TECHNICAL RESEARCH REPORT

Extending IP Services to Future Space Missions

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Extending IP Services to Future Space Missions

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Abstract

We outline the first steps of an effort to start defining the communication architecture for the next generation of space missions, that will support NASA's "faster, better, cheaper" concept and will enable new types of collaborative science, where investigators can access their data from space "anytime, anywhere" via direct communication with the instruments on the spacecraft. We discuss the building blocks for a conceptual design of a network architecture that could support and take advantage of IP-capable spacecraft. We show that access from a large number of ground stations (that could be directly connected to the existing Internet infrastructure) could increase spacecraft availability time by a significant factor. We discuss possible multiple access techniques that could enable the transition to an on demand operation, where spacecraft share space spectrum dynamically. We also discuss the particular requirements of a next generation of missions consisting of constellations of several small spacecraft and introduce a number of new complex network control, scheduling, routing, data management and communication problems that need to be addressed for this topology.

1 Introduction

We are beginning to witness a new era in space exploration, with the gradual deployment of the International Space Station (ISS) and an increasing number of scientific Earth observation or planetary missions. At the same time, advances in communications technologies could allow investigators on Earth to enjoy a virtual presence in space. In order to achieve all this however, there will be a need to provide high quality communications that will enable cost effective global access to experimental data from space missions. NASA is also interested to gradually facilitate IP services throughout its missions, eventually leading to a scenario where every spacecraft and instrument in NASA's network can have an IP address and an Internet connection. The first demonstrations of IP access to a spacecraft have been performed with the UoSAT-12 mission [1].

For these reasons we began an effort to start defining the communication architecture for the next generation of space missions. The objective is to support both NASA's "faster, better, cheaper" concept and to enable new types of collaborative science, where eventually investigators can access their data from space "anytime, anywhere" via direct communication with the instruments on the spacecraft. Extending Internet communication technology to space will also simplify design, reduce implementation cost, and make access more efficient.

In this paper we discuss the building blocks for a conceptual design of a network architecture that could support and take advantage of IP-capable spacecraft. We start by defining the long-term vision of NASA for the evolution of its space program that would provide an outline of the specific network topologies that need to be considered and the particular requirements in terms of traffic, Quality of Service guarantees and security concerns that need to be addressed.

2 On Demand Communications with Near Earth Missions

2.1 Trends in Internet Evolution

While the Internet currently serves millions of users, it is rapidly evolving to provide more services and integrate new technologies. The following potential evolutionary path and key trends might affect the directions of the study we are conducting:

- Quality of Service (QoS) with guaranteed rates of service for specific applications will become possible (DiffServ, Integrated Services).

- The service quality and security on the Internet could increase to the point where there is a major trend of both home and office users to use the Internet for their primary voice and other multimedia services.
- Supporting mobile users with anytime, anywhere connectivity and increased capacity at growing data rates is gradually becoming possible.
- New switching technology (MPLS) would generate improved performance and the Internet could get explicit rate flow control available end-to-end.

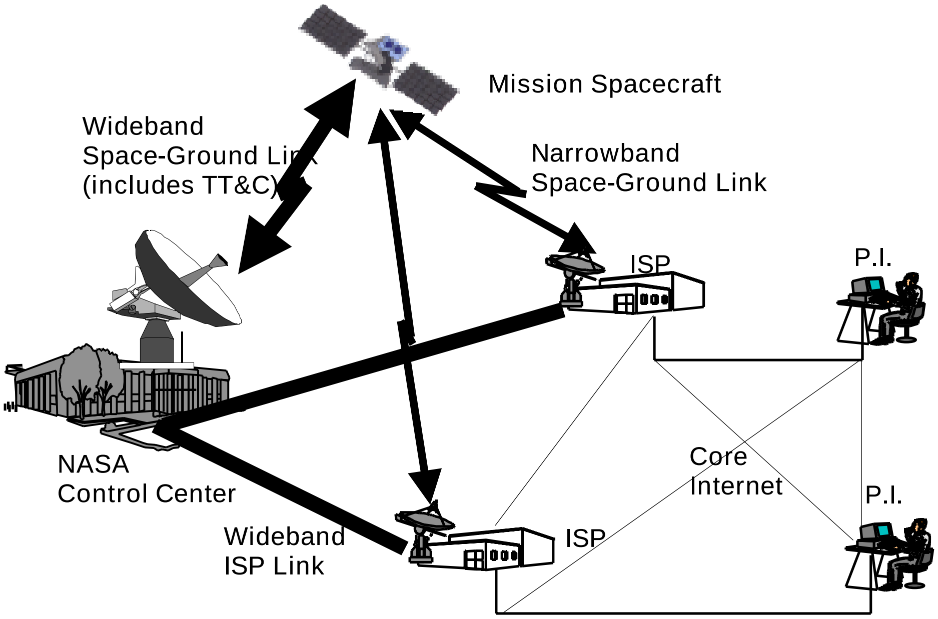

Figure 1. Scientists Access their Data from Space using the Internet

We assume that next generation IP-capable spacecraft would be equipped with one or more scientific instruments for specific tasks (e.g. cameras, atmospheric sensors etc.). These will have mainly one-way traffic demands (downlink of collected data) and occasional uplinks of commands or software updates. The instruments will have unique IP addresses, and would be inter-connected with an on-board Local Area Network. An IP router on-board could act as the access point to the flying network. We can therefore treat the spacecraft as a mobile platform, moving in a pre-determined orbit and accessing the NASA ground network or other Ground Stations with direct connections to the Internet.

We focus on two types of missions:

- Missions consisting of a single satellite in near Earth orbit.
- Missions consisting of a constellation of spacecraft, capable of communicating with other spacecraft in the constellation with inter-spacecraft links.

There are a number of research and technology issues that need to be addressed before this scenario becomes possible. Among the most important are issues related to:

- Supporting MobileIP
- Supporting security (IPsec)
- Tracking, coverage and antenna technology
- Multiple access techniques and network management that allow on-demand access to space data.

2.1.1 Pre-Planned and Dynamic Operations Concept

Starting from existing infrastructure it would be possible to gradually modify the ground and space components and move to an IP compliant pre-planned Operations Mode.

However, in order to take full advantage of IP flexibility that would support dynamic access, an On-Demand Operations Mode becomes necessary. As network size (number of spacecraft) grows the need for On-Demand Mode becomes even greater. Access from a large number of Ground Stations (that could be directly connected to existing Internet infrastructure) could increase spacecraft availability time, reduce time to download and accommodate more frequent downloads at lower data rates.

In the dynamic configuration we are studying, operation of future IP-Based mission support network becomes similar to terrestrial cellular network:

- Gateways act as Base Stations
- Spacecraft act as Mobile Platforms, registering with respective Gateways as they move in their orbit

Note that in most cases:

- Motion and approximate position can be predicted in advance:
- Active number of users (network size) is known and growth pre-determined (missions launched/decommissioned)

A scientist sending a command to the spacecraft via the Internet becomes similar to a user connected to fixed, terrestrial network sending a page to a mobile terrestrial user. Ground-to-space bandwidth is shared between all spacecraft (mobile users) based on suitable protocols/policies.

In the current "pre-planned" Mission Operations Concept:

- The scientist sends request for communications service to Space Network Control Center days to weeks ahead.
- The scientist receives schedule of allocated access times after completing conflict resolution.
- The scientist retrieves data from storage at allocated time (FTP).

The limitations and inefficiencies of this operation are obvious. Although fewer ground stations are required (since time of access is controlled) this operation supports controlled access rather than random access and only large data rates/high bandwidths can be efficiently supported. The distributed nature of the future space network however does not fit this scenario.

If a Dynamic Operations Concept could be implemented we could have a scenario where:

- The scientist accesses his instrument to set control parameters or retrieve data as desired. "Any Time, Any Where."
- If connectivity not available, network returns "subscriber not in service" message similar to terrestrial wireless services

In this, IP-compliant scenario, we could utilize Ground Access Points located throughout the world and even accommodate NASA antenna, RF, and baseband systems located on commercial geographically distributed ISP premises, through which the scientists can access their data via their workstations already connected to the core Internet via high speed terrestrial links. By augmenting existing NASA Ground Station locations with these large numbers of Ground Access Points more frequent and lower rate downloads can be accommodated improving access time and efficient use of the space spectrum. *Figure 1* shows the network topology we are considering here.

3 Comparison Results

For an example demonstrating this we model 4 typical LEO Earth Observation Scientific (EOS) missions:

- ***Landsat7***: Altitude: 705 km, 98.2 deg inclination (sun-synchronous orbit)
- ***Terra***: Altitude: 705 km, 98.2 deg inclination (sun-synchronous orbit)
- ***TRMM (Tropical Rainfall Measuring Mission)***: Altitude: 345 km, 35 deg inclination
- ***QuikScat***: Altitude: 800 km, 98.6 deg inclination

and the NASA Ground Network with:

1. 3 Main US NASA Ground Stations: AGS (Fairbanks), WPS (Wallops), LGS (Sioux Falls)
2. 23 additional International Ground Stations acting as global access points.

Figure 2 shows the projection of the trajectory of one of these missions (LandSat7) and the locations of the Ground Network access points.

Figure 2. LandSat 7 Trajectory and Ground Stations / Access Points.

Figure 3 shows the total access duration for EOS missions to US and International Ground Stations over a period of one day. Clearly, one can see that access from a large number of Ground Stations (that could be directly connected to existing Internet infrastructure) could increase spacecraft availability time by a significant factor.

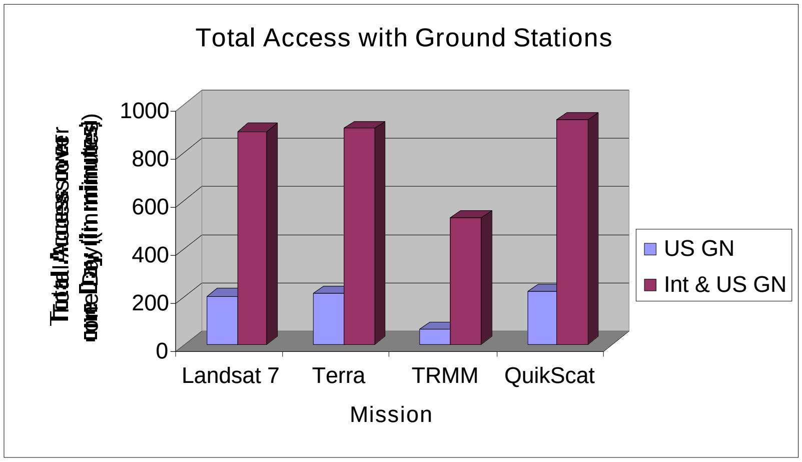

Figure 3. EOS Mission Total Access Time with Ground Stations in one Day.

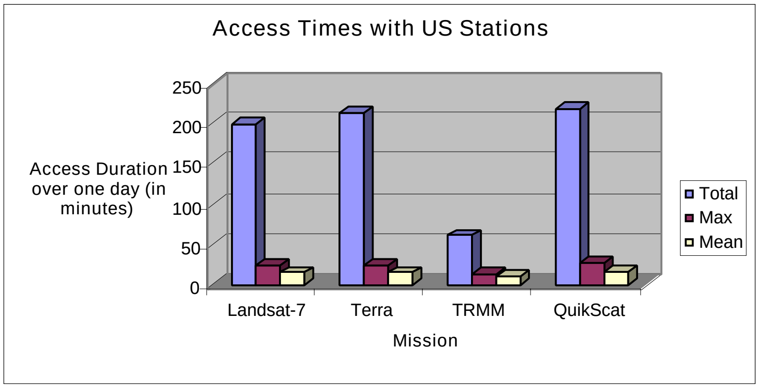

Figure 4. EOS Mission Min-Max Access Duration in one Day (3 Main GND Stations only)

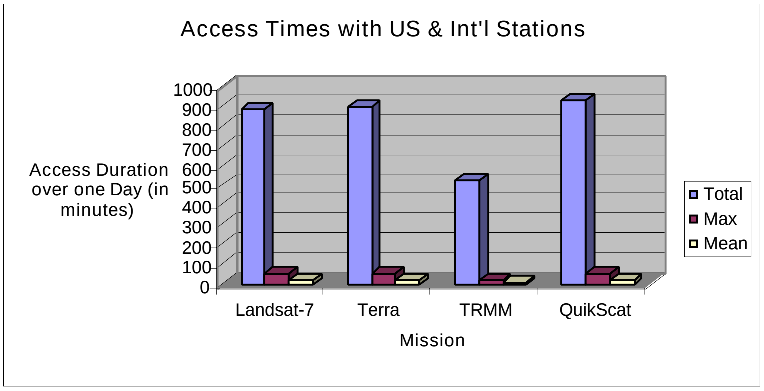

Figure 5. EOS Mission Min-Max Access Duration in one Day (3 Main GND Stations and 23 Global Ground Access Points)

Figure 4 also shows the maximum and mean access duration for the four missions we are considering for the case where we are using only the 3 NASA Ground Stations, while *Figure 5* shows the same results with the additional 23 Stations added to the network. Finally, *Figure 6* shows the impact of increased spacecraft contact time to the required bit rate for downloading data from orbiting spacecraft. Also note that since power and buffer size onboard the spacecraft are usually very limited, ability to download more frequently could influence the design and enable more reliable delivery of information to the ground.

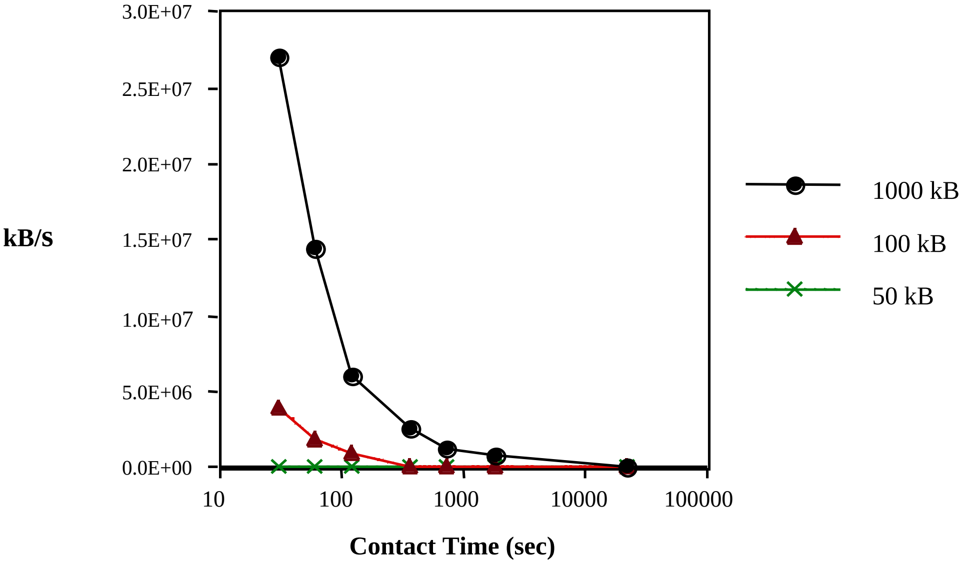

Figure 6. Impact of Required Bit Rate Vs Spacecraft Contact Time with Ground

4 Critical R&D Directions

4.1 Dynamic Multiple Access

For the paradigm shift that will enable the transition of operations from "pre-planned" to "on demand" mode, another key requirement would be the development of a new multiple access technique to support on demand space to ground communications, that takes into account the novel network topologies that need to be supported and introduces a new, unique Quality of Service requirement. Users (spacecraft) are visible by a ground station for a *limited time window*. Therefore, we have another dimension added to the traditional dynamic allocation problem: *dynamic allocation of capacity under a time constraint*.

We are trying to define a detailed scenario and evaluation criteria for suitable multiple access techniques for this operation, where:

- *A priori* bandwidth allocations still based on advance requests/scheduled passes over certain position.
- There is an option for dynamically assigned additional Bandwidth, either piggy-bagged to *a priori* reservation or available on demand as spacecraft enters coverage of ground station.

A suitable Multiple Access protocol must satisfy the following requirements:

- Provide required QoS/availability guarantees for different classes of traffic (TT&C, Scientific Data Req., other priorities)
- Support multiple spacecraft sharing common link to same Ground Station;
- Enable multiplexing of various traffic streams on-board for delivery to multiple destinations (multiple scientists);
- Accommodate several scientists sending commands/download requests to various instruments on-board the same spacecraft;
- Does not impose significant cost or complexity demands on hardware on-board the spacecraft
- Handle mobility of spacecraft ("mobile platform").

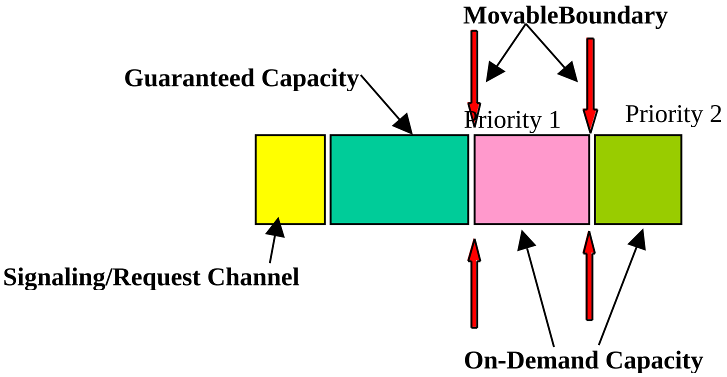

Figure 7. Dynamic Access Scheme - Movable Boundary Concept

A potential solution to the multiple access issues would be to implement a scheme utilizing a movable boundary concept (*Figure 7*), where transmission is organized in fixed size, slotted frames. The slots in the first part of the frame are dedicated for transmission of information on the user status, while the rest ***N*** slots are used for information transmission. Movable boundaries exist between the different types of service. The objective here is to optimize the boundary positions, for an optimal solution this could be done on a frame-by-frame basis [2].

4.2 Ground Network Modification Trade-offs

The NASA Ground Network needs to be modified in order to be able to support multiple missions on a demand basis. Particular questions that need to be addressed for this operation include:

- Automation for improved ground antenna scheduling/tracking:
- Use of Omni-directional antennas to listen for spacecraft downlink requests and to hail the spacecraft for uplink
- Use connected Directional High Rate antennas for Downloads/Uploads
- Must determine RF Hardware requirements for Both Antenna Systems and timing details for pointing and Tx/Rx functions.
- Temporary storage required at the Ground Station servers? (Storage size, hardware requirements, access speed, architecture options)
- Protocol interfaces required with the Ground Network/Internet.
- Need to support commercial protocols (ATM, TCP/IP, UDP/IP, html, XML, FTP)
- What are the required file structures for standardized data/command interfaces between the controller, the spacecraft, and the user?

5 Other Network Topologies

5.1 Constellation Missions

A new class of missions, consisting of large numbers of distributed, highly co-ordinated spacecraft performing a unified mission will play a major part in the new era of space exploration and earth observation. These new missions will introduce a number of new complex network control, scheduling, data management and communication problems that need to be studied in advance. We need to examine the operation of these issues that will also affect the dynamic access of the constellation to the ground under the framework discussed in the previous section. Enhanced capabilities will be required for inter-spacecraft communication and for space/ground communication.

5.1.1 Inter-Spacecraft Communication

Communication between constellation spacecraft is typically required to carry out the science mission. Information may need to be distributed throughout the constellation quickly and this presents unique communication requirements that are not present in missions consisting of a single spacecraft. Existing constellations of communication satellites often achieve their goal of transmitting data from one ground location to another via multiple space/ground hops (i.e. each spacecraft communicates with one single ground station with the ground station relaying information from one spacecraft to another, which then in turn relays it to another ground station), or may communicate among themselves serving as simple bent pipes. As such, they are not typically required to store data onboard, evaluate or perform scientific analysis on received data prior to re-transmitting it, communicate with more than one destination simultaneously, communicate with non-constellation spacecraft, initiate data transmission with data they originate themselves, or provide *reliable* transmission in the sense of guaranteeing the data is received successfully [e.g. via reliable transport protocols such as IP Transaction Control Protocol (TCP/IP), Spacecraft Communication Protocol Standards Transport Protocol (SCPS-TP), or Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP)].

Scientific constellations will often be required to perform additional activities:

- Determine and transmit updates to executable code
- Evaluate data to determine whether it is worth transmitting at all
- Evaluate and perhaps summarize or consolidate data received from other constellation spacecraft or non-constellation spacecraft
- Integrate data from multiple sources into a single repository of integrated science results
- Determine and attach related ancillary or metadata
- Disperse data rapidly throughout the entire constellation, requiring transmission to many destinations
- Record received data to ensure it is maintained until all intended recipients have received it
- Provide *reliable* transmission between constellation spacecraft and with the ground (i.e. guaranteed successful transmission)
- Generate automated onboard reports of data stored, received, or transmitted, including indication of which senders sent it and which recipients received it

In many cases communication between spacecraft within a constellation will be on a one-to-one basis, such as a mothership sending commands to individual members of its constellation, or constellation members providing science data, health and safety data, and science schedule execution status to a mothership. For constellations providing continuous line-of-sight between its members, such as in formation flying, inter-spacecraft communication is potentially available at all times, and requires only that all spacecraft within the constellation remain in active listening status for other constellation members [3].

5.1.2 Push-Pull Communications

In a manner similar to communications over the Internet, we could have communications on a *Push* or *Pull* basis.

For *push* basis communications, the following sequence of events takes place:

- The transmitter (spacecraft) sends data or commands
- The receiving spacecraft simply acknowledges receipt of the data.
- The sending spacecraft then ceases transmitting to the recipient, logs the data as successfully received by the recipient, and if necessary, deletes the transmitted data.

In cases of *pull* communication:

- A spacecraft such as a constellation leader, requests data from another constellation member.
- It then informs the sender when the data is received successfully, and instruct the sender to delete the data.

In cases where continuous line-of-sight between constellation members is not available, a spacecraft may attempt transmissions to another member through other constellation members within its line of sight. This requires knowledge (and updates) of position of all members with which the sender communicates, and processing capability for orbit propagation.

Another solution would be to establish a “hand-shake” first. A “blind” sending member may continually broadcast a request to transmit data, and begin transmission only after receiving acknowledgement from the intended recipient. This may be performed via omni antennas for which position of the recipient need not be known, or via steerable phased array or gimbaled antennas requiring less powerful transmitters but requiring knowledge of the recipient's relative (but not precise) position. This would be wasteful in terms of resources but requires less complicated positioning information and processing of updates.

5.1.3 Multicasting Capability

A common requirement in this type of mission would be for a constellation member to transmit the same information to multiple members of the constellation simultaneously. For example, a member detecting a science event will need to notify other constellation members so they may respond in unison. Such transmissions will presumably be via omni antennas encompassing the entire constellation within their field of view. In this case:

- A member broadcasts a command to all other constellation spacecraft
- The other spacecraft acknowledge reception of transmitted message
- Original sender continues sending until receiving acknowledgement from all intended recipients, or until a specified time-out is reached.
- Based on information from acknowledgements received enables co-ordination of scientific tasks between participating members.
- Information on members not acknowledging request may indicate which spacecraft have anomalous conditions requiring ground evaluation or for some reason are out of reach from transmitter.

5.1.4 Space/Ground Communication

In addition to typical space/ground communication capabilities used for non-constellation missions discussed in the previous Section, constellations with many spacecraft will pose unique communication requirements for simultaneous commanding of multiple spacecraft, and for monitoring the state of the constellation as a whole. Not only will multiple spacecraft be involved simultaneously, but ground control centers and other constellation users will need to communicate with them via multiple ground sites without keeping track of which spacecraft are visible to which ground sites at all times.

5.1.5 Mobile IP

One method for providing communication via multiple ground sites is using mobile IP, for which each constellation spacecraft is assigned an IP address. As it moves from one ground site to another it "registers" itself with whichever ground site is listening, so the ground system knows at all times which ground site can communicate with it.

It would be important to address the mobility issue at both the link level and network level. The link level provides the connectivity between the mobile platform and the access point in the terrestrial infrastructure and includes the algorithms for handoff between adjacent access points. Operating at the next higher protocol layer, the network layer encompasses the addressing information and routing algorithms to provide connectivity between the current access point and the receiving scientist host site on the terrestrial network. However, the initial Mobile IP concept that routed all traffic through a home agent may be very inefficient for satellite platforms. Therefore, ongoing IETF work in Mobile IP is the primary area to build on in this area [4].

5.1.6 Mobile Routing

Carrying mobile IP a step further, the onboard router in each spacecraft registers itself with whichever ground site is listening. In this case the onboard router is the registering agent with the ground, rather than an individual spacecraft or instrument as in mobile IP, so the individual instruments do not themselves require mobile IP software.

Instruments transmit to an IP address corresponding to a science user as if the user were on the onboard network, and the onboard router then passes the data on to whichever ground site is listening, which in turn passes the data on to the IP address of the science user. Science users send commands to their instruments via a similar path without ground users required to know which ground sites are in contact with the spacecraft. When the instruments receive the commands from the onboard router via their onboard network, they execute it as if the science user sending the commands were on their own network. Using mobile routing, only one mobile IP software capability is required on the spacecraft, provided by the onboard mobile router, and inter-spacecraft and space/ground communication are then provided for multiple instruments, each of which contains only standard IP node software and capabilities.

Networks of moving spacecraft are an interesting type of mobile network in that the nodes are moving rapidly with respect to slow moving or fixed ground nodes, causing frequent link handoffs. Although this network topology is highly time varying, there are some simplifying properties, as in most cases the topology changes of the satellite mesh (aside from equipment failures) can be predicted in advance. On commercial constellation designs of Low Earth Orbit networks the graph topology is somewhat regular and dense, leading to a multiplicity of similar routes to most destinations. In this case, routing algorithms can exploit these properties. However, there are also several complications compared to terrestrial mobile networks [5]. First, spacecraft hardware are both mass and power constrained, placing severe limitations on the amount of memory and processing on board. It is therefore necessary to look for routing algorithms that are efficient in memory and computational power use. Also, in broadband connections, it is usually necessary to try to conserve link bandwidth, especially in the links between ground and spacecraft. Finally, double coverage although desirable might not always be possible leading to potential shadowing problems.

For all these reasons operating traditional distributed routing protocols and using traditional means of hierarchy are not likely to lead to best performance. Distance vector protocols have well known convergence problems in time-varying topologies and could cause a significant increase in the protocol complexity. On the other hand, link state protocols converge more rapidly when topologies change, but there is the penalty of additional message traffic, protocol complexity and computational overhead [6,7,8]. While both of these types of routing protocol could work in this environment, it is probably better to look for specialized protocols that take advantage of the particular properties of this type of network. There is clearly a need for optimization of redundant routing and addressing alternatives where a large space network with links between different spacecraft and ground terminals is involved. The current challenge of routing for constellation networks is the provision of Quality of Service (QoS) Routing.

5.1.7 Scheduling

If a constellation is supported by one or more dedicated ground sites, communications scheduling is not as large a concern as if it shares NASA and commercial ground sites with multiple spacecraft users. If it shares ground sites with other users, negotiation may be required to provide mutually compatible site support, in analogy with user negotiations currently performed by the Network Control Center (NCC) for TDRS users, and by JPL for Deep Space Network (DSN) support of multiple simultaneous interplanetary missions.

5.1.8 Security

Considering the importance of the data security is a major issue. This is a major Internet issue in any case, and there are a number of existing protocols and algorithms that provide security services such Secure Sockets (SOCKS5), KERBEROS, as well as traditional link encryption algorithms. However, since our focus will on providing IP services, we will need to adopt the IETF IPsec technology [9] that is intended to provide a standard, robust, extensible mechanism to provide security for upper layer protocols in a way that is interoperable but can accommodate new algorithms. IPSec can be configured in this scenario to provide origin and data authentication, data confidentiality, and anti-replay services with electronic key management. It will be important to assess how well IPsec meets the needs in the mission environment and on the possible modifications to implement this in this environment.

6 Conclusions & Further Work

We have outlined the first steps of an effort to start defining the communication architecture for the next generation of space missions. We showed that access from a large number of ground stations (that could be directly connected to the existing Internet infrastructure) could increase spacecraft availability time by a significant factor. We discussed the need for multiple access techniques that could enable the transition to an on demand operation, where spacecraft share space spectrum dynamically. We also discussed the particular requirements of a next generation of missions consisting of constellations of several small spacecraft and introduce a number of new complex network control, scheduling, routing, data management and communication problems that need to be addressed for this topology. Use of multicast, mobile IP, and mobile routing as discussed above will significantly reduce the complexity, risk, and cost of scheduling for multiple constellation spacecraft, and enable more efficient data collection and dissemination.

We plan to continue working to establish traffic requirements and traffic models for the tele-science services that need to be supported and derive Quality of Service (QoS) requirements for these. We are also trying to define solutions that will optimize bandwidth allocation and establish a suitable multiple access scenario for the space-to-ground scenario and are collaborating with NASA in the investigation of network control and communication issues for future multi-spacecraft constellation missions.

References

1. James Rash, Ron Parise, Keith Hogie, Ed Criscuolo, Jim Langston, Chris Jackson, Harold Price, “Internet Access to Spacecraft” *Proc. Small Satellite 2000 Conference*, Logan, Utah, 2000.
2. Hadjitheodosiou, M.H., Geraniotis, E, “Dynamic Bandwidth Allocation for Multimedia Traffic in TDMA Broadband Satellite Networks”, *Proc. 17th AIAA ICSSC 98 Conference*, Yokohama, Japan, Febr.98.
3. Constellation Client/Server Architecture Testbed (CONCAT) Report, NASA Goddard Space Flight Center, Astronomical Data Center/Code 631, January 2001.
4. IP Mobility Support", Internet Engineering Task Force RFC-2002, October 1996
5. "The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks", Internet Engineering Task Force, Internet-Draft Mannet-DSR-03 , 22 October 1999
6. T. Henderson, “Networking over Next Generation Satellite Systems”, *Ph.D. Dissertation*, University of California, Berkeley, Fall 1999.
7. L. Wood, A. Clerget, I. Andrikopoulos, G. Pavlou, W. Dabbous,, “Routing issues in satellite constellation networks”, *International Journal of Satellite Communications*, Spring 2000,
8. "Cellular IP - A New Approach to Internet Host Mobility," ACM Computer Communication Review, January 1999
9. "Security Architecture for the Internet Protocol", Internet Engineering Task Force RFC-2401, November 1998

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