In the trade studies for the SNR Program, we looked at approaches for implementing out-of-band management using the router console port. We also looked at in-band management implementation. These concepts as applied to space vary greatly from their ground cousins.

Terrestrial routers are assumed to be mostly up and forward data within a reasonable amount of time from when the data arrives at the router. This is not so in space. Routers can only forward data to links that are up. Links to the ground or other spacecraft may exist for only finite amounts of time, such as during a pass over a particular ground station. Therefore, onboard data storage becomes important. Data is queued in storage for downlink to the ground station when the ground station link becomes available. Data storage can be implemented as a network file server. Instruments store data on the network file server until ground links become active. The ground station is then able to access the network file server independent of the instruments and the spacecraft handles issues associated with link delays and retransmission of dropped packets.