

Implications of Internet Protocol on LEO Micro-Satellite Communication Links

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ABSTRACT: Internet Protocol (IP) enables a session-based communication paradigm that is transaction-oriented rather than data stream-centric. This is a paradigm that is prevalent in ground systems (and arguably a significant factor in the success of the Internet), but is uncommon in space systems – even ones that have used IP. IP allows multiple, simultaneous, independent sessions over the same channel. This allows software that uses the space link to be written in a more modular and easily testable manner. It also allows commercial IP-based technology to be used independently of the application-specific software. For instance, a telnet session to the spacecraft could be active while an FTP transfer is taking place and at the same time the spacecraft health telemetry is being sent via UDP packets – all working independently of each other although sharing the same communication channel. This paper discusses the implications of the IP session-based communication paradigm on spacecraft system design, software design, implementation, and testing, and operations.

INTRODUCTION

Internet Protocol (IP) on space links has been proposed on many missions and even flown on several missions, such as SpaceDev's CHIPSat [1], Uo-Sat12 [2], and CANDOS. There has been debate about whether IP should be provided as a layer of Consultative Committee for Space Data Systems (CCSDS) [3] or more simply on top of High-level Data Link Control (HDLC) [4]. There has been much debate about the issues of the suitability of Transmission Control Protocol (TCP) over space links due to the inherent assumption in TCP that a packet loss is due to a collision and not a lossy medium [5]. However, there has been little discussion about how IP changes the paradigm of spacecraft communications. Traditional space links are data stream oriented. There is typically a dedicated uplink stream and one or more separate downlink streams. A downlink stream contains rigidly-defined telemetry frames and subframes with values assigned to slots in each subframe. The response (if any) to a command in the uplink stream is inserted somewhere in a telemetry frame. All messages must be coordinated into a consolidated frame structure. Hence, there is a high level of interdependence between software modules and therefore a higher associated cost in development and testing.

This paper discusses traditional space data link methods and the motivation that emerges for using IP-based space links. The benefits of IP on the link

are discussed and some of the significant impacts on operations are identified.

TRADITIONAL SPACE DATA LINKS

Time Division Multiplex (TDM)

The historical roots of telemetry arise from a technique in which a spacecraft's onboard computer samples one measurement at a time and transmits it as a time-ordered sequence of values (see Figure 1). On Earth, the samples are demultiplexed, that is, assigned back to the measurements which they represent. In order to maintain synchronization between multiplexing and demultiplexing the spacecraft introduces a known binary pattern at the beginning of every round of sampling (telemetry frame), which can be searched for by the ground data system. Once recognized, it is used as a starting point, and the measurements can be demultiplexed since the order of multiplexing is known.

One form of TDM is Pulse Amplitude Modulation (PAM). Early telemetry systems transmitted analog voltages using a commutator (rotary switch) at one end and a synchronized decommutator at the other end. We still use the words *commutator* and *decommutator* though most telemetry systems today use electronic switches and send digital data. PAM is sensitive to noise and frames cannot easily be reconfigured. Therefore, PAM is not in wide use today, although as we will show, much of current spacecraft data link operations are still designed as though PAM was being used.

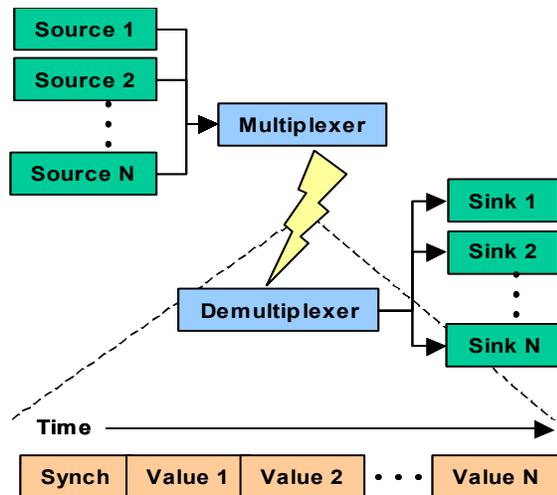


Figure 1: Time Division Multiplex.

A more modern TDM approach is Pulse Code Modulation (PCM). The PCM output is arranged into a digital data structure consisting of one or more frames. Each frame starts with a synchronization pattern followed by the data channel words. The synchronization pattern enables the PCM decoder to locate the beginning of each frame. When there are many data channels, the PCM output is structured into a Major Frame comprising two or more Minor Frames. Complex frame formats (Class II) may use several different formats indicated by a frame format identification word. IRIG Standard 106-96 is the primary PCM telemetry standard used throughout the world by both government and industry. IRIG covers all aspects of PCM telemetry, including transmitters, receivers, and tape recorders. Where PAM is analog, PCM is digital and relatively insensitive to noise. Therefore, PCM is very common today in a wide variety of applications such as phones and space communication.

TDM requires a high level of coordination to put measurement values into frames. For simple missions, this may not be an issue. But for a complex mission, thousands of data channels from a wide variety of sources must be handled, and each source may have a separate group of engineers responsible for it. These groups might be working at locations spread around the world. Therefore, the groups must rely on a central authority for coordination and changes to frame structures. This necessarily places limits on the flexibility and agility of the development efforts. It also increases cost due to the increased time in dealing with changing requirements. TDM is now being replaced by a newer method known as packetizing.

PACKETIZED SPACE LINKS

In packetizing, a burst or “packet” of data is transmitted from one onboard instrument or sensor, followed by a packet from another device, and so on, in a non-specific order. Each burst carries an identification of the measurement it represents so that the ground data system can recognize it and handle it appropriately. The scheme adheres to the International Standards Organization (ISO)’s Open Systems Interconnection (OSI) protocol suite that recommends how different types of computers can intercommunicate. Being independent of distance, the ISO OSI holds equally for spacecraft light-hours away as it does for local workstations.

In general, a packetized data link adds a layer of abstraction on top of the lower-level framing that is required for the physical channel. The frames are defined to be typically fixed-length portions of the packets. A packet is a variable-length logical grouping of bytes that correspond to a one-way message transaction. The frame contains the synch pattern (and possibly any error checking information) as with TDM, but the data payload is “opaque” in that the frame processing hardware and software do not need to parse the contents in order to perform their work.

Packetizing allows multiple, independent, simultaneous message transactions to be performed over the same physical data channel as though there were more than one “virtual” data channels. This allows separate groups to independently develop message packet protocols without requiring significant centralized coordination (other than perhaps assigning virtual channel numbers if needed). Software development costs are thus reduced and the development groups can respond quickly to requirement changes. It also reduces the cost of the communications hardware because if multiple simultaneous channels are needed with TDM, then the designer is forced into adding more physical channels. In fact, many spacecraft have multiple radio data channels. With packet switching, the choice to use multiple physical channels can be made based on bandwidth requirements and frequency allocation rather than the content of messages going over them.

Another significant feature of packetized space links is that the data pathways between the ground and spacecraft can be packet-switched as opposed to circuit-switched. In packet-switching, each packet is routed independently – even if it is part of a larger

message. This allows multiple nodes on the network to efficiently share a common data link. Circuit-switching establishes dedicated data pathways between nodes on the network. Bandwidth is optimized at the cost of decreased flexibility. Coordination is needed in order to switch the circuit to form a different network, increasing the costs for servicing multiple missions with the same equipment. The Air Force Satellite Control Network (AFSCN) is an example of such architecture.

There are many packetizing approaches for terrestrial systems, but only two are discussed here for space links: the Consultative Committee for Space Data Systems (CCSDS) and Internet Protocol (IP).

CCSDS

The CCSDS is a multi-space agency group, with members from North America, Europe, Japan, and elsewhere around the world. This committee was established in the early 1980s to assist in standardizing the space/ground links of the various agencies to increase the interoperability of their spacecraft and communications systems. CCSDS has established recommendations for telemetry, telemetry coding, commanding, time codes, data formatting, and radio frequency and modulation. The telemetry and telecommand recommendations are the ones that most directly impact the development and operation of flight systems.

The telecommand recommendations define the formats, coding, and protocol for commanding a spacecraft. The protocol and coding assures a high probability that only correct, in-sequence commands are accepted by the spacecraft. The protocol provides an efficient mechanism for uplink to on-orbit spacecraft, where the communications latency is within a few seconds. The command protocol depends on a Command Link Control Word in the telemetry data to handle the acknowledgments.

There are two telemetry recommendations. The first, Packet Telemetry [6], was developed in the mid-1980s and features up to 8 virtual channels. The second, Advanced Orbiting Systems (AOS) [7], was developed in 1989 for potential application to missions such as Space Station. AOS telemetry accommodates a more diverse set of data types, including voice and video. A subset of the AOS Recommendation, the Path Service, is similar to Packet Telemetry except that it supports 64 virtual channels.

CCSDS telemetry has two primary data constructs: the telemetry packet and the transfer frame, for Packet Telemetry, or Virtual Channel Data Units (VCDU), for AOS. The telemetry packet is a logically connected set of parameters. Telemetry packets are carried by a stream of fixed-length transfer frames/VCDUs, which provide a means of frame synchronization and error correction encoding. Each transfer frame/VCDU has a virtual channel identifier associated with it. These identifiers allow the downlink to be treated as if it is composed of multiple virtual downlinks. Virtual channels are used to differentiate data types, for example, real-time data from recorded data and science data from engineering data.

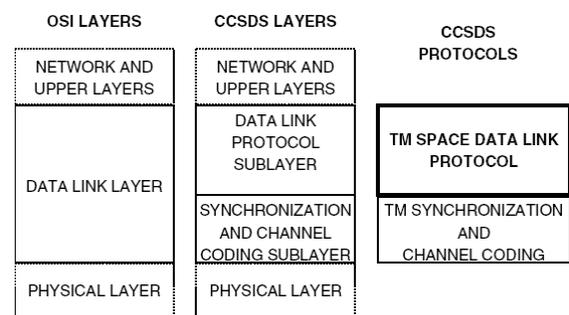


Figure 2: CCSDS layering mapped to the OSI model.

In Time Division Multiplex (TDM) systems, the Command and Data Handling (C&DH) synchronously collected telemetry from different sources. The format of the data was a set of minor frames organized into a major frame. Telemetry points from the entire spacecraft were assigned specific positions within the major frame. Each mnemonic format and location was assigned globally by the data system engineer for TDM formatted telemetry. Modifications to the telemetry format were managed centrally and this was a very resource-intensive job, especially for projects in which subsystems and instruments were developed in geographically remote locations. In contrast, by using the CCSDS path service, each subsystem is simply allocated a telemetry rate budget. The telemetry is multiplexed at the packet level and the details of the packet contents are left to the respective subsystem engineer. Only the total bandwidth is managed centrally, to ensure that the sum of the data generated by the subsystems does not exceed the downlink data rate.

Internet Protocol (IP)

IP is of course the backbone of the Internet. It is a simple packet definition that contains a 20-byte header and the “payload” data. The header contains a 32-bit source address, a 32-bit destination, the packet length, a checksum, and packet routing information. IP fits into the OSI model at the networking layer. It is ambivalent about the content of the payload data it carries, and is also ambivalent about the physical layer on which it is carried. Therefore, IP can be implemented over a wide variety of mediums. The most popular is Ethernet, however, few physical layers are appropriate for space data links due to some of the unique characteristics such as world-wide frequency allocation and Doppler shifts.

IP can be implemented within CCSDS packets [2]. IP packets are mapped onto CCSDS data channels. One issue when forwarding IP packets is determining the correct data link layer address of the next IP hop. Many shared media subnetworks (e.g. Ethernet) define protocols that allow link endpoints to automatically determine data link addresses given an IP address, a process referred to as address resolution. Address resolution protocols generally rely on the existence of a link layer broadcast address. The resolver can then transmit a request to this broadcast address that is answered only by the resolvee. In the CCSDS protocols, the data link layer address is defined by the GSCID. There is currently no broadcast GSCID defined in CCSDS, so the utility of IP over CCSDS is limited.

Ironically, modern ground telemetry processing components typically convert CCSDS/TDM data streams into IP packets for transmission across ground networks. If IP was available all the way to the spacecraft, such conversion would not be necessary.

A far simpler approach compared to IP over CCSDS is IP over High-level Data Link Control (HDLC) or Frame Relay. Basic HDLC can be used when the space link is effectively a point-to-point connection (i.e. between a single ground station and a single satellite). If there are more than two endpoints, however, Frame Relay can be used, which adds simple networking capability to the HDLC data link protocol. In either case, the synchronous data link protocol readily interfaces to existing ground systems that expect a synchronous serial connection.

One of the immediate benefits of using IP is that there already exist many standardized services that

become available nearly “for free” [8]. These include:

- Internet Control Message Protocol (ICMP) provides several network management services such as “ping” to determine if a link is operational. ICMP can be used to measure satellite data link performance and diagnose failures.
- File Transfer Protocol (FTP) provides a convenient mechanism to reliably move data between locations. There are several variants of FTP that differ on such things as the underlying protocol used, the security measures used. As we will discuss later, FTP can be used to download telemetry files as well as upload software updates.
- Network Time Protocol (NTP) provides a mechanism to synchronize system clocks on a network. If a GPS clock is not available, a microsatellite system clock can be synchronized with the ground clock. This service was used on CHIPSat, which lacked a GPS-based system clock.
- Simple Mail Transfer Protocol (SMTP) provides a mechanism to send emails between nodes on a network. SMTP allows storing and forwarding of emails when a direct connection is not available. An intriguing concept for routine spacecraft monitoring is to have the spacecraft automatically send a daily status email to the ground operators. The email can contain the results of self-tests and a summary of any commands that were executed.
- Hyper-Text Transfer Protocol (HTTP) provides the mechanism for allowing web servers to communicate with web browsers over the network. The spacecraft can run a web server to supply status and telemetry information to a browser on the ground. The spacecraft could also communicate with ground web servers to retrieve information it needs.
- Internet security is a service that is constantly improving. There are many levels of encryption, ranging from simple “soft” methods to “hard” routable methods like Highly Assured Internet Protocol Encryption (HAIPE) and non-routable

methods that encrypt the entire IP packet (including the header).

Satellite operations can be improved by taking full advantage of standard IP services. One could implement PCM frames in a UDP IP packet and provide the same functionality as a legacy system. However, this does not leverage the full potential of IP. Instead, telemetry can be broken into separate UDP packets based on logical groupings. For instance, the telemetry from a given device can be put into a separate packet structure rather than trying to consolidate everything into a few UDP structures. But even more significant is that telemetry can be stored in log files on-board and later downloaded via FTP. Traditionally, spacecraft have not had sufficient on-board storage but modern systems can have gigabytes of solid-state persistent storage. This fact combined with the observation that Low Earth Orbit (LEO) satellites rarely have continual communication coverage with the ground motivates us to store and retrieve telemetry rather than send all of it all the time. In addition, we can use standard file compression utilities to drastically reduce the amount of bandwidth needed on the downlink. There is still the need to send best-effort (UDP) telemetry, but now it can be a much reduced set of critical health and status information that lets the ground operators know the satellite is functional.

FTP can also be used for software updates. Rather than a command that replaces memory locations on the flight computer, the ground uses FTP to upload a compressed file containing the patch. The file is uncompressed and verified on-board before applying it.

For commanding, there are two primary methods available with IP: User Datagram Protocol (UDP and Transmission Control Protocol (TCP). UDP should be used for emergency commands in case the downlink is non-functional. In normal operation, we want to use TCP so that we can get reliable, confirmed delivery of a command. The command response can then be sent back immediately on the same socket rather than placing the response in the telemetry. This follows a more modular, encapsulated approach that reduces the complexity of the command software (on the ground and on the spacecraft). Development is simpler because each command can be tested independently without requiring telemetry processing.

Because IP is a routable protocol, it provides a powerful method to communicate with payloads.

Rather than have the spacecraft bus be aware of the contents of the payload messages, the bus is merely a router that forwards payload messages between the payload and the ground. This decouples the software development of the bus from the development of the payload, a key feature of a modular system. A payload can be developed on the ground with an IP Ethernet connection and work on the spacecraft with no software changes.

IP does have its disadvantages. It introduces a small amount of overhead (20 bytes per packet). For this reason, it is not likely appropriate for severely bandwidth-limited systems. However, there are header compression techniques that can mitigate this [9].

CONCLUSIONS

Packetization over the space link provides significant benefits, regardless of whether it is implemented with IP or CCSDS. However, IP allows using the wealth of lower-cost commercially-available equipment and standard interfaces between ground systems spread across the globe via the Internet. IP also has the advantage of many more “virtual” data channels than CCSDS, along with standard services defined for some of those channels (such as ICMP, SMTP, FTP, SSH, etc.). A few spacecraft have used IP, all successfully. More microsatellites are currently being designed to use IP. For instance, SpaceDev is developing microsatellites for the Missile Defense Agency that use encrypted IP over HDLC. The momentum is gaining for wide-spread use of IP on space links in the near future, promising significant reductions in spacecraft development and operation costs.

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