Internet Protocol (IP) as a Standard for Command and Control of Satellites

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ABSTRACT: Internet Protocol (IP) is gaining more and more attention as a means for achieving "net-centric" operations for satellite programs. The reason for this is the fact that the computer and Internet industries have defined and continue to improve a global network that the government, commercial, and private sectors rely on everyday for their business infrastructure and operations. It only makes sense to strive for an efficient means of integrating our routine and secure operations of satellites into this network. There is evidence of moving toward this strategy within NASA's Consultative Committee for Space Data Systems (CCSDS) and the DoD's Transformational Communications Architecture (TCA) and Satellite Control Network modernization programs. IP commanding and management of satellites dramatically increases the "sensor to shooter" capability in an operations network. Combined with other common Internet tools and applications, it also allows for rapid development of a single system's software development, operating system, data routing, and displays. With IP, a "standard" for data communications is already defined; it is the implementation of this standard from earth to space that is the challenge. This paper will focus on how IP might be implemented as a standard for satellite operations. It will consider lessons learned from recent IP satellite demonstrations, the impact of the typical satellite operator and user needs, and the physical limitations of a strict implementation of the network and transport layers used with the terrestrial Internet. The paper will address how IP is best utilized within communication architectures and how that gets transformed to an interface standard for mission operators. The small satellite industry is an ideal match for reaping the benefits of an initial implementation, and such an effort is currently underway with sponsorship of the California Space Authority (CSA). The end result will be a demonstration of a prototype IP network management center for command and control of a future satellite that meets the required interface standard.

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INTRODUCTION

Typically small satellites are challenged with one primary constraint, money. Size, weight, complexity, and risk all contribute to the cost of any spacecraft development. Communications systems on the spacecraft and on the ground are critical to all missions. No communications, no mission! The need for cost effective spacecraft communication is driving small and large satellite programs to implement readily available protocols that can be used from end-to-end in the life cycle of mission development and operations.

The use of IP reduces mission cost and risk by reducing engineering of specialized interfaces, configurations, and testing. IP is used daily by billions of people. A sensor tested in a university lab using IP as its method of communication has little risk of not being able to communicate with a spacecraft bus if is also using IP. Risk reduction means less required testing and less overall cost to the mission.

IP as a standard for space communications is a logical choice for cost-constrained missions or missions desiring responsive development and operations. Using TCP/IP as a standard for satellite communications would bring the ability to have office-like connectivity in even the most remote part of the Earth. This paper will address two aspects of IP as a standard for satellite command and control: the RF link and the Ground Segment. It should be noted that use of IP on-board a space system will not be specifically addressed here, but it has significant advantages communications, software development, software reuse, and high-performance commercial-off-the-shelf (COTS) component technology (including on-board routers).

IP ON THE SATELLITE RF LINK

Standards on Each Layer of the OSI Reference Model

Figure 1 defines the Open System Interconnection (OSI) reference model for the case of TCP/IP.

"TCP/IP" is the common term to define the category of data/network services used in Internet technology.

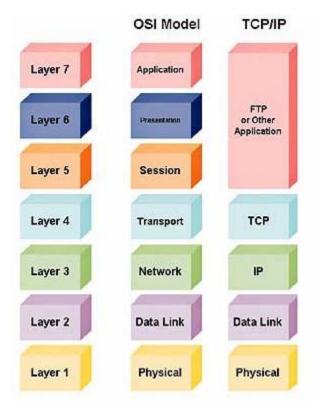


Figure 1 - TCP/IP & The OSM Reference Model

For link services, we define Layer 1 as RF. The RF layer in standard wireless networks like the ones utilized by common land-based routers is defined by the 802.11 wireless specification. For a space link, we cannot use 802.11 in its various COTS implementations for several reasons including non-support of bandwidth asymmetric links. limitations regulations, and poor bit-error-rate (BER). It would also typically require power amplification. International Telecommunication Union (ITU) provides us with boundaries on frequencies and bandwidths for space communications to primarily prevent interference with other RF sources. As a result, we have developed standards, methods, and equipment to optimize communication links over specific ranges of frequency bands from VHF to X-Band.

At the data link layer, the most common protocol for RF communications is High-Level Data Link Control (HDLC). HDLC is widely used, and it forms the basis for other data link control protocols that use similar formats and mechanisms used in HDLC. The data link layer is responsible for transmit and receive functions over the network. It provides the frame insertion and

extraction to the physical layer, and it includes an error detection function.

From there, the network through the application layer is protocols with which we are quite familiar. The IP network layer provides automated management of routing tables; it is implemented in routers and end-system operating systems. The network layer is the key to the success of the Internet; it provides a standard, fixed–format protocol header, which is the key to global interoperability. It is analogous to the postal service in that it provides a source and destination address for data transport. If the IP header is not followed exactly, communicating across the Internet is impossible.

Transmission Control Protocol (TCP) and less commonly in terrestrial networks, Universal Datagram Protocol (UDP), are transport protocols that provide virtual point-to-point connection. TCP is a connectionoriented protocol that provides reliable data delivery via a tight feedback loop between the receiver and transmitter. UDP is a connectionless protocol where there is no feedback mechanism from receiver to transmitter. It works on unidirectional links but the data may be received in error. Because there is no feedback path with UDP, data is unaffected by propagation delay and can be transmitted much more quickly. If reliable data delivery is required with UDP, the user has to create a function (in software) to provide a feedback loop. There is no widely used UDP-based application for ensuring reliable data delivery; however the Internet Engineering Task Force (IETF) Reliable Multicast Transport (RMT) working group is establishing a NACK-Oriented Reliable Multicast (NORM) protocol for reliable transport with congestion control¹. Current missions that experimenting with or using IP communications have established their own UDP-based data delivery assurance methods.

Last, the application layer includes IP services such as FTP, ping, TELNET, store and forward delivery, time synchronization, etc. The important point is that applications used or created in any IP network on the ground can typically be utilized to operate a vehicle in space.

Advantages to Using IP as a Standard for Satellite Communication

One of the main advantages to using IP for satellite communications is that the systems on a spacecraft will each act as an IP node on a local area network. While each subsystem will be IP-based, only the relevant networking software modules will be used to conserve code space and optimize performance. For instance, it

is anticipated that all subsystems will support at least Internet Control Message Protocol (ICMP) and UDP. Some will probably support FTP for large data transfers and some will support TELNET for direct control over the subsystem. These features translate into the ability to do routing, firewall and secure protocols on the RF (Radio Frequency) link. On a distributed system, the transceivers can even become communications subsystems that have full encoding, decoding, encryption and formatting code. The communications subsystem acts as a full router between the spacecraft LAN and the user network (Internet/SIPRNet). Figure 2 depicts a representative communications concept for a spacecraft LAN.

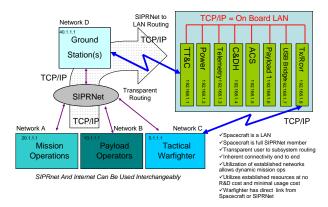


Figure 2 - Spacecraft LAN Communications Example

One of the key advantages of utilizing IP communications on a spacecraft is the proliferation of IP-based networks on the Earth. The most established commercial network, the Internet and its military equivalent, the SIPRNet, are both based on an IP backbone. By turning the spacecraft into a small LAN we will further enhance the integration of space assets into the resources available to spacecraft operators and ultimately, the end user. Extension of an IP network to the spacecraft LAN means that the ultimate "sensor-to-shooter" and "shooter-to-sensor" capability is truly realized by simply allocating the sensor (payload) an IP address on the spacecraft LAN. Not even a single line of code requires modification on the spacecraft.

Furthermore, since TCP/IP and Ethernet are both openly documented and supported by commercial vendors, spacecraft designers won't need to spend time understanding unique communication protocols for each periphery or subsystem. Also, since IP is so popular, almost every vendor has an IP stack built right into the BSP (Board Support Package) for the spacecraft designer to choose from. The real advantage here is that the purchased stacks are commercially proven by millions of users that have thousands hours

actually running the code. Communications hardware availability becomes much less of an issue as unique protocols such as SGLS, CCSDS, X-25, etc. are not required. Widely used and very affordable telemetry transmitters and receivers become potential options for the spacecraft designer.

A final advantage to using IP for satellite communications is that similar to all other vehicle systems, whenever open, tried, proven and evolving standards are used, a system is guaranteed to provide a reliable and expandable capability down the road. In the case of IP, this advantage extends well beyond a standard for aerospace vehicle design; it encompasses multiple industries, especially the computer industry, with orders of magnitude greater production. Straight implementation of the standard IP services and applications, however, does have its limitations over satellite RF links.

Disadvantages to Using IP as a Standard for Satellite Communication

TCP, and hence FTP, can be inefficient using satellite links due to latency created by long transmission path lengths and the noise associated with wireless links. TCP can be optimized for operation over satellite links to a certain degree; however, it does not consistently perform well under the full range of varying conditions that are expected to occur when the communications path comprises one or more airborne/satellite and/or terrestrial wireless segments. These conditions include error rates caused by channel noise (not simply network congestion), long propagation delays, and interrupted connectivity. TCP adapts to the available bandwidth of the network by increasing its window size as congestion decreases and reducing the window size as it increases. The speed of the adaptation is proportional to the latency, or the round trip time of the acknowledgment. For satellite communication with longer latency such as geo-based or deep space systems, bandwidth adaptation takes longer and, as a result, TCP congestion control is not as effective. TCP's congestion control algorithm works well in dealing with congestion-induced loss, but only results in reduced throughput on uncongested, noisy links without providing any benefits².

Another detriment to using IP on satellite comm. links is bandwidth overhead. Wired networks typically offer more bandwidth than wireless networks; this problem is exacerbated by the need to reduce power requirements on a satellite while making sure bit efficiency is maintained. We mentioned earlier that strict use of the IP header format was required to make communications across the Internet possible. There is substantial bit-overhead associated with the TCP protocol, especially

when using small segments to increase the probability of successfully transmitting a packet without incurring a bit-error. This overhead, at least 20 bytes of TCP header per packet, can consume a sizable share of a limited-bandwidth channel².

A final disadvantage of IP links worth mentioning especially for missions requiring high data downlink rates is that often the downlink bandwidth (from the spacecraft to the ground) is substantially larger than the uplink bandwidth, with ratios of 1000:1 not uncommon. This asymmetry is a result of various engineering tradeoffs (such as power, mass, and volume), as well as the fact that for scientific missions, most of the data originates at the satellite and flows to the ground. The return link is generally used for commanding the spacecraft, not bulk data transfer. TCP is relatively unhindered with link asymmetry at a 50:1 link ratio for 1KB packets; however, as the ratio increases (e.g., downlink rates required for bulk imagery or streaming video), throughput performance becomes limited by acknowledgment channel capacity.

Small Satellites and IP as a Communication Standard

IP is such a worldwide standard and along with its related applications in software and hardware, it offers small satellites a high-level of performance and an inherent ability to be extremely modular and evolve. But satellite communications pose challenges with which the global Internet solves much more easily through terrestrial networks or is simply not concerned. The space industry has and continues to invent methods and techniques to overcome these challenges. By simply considering how SGLS, STDN, and CCSDS have been utilized for the DoD and NASA, we realize the importance of space communication standards.

The problem is that the space industry does not have the market to promote rapid technology advancement and/or a plethora of component vendors. As a result, these standards create technology that becomes stale, non-COTS, and the costs are immense. The standards are adequate (performance, security, etc.), and we'll no doubt continue to need unique standards in our industry. The difference is that, especially in the small satellite forum, we have a clear recognition for affordability and responsiveness. To achieve that, we may have to sacrifice some of the traditional RF communication metrics. For example, the additional overhead on the IP packet header can be offset by allowing the use of software encryption methods.

Still, using the common protocols and services with IP on all data communication layers is likely not a general solution for reliable satellite communications. Some IP

applications, especially high throughput or highly interactive ones, do suffer from the inefficiencies of the current TCP standard over high-bandwidth long-latency links. The challenge is deriving a space communications standard that provides the advantages of commonality with a widely used data standard throughout the planet while providing decent gain and reliable link performance. Improvements can be made at the protocol level by extending the current TCP standard, although much work needs to be done on possible extensions to ensure that they do not negatively affect the Internet as a whole³. There are several organizations pushing forward in this arena including the DoD's Transformational Satellite (TSAT) and Transformational Communication Architecture (TCA) groups along with NASA's Lewis Research Center. It is paramount that those efforts stay abreast with those of the IETF, Institute of Electrical and Electronics Engineers (IEEE), and others to achieve commonality in the protocols, applications, and hardware at the core system level whether that system is a computer, automobile, satellite, or other.

For the near term, a concentrated effort should be made on using the strict implementation of TCP/IP protocols in order to maximize the return on COTS capability and availability including operating systems, drivers, utilities, and software applications. This direction is ideally suited for the small satellite community and the government agencies in search of greater access to space and responsive space. Several missions including NASA/UCB's CHIPSat, Surrey's Uo-SAT-12 and UK-DMC, and NASA GSFC's CANDOS have already shown that many popular IP applications perform to user expectation over a satellite link. The optimal implementation at the physical layer is where the satellite community should focus "standardization" efforts in order to achieve greater TCP/IP link performance and commonality in RF signal characteristics. To date, each mission designer has implemented different methods or systems for the TCP/IP RF layer. In an effort to determine the optimal implementation, Innoflight, Universal Space Network (USN), and Millennium-Space Systems are involved in an effort to establish efficient IP link operations in a seamless Internet-based user segment maintained by USN and their global network of ground antennas.

Thus far we have focused on the use of IP as a standard for satellite communications mostly centered on the RF link. The ground segment is of equal importance in achieving the benefits of IP communications and "netcentric" operations of space systems.

IP AT THE GROUND SEGMENT FOR SATELLITE OPERATIONS

Access Points for Spacecraft

Generally, satellite ground stations have fallen into three categories; single mission/customer, amateur systems, and high-end multi mission systems. Amateur systems have satisfied many in small missions with an ad-hoc global networks of low-rate VHF stations. The small missions have been evolving from low-rate student experiments into significant scientific opportunities. With this transition comes the need for higher bandwidths requiring the use of S/X/Ka bands. The one thing that has not changed is that budgets are decreasing. Reducing the cost of missions during Integration and Test and later though Operations is pushing an end-to-end use of Internet Protocols.

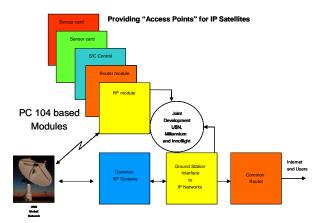


Figure 3 – High Level for Modular Spacecraft Development

Now we have to apply these standards to ground stations (Figure 3). High performance ground station networks provide missions with access to large aperture antennas that reduce spacecraft costs for power and weight of transmitters and spacecraft antennas. On the other hand, the large aperture on the ground provides missions with greater bandwidths for mission data. Whatever the trade, these ground stations need to communicate with the spacecraft just like the sensor in the university lab.

Development of Ground Station Architectures to Support the Throughput of IP

Universal Space Network (USN) has been on the leading edge of developing solutions for "IP in space." USN has supported the both NASA Glenn Research and the DOD in this development. As mentioned previously, USN has teamed with Millennium Space Systems, and Innoflight (with Cisco Systems as an

advisor) to further the development of end-to-end architectures needed to support IP to the spacecraft. This effort spawned from a California Space Authority (CSA) initiative is not an attempt to development new standards but to recommend a suite of standards that support IP from end-to-end. By following these design recommendations the spacecraft designer will avoid considerable design and testing effort that ultimately drives costs. In addition, USN is implementing "access points for satellites" at three of its stations around the world.

These "access points" are analogous to network access points in office buildings, on a university campus, or near urban centers. Users of conventional access points have wireless devices that adhere to a set of standards. With defined rules for access these users establish connections and transfer data without a thought of "How will my data be routed?" RF specifications are recommended that are compatible with high-end receive equipment at the stations. The building blocks for creating these "access points for satellites" are being developed today.

The technical hurdles associated with these access points involve the interfaces between RF systems and wide area networks (WAN), mismatch of spacecraft and WAN bandwidth, Data Management and Mobile IP.

IP Satellite Access System

The interfaces between current high-end station equipment and standard CISCO routers require enhancements to support a wide variety RF coding used to improve link quality. For instance, a CISCO router would not handle convolutional or Reed-Solomon coding. These codes provide gains of 5dB and 1.5 dB respectively which can be significant in small spacecraft communications links. In order to accommodate these current standards MSS and Innoflight have begun development of a system called IP Satellite Access System (IPSAS).

The IPSAS is a system that interfaces the ground station Radio Frequency (RF) equipment to the serial interface on the CISCO routers. The output of the demodulator is a baseband signal that has within it encoded data and timing information. The data must first be bit synchronized to reproduce clock (bit timing) information in order to further process and decode the data. Many types of decoding can then be applied to the data to gain many times effective signal to noise improvement. The IPSAS ground unit also handles temporary file archiving and file forwarding for partial file (Mobile IP protocols) reassembly at a central data

depository. The IPSAS unit finally does any needed electrical signal protocol conversion in order to interface the RF ground equipment into the CISCO router interface as well as functions in the forward direction as a command interface. See Figure 4 for notional interface of IPSAS unit.

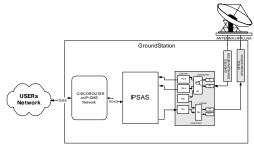


Figure 4 – IPSAS Interface At A Ground Station

Asynchronous Links

Typically the uplink and downlink to and from the spacecraft are at different rates. In addition the available bandwidth from the stations can vary causing bottlenecks for high-speed downlinks. Health and status data from the spacecraft is usually slow enough that a traditional IP socket connection supports the transfer back to the end user. In the case where the spacecraft downlink exceeds the terrestrial links, USN is using intermediate steps allow maximum use of the spacecraft downlink by initiating FTP from the station and transferring the data post-pass to the user.

Mobile IP

One of the problems associated with gathering data from orbiting satellites is access time and location. Mobile IP approaches continuous services as the host transitions from one access point to another. We are faced with outages that could last hours. Data recovered at multiple locations has to be reconstructed to the original file without the user involvement.

The notional baseline design uses CISCO routers at each Remote Ground Station (RGS) for IP Interface. RGS's become Mobile IP Access Points for the orbiting routing system. Each ground station will be configured as a "Foreign Agent" (FA) to the mobile, space based router. The space based router "Home Agent" (HA) is the Network Management Center (NMC). The router attaches to the FA and the HA is notified. All traffic to the Mobile Router is routed from the user through the HA at the NMC. The IPCMS network is firewall protected. The data paths are IPSec VPN between the NMC and each station. All users access the network by connecting to the NMC as shown in Figure 5.

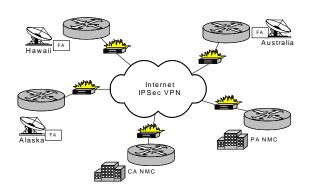


Figure 5 – Network Topology

Security Requirements

Data transfer will be on the open internet. Data protection across the internet is provided by 3DES IPSec LAN to LAN connectivity using Internet Key Exchange protocol. Cisco PIX firewalls at all sites allow only predefined traffic in order to protect USN Operations network. Internal addresses are masked by Network Address Translation.

Ideal LARGE Image Transfer – Multiple Ground Stations Proposed application

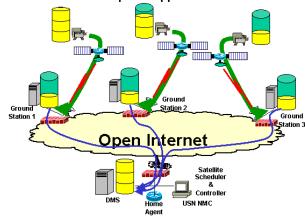


Figure 6 – Concept For Data Downloads At Multiple Stations Using Mobile IP

Data Management

The USN Data Management System (DMS) component in their ground system infrastructure is enhanced to provide post-pass data management functionality for the IP-to-Space FTP transactions to the spacecraft (Figure 6). Technologies relating to Mobile IP and segmented FTP transfers are being researched and prototyped. Standardized interfaces for distributing data files to the customers are also being researched. USN will publish an Operations Concept document as a part of the CSA initiative.

A new scheduling feature provides support for scheduled events that span multiple ground contacts at different ground site locations. The scheduling software engine assesses resource availability and allocates the proper RGS resources necessary to meet the transaction requirements. Scheduling standards such as the CCSDS Space Link Extension (SLE) are being studied for use in USN's IP scheduling Ops concepts. Scheduling software enhancements are added to determine access times and resolve resource availability on a multi-node network. Concepts to schedule events spanning multiple ground contracts are also being researched and prototyped. The customer scheduling interface provides an optimal, cost-efficient scheduling of USN resources. This provides flexibility for the customer to request transactions, such as an FTP download by providing an FTP schedule request that is automatically assigned the proper level of ground contacts.

Data downlinked during an RGS FTP session is transferred by the DMS to the central data repository at USN's Network Management Center (NMC). The DMS software includes modules required to process and manage large FTP transactions spanning multiple contacts at different ground sites. The NMC DMS software modules manage data processing for segmented FTP transactions providing a capability to generate a composite data set for a FTP session that spans multiple ground contacts. Centralized NMC DMS System Monitoring presents the NMC Controllers insight into the operational status of all DMS nodes.

CONCLUSION

IP is a widely accepted standard that can significantly enhance the small satellite industry's ability to design and operate affordable spacecraft and fill the space industry's current void for responsive space. Since the standard is already defined, the challenge for the satellite industry is to implement IP (HDLC, TCP, etc.) in its most common form with the exception of the physical layer where we can use optimal methods to extract the most performance on the RF signal. The signal is then received by access points on the ground and seamlessly connected to the end user for real-time command and control at any location via a worldwide Internet. A prototype implementation of this TCP/IP communications implementation will be demonstrated on a future small satellite by USN, MSS, and Innoflight with sponsorship from the California Space Authority (CSA).

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