TECHNICAL RESEARCH REPORT

A direct-to-ground architecture for supporting Commercial Communications from the International Space Station

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Abstract-**We outline the first steps of an effort to start defining a communications architecture for supporting broadband data communications from the International Space Station. We address three communications options and focus on a direct-to-ground architecture, which could serve as an intermediary solution to satisfy near term communications needs of commercial experiments and payloads on the ISS and overcome certain limitations of the current ISS communications infrastructure. A high-level analysis of the architecture for the direct to ground option is performed, focusing on a particular user's requirements, communications links, and coverage availability. We also discuss system, mobility support and protocol issues that need to be addressed for this solution to be a feasible alternative.**

1. INTRODUCTION

The deployment of the International Space Station will provide a unique platform for tele-presence / tele-science in space, and generate a vast and diverse set of multimedia and data communication requirements. NASA is currently trying to upgrade the communication capability for commercial payloads on the ISS to enable broadband support of a variety of multimedia services. We are investigating alternative long-term solutions for supporting communications from ISS payloads, including the use of commercial technology and commercial assets and infrastructure in space and on the ground.

In the interim, however, a solution could be the option to transmit commercial data from the ISS directly to existing commercial or NASA Ka-terminals on the ground. While utilizing these existing terminals could save costs, their properties (such as location or tracking capability) may not be optimum for this service.

In this paper we address three communications options focusing on a particular user's requirements, communications link, and coverage availability. We also discuss system, mobility support and protocol issues that need to be addressed for this solution to be a feasible alternative.

2. COMMUNICATION OPTIONS

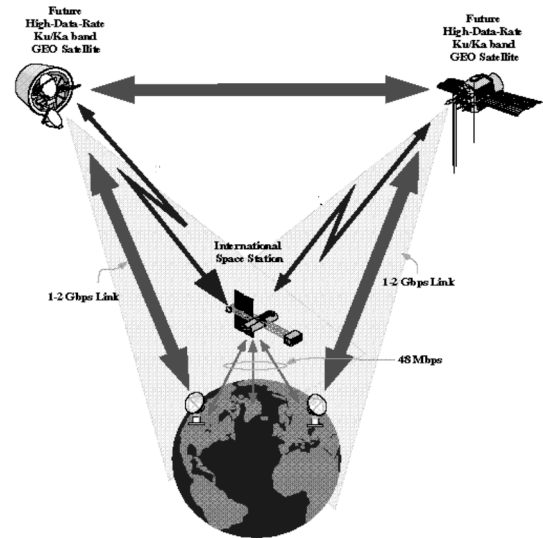Figure 1 shows the possible options that a commercial user can use to transmit data.

Figure 1. Communications alternatives to/from the ISS

2.1. Option 1: Using existing TDRSS

This option is essentially the current communication infrastructure for the ISS, whereby an antenna on the ISS points upward to communicate with one of the TDRSS satellites, which relays the data to the NASA's ground terminals. However, there are currently limitations on the main ISS Access Communication System:

- The current design of the ISS high-rate Ku-Band antenna uses NASA proprietary components, making any future communication system expensive and difficult to implement in a short turn-around time.
- The main Ku-Band space-to-ground antenna that will be used for broadband communications could occasionally be blocked from TDRSS.
- Limitations in the current NASA ground network connectivity means that high rate global data dissemination could face significant limitations.
- Many commercial users will need commercially supported broadband communications.

For all these reasons it makes sense to adopt a new uniform architecture that is based on commercial standards to support future commercial services.

2.2. Option 2: ISS to a commercial satellite constellation acting as relay (In GEO or non-GEO orbit)

This is likely a long-term solution, as there are currently no commercial systems operating at these frequencies that can communicate with moving assets in space. However, if potential interest develops, satellite companies could add a payload to future system expansions that could do that and then offer the relay-to-ground option as a service to NASA or other paying customers.[1]

In review of these options, we find that the current option of using TDRSS has limitations that do not satisfy requirements of certain potential customers, such as those requiring daily transmissions of images in the order of 1 Terabit. The option of relaying data over commercial in-space assets is a long-term one. While the option of communicating directly to the ground may be a good interim solution, the best may be to consider using NASA's existing ground stations, which is where we will focus on in this paper.

2.3. Option 3: ISS direct to Ka-band ground terminals

Several satellite companies are planning to deploy Ka-band satellite systems, complete with corresponding ground networks connected to the Internet. These ground networks could be used as access points for downloading ISS data from the ISS. We are in the process of evaluating the feasibility of using existing commercial ground Ka-band terminals for ISS communications in the near future, and perform a trade-off analysis between this option versus using existing NASA facilities throughout the globe.

The main technical issues of this option include:

1. The commercial ground terminals may have limited capability to track the ISS, as they are designed for mainly their commercial constellations in GEO orbit.
2. The cost for building and maintaining new ground facilities may be significant, and their location may be dependent on the type of applications used.

Because it is uncertain when these commercial systems will actually be realized, however, this option can instead involve the ISS communicating directly to current NASA ground stations already being used by NASA missions, or new, dedicated ground terminals operated by NASA.

3. COMMUNICATION PROTOCOLS

In order to get the best application performance with the consideration of cost, we need to design the whole communication protocol stacks carefully. Although protocol issues in ground based networks are well understood, additional challenges with communicating in the space environment require consideration of more constraints as well as compatibility with ground networks. We first discuss an overview of the protocol stacks for a potential ISS communications payload.

3.1. Link Topology and Physical Layer

The topology of all the nodes in the network supporting the ISS and the physical layer protocol set the hard limit of our protocol design. Such limits include ground customer coverage, propagation delay, frequency and bandwidth choice, power consumption, and bit error rate. Table 1 shows a summary of possible systems for relaying data in space and their properties as compared to communicating directly to ground. We focus our discussion of the other protocol layers on the direct-to-ground link.

Relay system:	Delay	Bandwidth constraint	ISS Power Consump-tion	Antenna tracking	BER
TDRSS (GEO)	Long	S, Ku, Ka	Small	Easy	High
Commercial GEO	Long	Various	Small	Difficult	High
Commercial LEO or MEO	Short w/large variance	Various	Small	Difficult	Low
Direct to Ground	Short w/large variance	Ku, Ka	High	Easy	Low

Table 1

3.2. Link Layer

The two basic functions of the link layer is framing and providing multiple access. As seen in Table 2, these are accomplished through the static channel partition, random access, and dynamic channel partition methods.

Method	User capacity	Sub-Channel Availability	Bandwidth	Protocol overhead	Channel utilization
Static channel patrician	Fixed	Guaranteed	Guaranteed	Low	Low
Random access	No limit	No guarantee	No guarantee	High	High
Dynamic partition	No limit	No guarantee	Guaranteed	High	High

Table 2.

Another constraint comes from the optimization of channel utilization. This is because the downlink and uplink of satellites are highly asymmetric, with asymmetry ratios ranging from 10:1 to 1000:1.

Before we go further discussing the upper layer protocols, we have to consider using either a layered

protocol or an integrated layered protocol (ILP) architecture. With ILP, all the network function can be implemented together, yielding more code efficiency and fewer inter-layer overhead and redundancy. However, this can only be designed to support certain applications, resulting in less flexibility and compatibility with current layered networks such as the Internet. A Layered protocol architecture approach, on the other hand, would provide greater flexibility and better integration with the terrestrial Internet. Thus, we will focus our discussion on a layered protocol architecture.

3.3. Network Layer

The basic functions of the network layer are:

- forwarding the packets from source to destination
- multiplexing transport protocol, and
- segmenting and reassembly if necessary

Additional functions could be multicast, mobility support, and QoS support. The main problem of the current network layer is low bit efficiency considering the valuable bandwidth resource in space. In addition, both IP and ATM do not have a good mobility support with certain QoS support. Thus, for the optimization of this layer, we should mainly focus on bit efficiency and mobility support. Otherwise, we can just use the current IP protocols, which have better compatibility with the Internet.[2]

3.4. Transport Layer

The basic function of the transport layer is to provide end-to-end packet delivery and multiplexing of applications. Additional functions can be error control, flow control, and congestion control.

The current Internet uses UDP, which has limited support, and TCP, which supports fully reliable end-to-end delivery of packets but at the extra price of congestion control. Instead, XTP puts these functions orthogonal to each other so that each application can configure their own transport layer with control packets. NetBlt is especially used for large block data transport.

There is currently much research on TCP extensions for space links. For the ISS direct-to-ground link, the main problems are high RTT variance, higher channel corruption, intermittent connections, and asymmetric bandwidth. The SCPS also includes a Transport Protocol standard that essentially adapts TCP Vegas during congestion, uses explicit corruption loss notification, and pause transmission during intermittent phase. They put several TCP extensions optional to application layer as XTP did. If we choose to use the TCP extension, the

additional constraint on the design is the performance and compatibility with TCP on the ground network.

3.5. Application Layer

The application layer needs to be designed to specific applications. A current possible application being considered is that of a remote sensing instrument onboard the ISS downloading large file images (12 Gbits each) to the ground. The same application protocol with extensions at the ground network for their correspondence can be used, or a special space application protocol can be designed. The idea of application level framing (ALF) is being considered, which assumes the basic function of the transport layer, and optionally implements functions like sequencing, reliability, flow control, time stamping on its own. This would most likely be implemented over UDP to avoid the complex research for TCP performance and compatibility. For example, the SAFE (Simple Automatic File Exchange) protocol implements sequencing, reliability, automatic transmit, and congestion control optionally on its own, and can run over UDP and TCP (mostly on UDP in space, TCP in ground). Also, RTP (Real-time Transport Protocol) implements sequencing, multiplexing, and time stamping on its own, so that it can run over UDP and provide real-time functionality and compatibility with the Internet Stacks.

4. MOBILITY SUPPORT

Currently we focus on the mobility support at the network layer.
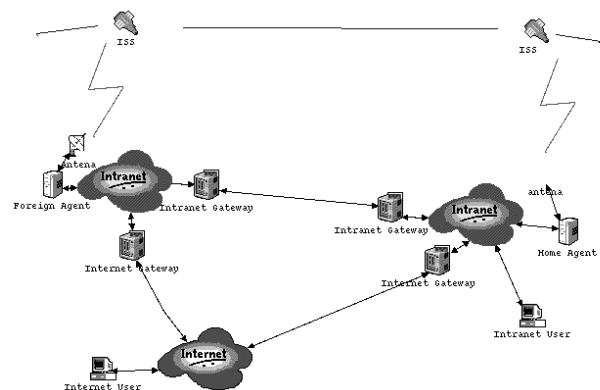

Figure 2: ISS direct-to-ground protocol architecture.

The ISS can be modeled as a single host with different modules, or as a space LAN segment with different hosts. For the former, we are trying to simulate it with basic functions in Mobile IP of IETF. However, the mobility of the ISS in space is different from that of a mobile ground host, and results in several advantages:

4.1. Fewer mobile hosts and foreign agents.

Compared to the hundreds of thousands of mobile hosts on the ground, there are only about 10 ISS modules. Thus, the state information of each host can be saved in advance without much worry about scalability. Also, fewer foreign agents can also mean that some semi-permanent connections can be setup in advance.

4.2. Predictability

Unlike the random movement of ground mobile hosts, the ISS is moving within a predictable orbit, and access time to each ground terminal is highly predictable. Thus, greater intelligence can be added to the location management.

4.3. Centralized Management

ISS communications will have to be managed in a central way by NASA. However, for supporting commercialized service, the access needs to be controlled in the network center. We can further optimize the mobility support by considering these particular properties. If we want to model ISS as a mobile LAN, the main focus will be on the mobile router, which serves as the interface between the space LAN and the ground network. Except the similar function as Mobile IP, we can add further complex routing scheme and QoS support like diffserv.

5. COVERAGE CONSIDERATIONS & COMPARISONS

5.1. Coverage

The initial design of an ISS to direct to ground communication system involves various issues of coverage. These include:

- Antenna power,
- Total coverage availability,
- Duration of each link, and
- Speed of each link.

An initial framework for analyzing this communication system is developed using Satellite Tool Kit (STK) with the ISS in a 400 km circular orbit at 51.5 degrees inclination. The antenna on-board the ISS is assumed to be a phased array antenna with a scan angle of up to 30 degrees from the boresight and pointing towards the earth surface. The ground station antennas communicate directly with the ISS and have the ability to track the ISS.

To determine a first-order coverage capability of the direct-to-ground architecture, we focus on an imaging application on the ISS. An onboard remote sensing device will take images of the surface of the earth or collect other data on or under the earth surface into an image format. The images are temporarily stored onboard the ISS, and downloaded to the ground at the next available ISS contact with a ground station. The application has a minimum requirement of being able to download at least 120 images per day, with each image size about 12 Gbits. These images, which require a total throughput of 1,440 Terabits in every 24-hour period, must be available for commercial customers in the US.

We first determine the ground stations needed to provide this throughput requirement knowing that stations placed near the satellite's inclination provide the best coverage.[3] Coverage is defined as the total amount of time the ground stations have contact with the ISS over 24 hours. The simulations were run for 10 days then averaged for one day. Using the database of NASA facilities in STK, stations were chosen closest to the ISS's inclination with minimal overlapping of their coverage cones. Figure 3 shows the placement of the 6 US ground stations providing the best coverage with 10-degree minimum elevation angle and ISS antenna scan angle of 60 degrees.
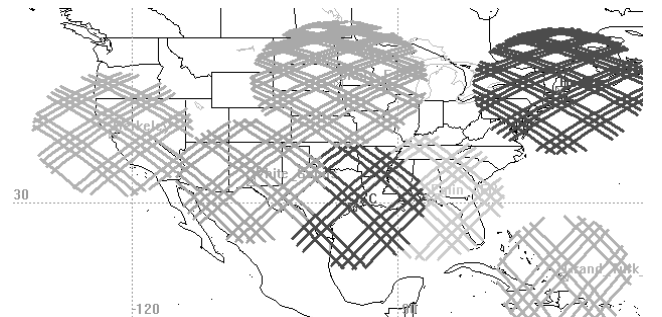

Figure 3. Ground track of ISS with access to 6 US stations.

The stations are ranked in order of best to worst coverage in Table 3. The table also shows the cumulative coverage achieved first for the best station, Sioux Falls, and for adding each subsequent station to the group of stations that can communicate with the ISS.

	Individual Access (seconds)	Cumulative Access (seconds)	
		10 days	1 day
Sioux_Falls	6416	6,416	642
Boston	5968	12,310	1,231
Berkeley	4302	16,476	1,648
White_Sands	3723	19,973	1,997
Eglin_AFB	3633	23,984	2,398
JSC	3585	25,630	2,563

Table 3. Coverage of stations.

From this data, we can determine the best stations to use by calculating the throughput for using the best station, and adding each subsequent station until the desired throughput is achieved. Table 4 shows the amount of

throughput achieved with each incremental station in Gigabits per day for transmit speeds of 180 Mbps, 361 Mbps, and 622 Mbps. If each downloaded image size was 12 Gbits, the table also shows the number of files that can be downloaded in a 24-hour period.

	Data Throughput (Gb) for specified transmit rates (Gbps)			# Image downloads for Image size 12 Gb		
	180 Mbps	361 Mbps	622 Mbps	180 Mbps	361 Mbps	622 Mbps
Sioux_Falls	115	232	399	9	19	33
Boston	222	444	766	18	37	63
Berkeley	297	595	1,025	24	49	85
White_Sands	360	721	1,242	29	60	103
Eglin_AFB	432	866	1,492	35	72	124
JSC	461	925	1,594	38	77	132

Table 4. Throughput for stations.

Thus, using a direct to ground architecture does provide enough coverage for a typical store-and-forward application on the ISS.

5.2. Comparisons with Other Architectures

Overall, as shown in Table 5, the Direct to Ground architecture is suitable for store-and-forward applications that do not require large amounts of coverage. The TDRSS is the best option to use for video conferencing type applications due to its continuous coverage. While the Direct to Ground option offers flexibility, using a commercial relay system may allow easier setup and less initial cost investment.[3]

	Direct to Ground	Commercial Relay	TDRSS (Ku)
Advantages	Flexible, Scalable, Prices competitive Good for store-and-forward applications	Very little system setup required	100% coverage, Good for real-time or on demand applications
Disadvantages	Not good for real-time applications, Requires additional building of facilities	Prices and entire system uncertain, Systems not tailored to needs of ISS customers	Possible slow ISS onboard communications system, Capacity for commercial applications may be limited later

Table 5. Comparison of strengths of three architectures.[3]

In comparison with the commercial relay system, the direct to ground option offers about the same amount of coverage at similar costs. As shown in Table 6, the TDRSS offers complete coverage, at relatively low cost for the Ku band satellites. The new Ka band satellites will likely be slightly more costly.[3]

	Direct to Ground (Ka)	Commercial Relay (Ka)	TDRSS (Ku)
% Coverage	13.3%	16.7 %	100%
Cost / Mbyte	$0.25	$0.05-$0.5	$0.09-$0.13
Transmit rate	622 Mbps	Up to 110 Mbps	300 Mbps

Table 6. Comparison of coverage & costs for architectures[3]

6. CONCLUSIONS & FURTHER WORK

In the initial steps to define a communications architecture for the ISS, a modular simulation model has been developed consisting of the ISS module, the NASA Ground Network, alternative commercial Ground Support Infrastructure, candidate commercial Satellite Constellations, and specific payload traffic patterns.

We performed an initial coverage analysis for a sample scenario, and determined the duration of connectivity and data throughput characteristics for various data transmissions rates. Also, we have discussed traffic generation issues and File Transfer protocol Support, and evaluated the functions, requirements, and characteristics of the various protocol layers as it applies to ISS communications directly to the ground.

We are in the process of developing the framework for handover / connectivity support analysis and plan to continue developing the simulation platform to:

- Perform end-to-end optimization & suggest solutions to support particular protocols or QoS requirements for specific services over the space-to-ground link,
- Investigate traffic characteristics of particular services and find ways to optimize dynamic resource / capacity sharing that would maximize revenue,
- Analyze the business case study and explore ways to maximize revenue by 1) estimating the bandwidth cost of this commercial service, and 2) investigating dynamic pricing solutions for different customers

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