

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 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. We address three communications options and evaluate an architecture for the direct to ground option, 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

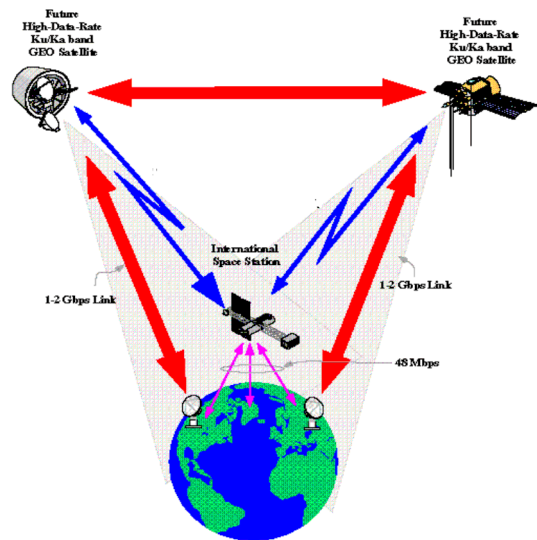


Figure 1. Communications alternatives to/from the ISS

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 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 direct to existing / planned 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 fixed ground Ka-band terminals for ISS communications in the near future, and perform a trade-off analysis between this option versus building new ground terminals at optimally placed locations.

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. Due to the possible limited tracking capability, the coverage these terminals provide to a rapidly moving LEO spacecraft might not be sufficient, and there might be a need to augment the coverage by adding additional terminals distributed globally.

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.

2.3. *Option 3: ISS to a commercial satellite constellation acting as relay (In GEO or non-GEO orbit)*

This option could be a later 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.

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.

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 Consumption	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 partition	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. Table 3 describes the required and optional functions needed for this application for the two current network layer protocols: IP and ATM.

Function	IP	ATM
Routing	Connectionless (address in each packets)	Connected (connection is setup, then VCI is used in each cell)
Multicasting	Yes via IGMP, DVMRP, PIM	Yes, via virtual multiple connections
Mobility support	Yes, via Mobile IP (Home Agent, triangle routing)	Yes, via Wireless ATM (dynamic connection setup)
QoS support	Yes, via Best effort (possible improvement with Intserv, Diffserv, MPLS)	Yes, via ABR, CBR, VBR, UBR
Header overhead	High (≥ 20 bytes used for header in each packet, may segmentation)	High (5 out of 53 used for header in each ATM cell, greater if AAL is used)
Signaling	Yes, via ICMP (error signaling, no congestion assist)	Yes, End-to-end congestion assist
Optional routing schemes	Partial support	No support

Table 3.

As we can see, 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.

3.4. Transport Layer

The basic function of 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.

	UDP	TCP	XTP	NetBlt
Multiplexing	Yes, using port number	Yes, using port number	Yes, using key	Yes
Error resilience	Unreliable (checksum)	Reliable (duplicated ack, retransmission)	Error control policy (fully reliable to uncorrected)	Reliable (SNACK)
Flow Control	No	Yes (recv window in every packet)	Rate control (can change during transmission)	Rate control (can change)
Congestion control	No	Yes (slow start and congestion avoidance)	Rate control	Rate control
Packet size	Variable (\leq MSS)	Variable (\leq MSS), can use option field to negotiate MSS	Fixed-size 64-bit aligned frame	Large packet size (contract)
Receiver Buffer size	Unspecified	16-bit sequence number, Window scaling factor can be set to use option field	Can be set to use alloc message	Contract between transmitter and receiver
Real-time support	Can run RTP at the upper layer	No	N/A	N/A

Table 4.

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 problem 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, use 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 using 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.

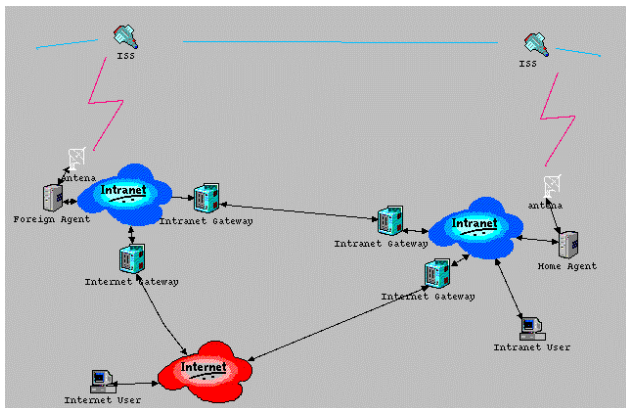


Figure 2: ISS direct-to-ground protocol architecture.

The ISS can be modeled as a single host with different modules, or as a space LAN segment with different hosts. For the former, I am trying to simulate it with basic

function 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 mobility support issues that need to be considered.

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, then 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 & ANALYSIS

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 assumed with the ISS in a 400 km circular orbit at 51.5 degree inclination. The antenna on-board the ISS is assumed to be fixed pointing nadir (towards the center of the earth), while the ground station antennas communicating directly with the ISS are tracking the ISS.

The geometric access for this scenario is considered, for the case of the on-board antenna having half angles of 30 degrees and 90 degrees (full field of view) communicating

to 3 domestic NASA ground stations, and 23 international stations within a 24-hour period.

Total all links	Longest link duration	Mean link duration
133.1	1.2	0.9

Table 5: ISS to Ground Access Times (in minutes), for 30° Antenna.

Total	> 1 min	> 2 min
156	61	0
100%	39%	0%

Table 6: Number of Links within 24-hr period.

For the case of the 30° cone angle, we find that there are 133 links within this 24-hour period that provide 156 minutes of connectivity, and nearly 40% of the links have durations between 1 to 1.2 minutes.

Transmit Rate	Total all links	Longest duration link	Avg duration link
0.180 Gbps	1,437	12	9
0.361 Gbps	2,883	25	18
0.622 Gbps	4,967	43	32

Table 7: Amount of Data that can be Transmitted (in Gigabits)

For these communication links, we consider the total amount of data that can be transmitted for three varying transfer rates: 180 Mbps, 361 Mbps, and 622 Mbps. Table 8 shows that a transfer rate of 361 Mbps can provide over 2.88 Terabits of data per day, which is enough to satisfy a customer’s need to deliver 120 of 12-Gbit images per day, and still have plenty of additional downlink margin for re-transmission of errors or for providing communication services to other ISS users. However, only an average of about 18 Gigabits of data can be sent continuously without interruption. For data such as images that are close to this size, both on-board and ground processing as well as extra transmission overhead may be required to assemble these file fragments into full files during links with shorter durations.

Total	> 1 min	> 2 min
559	553	542
100%	99%	98%

Table 8: ISS to Ground Access Times (in minutes), for 90° Antenna.

Total all links	Longest link duration	Mean link duration
5,649.1	35.8	10.1

Table 9: Number of Links within 24-hr period.

Transmit Rate	Total all links	Longest duration link	Avg duration link
0.180 Gbps	61,010	386	109
0.361 Gbps	122,359	775	219
0.622 Gbps	210,824	1,335	377

Table 10: Amount of Data that can be Transmitted (in Gigabits)

Table 10 shows that the number of links in one day and the link duration can increase significantly as the antenna cone angle is increased. Correspondingly, the total daily data throughput can be increased by an order of magnitude or more. In addition, the number of ground stations and location of these stations also could greatly affect the available capacity.

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 and suggest solutions that would 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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ACKNOWLEDGEMENTS

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