Assessment of the Internet Protocol Routing in Space—Joint Capability Technology Demonstration

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The Internet Protocol (IP) Routing in Space (IRIS) was developed by an industry group, under the auspices of the DoD, as a Joint Capability Technology Demonstration (JCTD). The primary goal of the IRIS JCTD was to assess the network capability and operational utility of an IP router in space. The capstone demonstrations using the on-orbit IRIS capability onboard a commercial satellite (Intelsat 14) were completed in March and April 2010. These demonstrations were preceded by a series of technical and operational demonstrations, conducted during the prior 3 years, using simulated and prototype-based surrogate capabilities in preparation for the final on-orbit demonstrations. This article describes the capabilities of the IRIS network and presents the highlights of the on-orbit demonstrations, along with key results and findings.

INTRODUCTION

During the past 3 years, a significant collaborative effort between industry and government took place with the goal of placing an Internet Protocol (IP) router (IPR) onboard a commercial geostationary orbit satellite and demonstrating its operational utility to government users.[1] The IP Routing in Space (IRIS) Next-Generation Global Services (NGGS) network was developed by an industry team led by Cisco Systems, Inc. The network consists of the IRIS payload onboard the spacecraft, ground-based IRIS-compatible terminals, and an IRIS Network Operations Center.[2] After significant development and testing efforts, the IRIS payload onboard Intelsat 14 was launched successfully into geosynchronous orbit on 23 November 2009.

To assess this new capability and the potential utility to government users, the IRIS Joint Capability Technology Demonstration (JCTD) was established under the auspices of the DoD. The assessment approach consisted of a series of demonstrations leading to a final on-orbit demonstration. Operational demonstrations with user group participation were designed to assess the operational utility of IRIS, while laboratory and field technical demonstrations were designed to evaluate the network features and service capabilities of IRIS.

Both types of demonstrations provided complementary insight, operational versus technical, toward developing a final assessment. As the independent operational test agency for the IRIS JCTD, APL conducted the assessment. The Massachusetts Institute of Technology (MIT) Lincoln Laboratory, the IRIS JCTD technical agent, developed the customer network emulation, operating the customer network during the tests and collecting and processing the data.

The demonstrations were designed primarily to evaluate the performance of user applications over the IRIS network and the operational impact on potential joint, interagency, intergovernmental, and multinational (JIIM) users (i.e., users from DoD branches, government agencies such as the Federal Bureau of Investigation and the Department of Homeland Security, U.S. allies, and U.S. agencies in foreign countries).

BACKGROUND

Transponded ("bent-pipe") satellites have carried Internet traffic for many years, but satellites with onboard processing and regenerative capabilities for broadband commercial communications have become available only recently.[2] Although some of the regenerative satellites provide layer-2 packet-switching functions (e.g., asynchronous transfer mode switch), an IPR as a communications network node in space did not exist until IRIS. [Note that some of the IRIS capabilities resemble those of DoD's Transformational Satellite Communications System (TSAT),[3] which was cancelled in 2009; however, TSAT was conceived as a secure global communication system, whereas IRIS is an unprotected network with limited capacity and reach, and it was planned to carry both commercial and government traffic.]

IRIS has the potential to provide significant advantages over other existing systems and could offer important benefits to the end user, including, for example, the following:

- Instant and seamless IP packet routing across satellite RF channels, transponders, or antenna beams
- A "point-to-network" paradigm through a single connection to the satellite router and thereby to any other IRIS terminal
- "Any-to-any" broadband communications, providing direct access to the Internet and to private networks
- "Peer-to-peer" direct connectivity between user terminals in a single hop, thus eliminating the need for a terrestrial hub
- Application performance supported by end-to-end quality of service (QoS) capabilities and flow control techniques
- Higher data throughputs from small terminals, in comparison with those on bent-pipe satellites, achieved by the higher carrier-to-noise ratio afforded by the onboard router's signal regeneration capability

The envisioned future IRIS architecture contains a full complement of space-based network nodes interconnected by cross-links to support an IP network layer in space. The IRIS JCTD represents the first instantiation of this vision, and it introduces some of these future capabilities. The IRIS payload demonstrated by the JCTD acted as a single network node in space with no cross-links to other satellites.

Assessment Approach

To develop the Operational Utility Assessment, APL utilized a hierarchical approach in which critical operational issues (COIs) were developed from capability gaps and operational needs identified by IRIS JCTD stakeholders. These COIs were supported by measures of merit, measures of effectiveness, and measures of performance. Table 1 lists the COIs for the IRIS JCTD.

In conducting the demonstrations over a 3-year period, an incremental "crawl, walk, and run" approach was used. A specific set of technical and operational demonstrations was conducted, each time with increased scale, fidelity, and complexity, leading to the on-orbit assessment events. Figure 1 depicts the spiral approach and the time line of demonstrations.

Table 1. COIs developed from capability gaps and operational needs identified by IRIS JCTD stakeholders.

Issue Designation	Definition
COI 1: Functionality/system performance	How does IRIS affect satellite communications capabilities?
COI 2: Operational impact	Does IRIS enhance and extend the JIIM user's capability to conduct net-centric operations?
COI 3: Interoperability	Do the IRIS capability and supporting technologies integrate into current command and control infrastructure, and are they interoperable with evolving network architectures?
COI 4: Suitability	Is IRIS suitable for the JIIM user community?

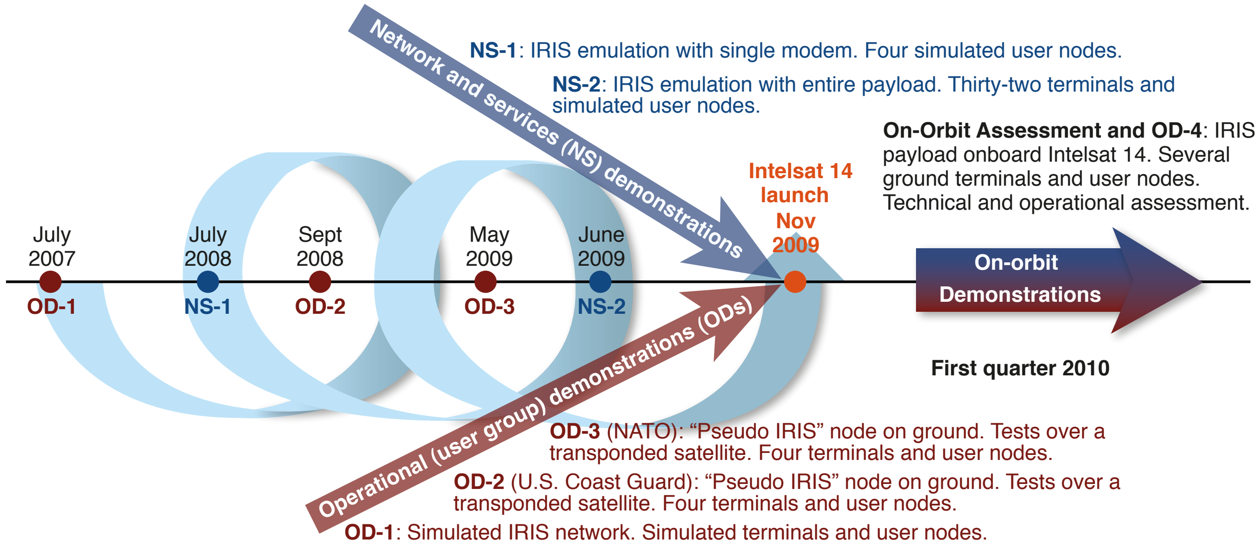

Figure 1. Time line of the IRIS JCTD.

Prior to the launch of Intelsat 14 (see Fig. 2), two network and services demonstrations and three operational demonstrations were conducted. These demonstrations provided insights into supportable service performance and the potential operational impact that can be expected from the on-orbit IRIS capability. Once Intelsat 14 was placed into orbit, two separate demonstrations were conducted (from 16 February to 1 April 2010) to evaluate the network and service capabilities and the operational utility of IRIS.

Figure 2. Intelsat 14.

IRIS NETWORK ARCHITECTURE AND SERVICES

The IRIS NGGS network consists of the IRIS payload, the IRIS ground terminal nodes, and the IRIS Network Operations Center. The payload consists of the Programmable Satellite IP Modem (PSIM), the IPR, and upconverters and downconverters. Figure 3 is a diagram of the IRIS payload on Intelsat 14, and Fig. 4 shows the flight IRIS PSIM and IPR. The PSIM provides all

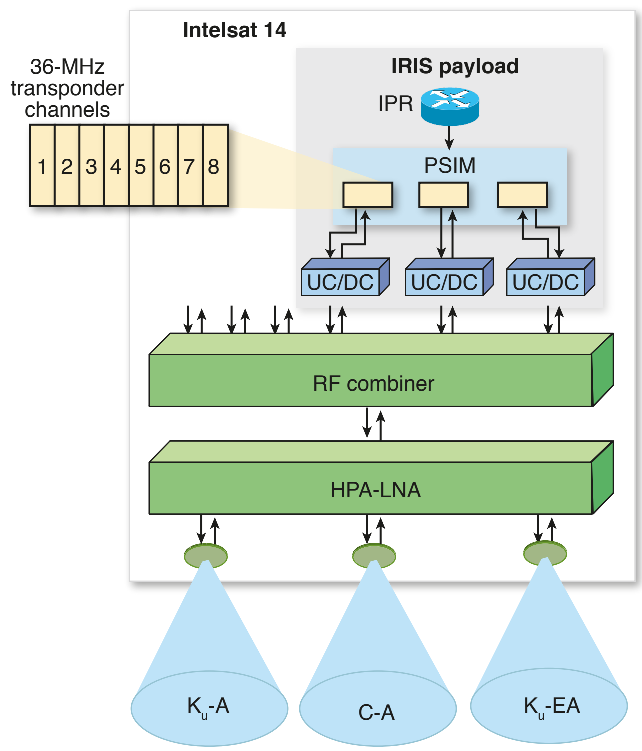

Figure 3. IRIS payload on Intelsat 14. HPA-LNA, high-power amplifier–low-noise amplifier; UC/DC, upconverter/downconverter.

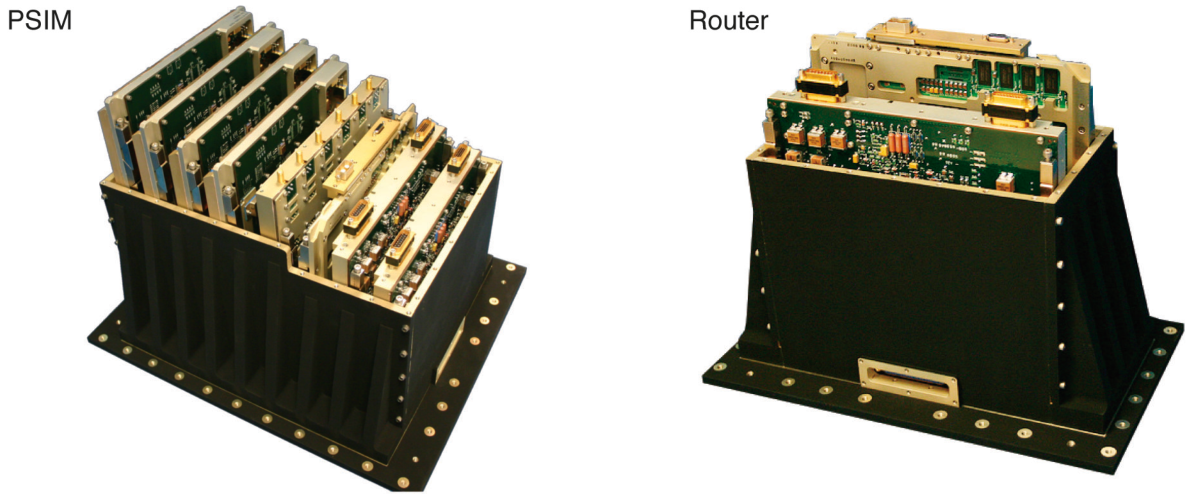

Figure 4. PSIM and IPR. Hardware designed and manufactured for the Cisco Systems IRIS project by SEAKR Engineering (images reproduced with permission

the functions of an IP modem, i.e., encapsulation and segmentation of layer-3 IP packets, modulation, coding, and Bandwidth on Demand (BoD) features. [The waveform selected for the PSIM is ViaSat's Linkway Multi-Frequency Time Division Multiple Access (TDMA) modem.] Each 36-MHz IRIS-enabled transponder supports a small set of channels with symbol rates of 1.2, 2.5, and 5 megasymbols per second (Msps). The IRIS PSIM is connected to three antenna beams of Intelsat 14: C-Band Americas (C-A), K_u-Band Americas (K_u-A), and K_u-Band Europe–Africa (K_u-EA).

Each ground terminal node includes a Linkway modem (LM) and a Cisco Ground Router (CGR). The modems and the PSIM enable dynamic BoD and support specific committed information rates (CIRs). Each terminal enables a permanent virtual circuit with the PSIM. The CGR provides Differentiated Services (DiffServ) Code Point (DSCP)-based QoS with traffic conditioning, while the LM provides DSCP-based priority queuing. The CGR interfaces support Dynamic Host Configuration Protocol (DHCP) or External Border Gateway Protocol (eBGP) routing protocols. This allows direct connectivity and network convergence of small and large terminal sites or network nodes. Additional details on the IRIS NGGS QoS and BoD architecture are provided by Connary et al.[4]

The IRIS Network Operations Center consists of a Network Control Center for managing the LMs and the PSIM functions as well as a network management system for managing the GCR and the IPR. Details on the IRIS network management system architecture are provided by Johnson et al.[5]

Network Features and Capabilities for Assessment

The following IRIS network features and capabilities were available for the on-orbit demonstration:

- Intrabeam, interbeam, and cross-band connectivity
- BoD capability for dynamic reallocation of bandwidth among all terminals
- Multiple virtual private networks (VPNs) through BGP policy-based routing and IP security encryption
- IP QoS features with DiffServ, weighted random early detection (WRED), and class-based weighted fair queuing (CBWFQ)
- Connectivity between various types of user networks through eBGP, DHCP, and static routing protocols
- Multiple terminal service grades with a choice of access speeds and CIR settings [Note that, according to Cisco's NGGS design, user terminals that choose a "premium service" have a service-level agreement with a specified CIR, while "best effort" (BE) users have no service guarantees and no CIR. Terminals with premium service may choose P0, P1, P2, or P3 service grades. P0 provides the highest data rate and CIR, and P3 provides the lowest data rates and CIR.]
- Transmission Control Protocol Performance Enhancement Proxy (PEP), compression, and caching capability through Cisco's Wide Area Application Services units
- Public Internet access with global addressing through a dedicated Internet gateway

QoS Architecture

The IRIS NGGS has implemented the QoS "Trust Model" for user traffic classification. Under this model, traffic classification rules are known and agreed to in advance by both the customer and the service operator.[4]

Table 2. QoS policies supported.

Traffic Types	DSCP	Traffic Conditioning	LM Priority Queue
Real-time applications (VoIP)	EF	Policed < CIR; LLQ (low-latency queuing)	5
Video and VTC	AF4x	Minimum bandwidth	4
Call signaling (session initiation protocol)	AF3x	Minimum bandwidth	3
Critical applications, network management system, chat	AF2x	Minimum bandwidth	2
File transfer, e-mail, hypertext transfer protocol (http)	BE	Weighted fair queuing	1

The trust model requires that traffic be classified at the source into five service classes by using appropriate DSCP settings: Explicit Forwarding (EF), Assured Forwarding (AF4x, AF3x, and AF2x), and BE. The CGR and the LM accept these DSCP settings without any DSCP remarking. DSCP settings that are not marked as one of these five service classes (EF, AF4x, AF3x, AF2x, or BE) are treated as BE class by CGRs and LMs. Table 2 summarizes the respective QoS policies.

NETWORK UNDER TEST

The test bed architectures designed to support the laboratory and field evaluations consisted of the IRIS NGGS network (payload, ground terminals, and Network Operations Center) and the user network, consisting of the government customer-emulated network.

Laboratory Emulation Network

As the JCTD program unfolded, the laboratory emulation capabilities evolved, becoming increasingly complex and providing higher fidelity. During the July 2009 laboratory demonstration, the emulated IRIS network included payload engineering models of the PSIM and the IPR. The test bed provided a realistic network scale with a large number of terminals (32 user nodes) that loaded the network, better traffic generation capabilities, and a more refined set of tests and testing tools than those used in previous IRIS demonstrations. The laboratory emulation test bed is shown in Fig. 5.

The PSIM included the three IRIS-enabled transponders to emulate interbeam, intrabeam, and cross-band connectivity between users. The IRIS portion of the test bed also included three other nodes: the teleport node for Internet-like access, a Network Operations Center terminal for network management system functions, and a Network Control Center terminal for LM–PSIM performance monitoring and control.

The 32 user nodes were assigned to different antenna beams and configured to represent different terminal service grades. The hosts at each node were assigned to different closed user groups (VPNs). Some hosts had access to both VPNs and the Internet. The user network portion of the test bed was emulated by the Traveling Network and Link Emulation Test Bed (TNLET), which emulated the government nodes, and the Lincoln Adaptable Real-time Information Assurance Test bed (LARIAT), which generated the instrumented applications and provided automated management of virtual users. (Note that TNLET and LARIAT were developed by MIT Lincoln Laboratory.)

On-Orbit Network

The test bed for the on-orbit assessment consisted of two user terminal nodes and the Internet gateway node. Node-1 was located in Fort Gordon, Georgia, and Node-2 was located in The Hague, Netherlands. Intelsat's teleport in Atlanta, Georgia, provided the Internet gateway function and hosted Linkway's Network Control Center. The Cisco Research Triangle Park node located in Raleigh, North Carolina, provided the IRIS Network Operations Center function and enabled a customer web portal for performance monitoring. Figure 6 shows the test bed architecture for the on-orbit assessment.

Node-1 had equipment that could operate on the C-A beam, the K_u-A beam, or the K_u-EA beam. This node was used to demonstrate cross-band, interbeam, and intrabeam connectivity. Node-2 was configured to operate only on the K_u-EA beam.

The test bed supported two user groups, a surrogate Internet user group and a VPN user group. The peer-to-peer connection from the user hosts to the CGR was through DHCP. All user traffic was emulated by automated instrumented applications.

Test Traffic Generation

The test traffic was generated by TNLET, LARIAT, and DVQattest, a test tool developed by Telchemy for generating voice over IP (VoIP) and video teleconference (VTC) applications traffic. The instrumented applications consisted of VoIP calls, VTC, file downloading with file transfer protocol (FTP), web browsing, and instant messaging (chat). TNLET simulated a surrogate Internet, surrogate intranets, network servers, customer edge devices, and end-user workstations. TNLET also generated ping packets between hosts and virtual users' traffic such as FTP file downloads, Internet web browsing, and chat conversations at each user node. LARIAT provided automated large-scale management of virtual users and network services such as domain name service (DNS). DVQattest was used to generate VoIP and VTC application traffic at the two user terminals. All

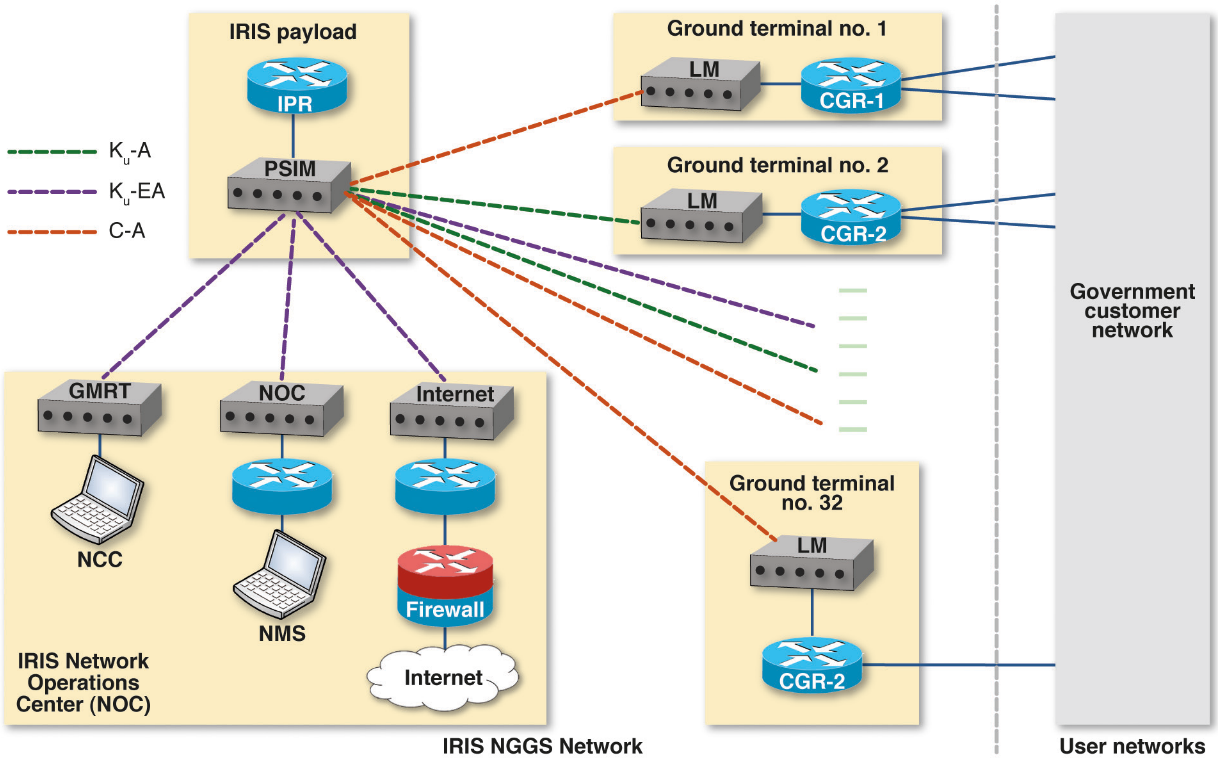

Figure 5. Laboratory emulation test bed. GMRT, ground master reference terminal; NCC, network control center; NMS, network management system.

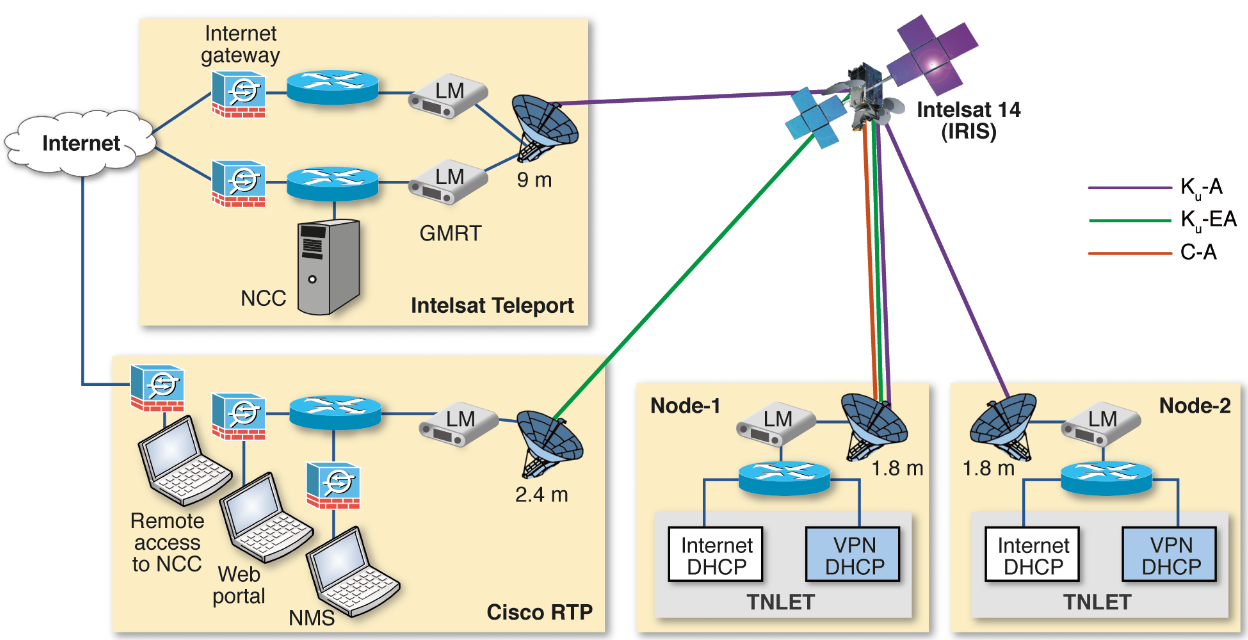

Figure 6. Test bed architecture for on-orbit assessment. NCC, network control center; NMS, network management system; RTP, Research Triangle Park.

sessions were initiated by the emulated virtual user and were marked at their source with the appropriate DSCP.

Two traffic loading profiles were used. A “medium traffic” loading profile was used to simulate normal traffic conditions at each host and at each terminal. A “heavy traffic” loading profile was used to simulate periods of intense activity generated by each host of a terminal.

Measurement and Monitoring Tools

Various tools were used to support the assessment requirements and the desired performance metrics. LARIAT collected performance and traffic statistics for FTP, web, and chat. LARIAT also provided a limited capability for traffic monitoring. DVQattest generated packet payloads with characteristics similar to real voice conversations and VTC sessions. NetFlow was enabled at every CGR in the test bed to collect IP packet data for specific traffic flows. (Note that the Network Control Center control messages are not part of the overhead, because these messages are transmitted over a separate dedicated signaling channel common to all terminals within a control group.) The Linkway Network Control Center provided layer-2 data such as RF burst requests and allocations, per link. Cisco’s NGGS customer web portal provided near-real-time Network Control Center performance monitoring reports per terminal, such as RF bandwidth utilization consisting of TDMA burst requests and allocations.

PERFORMANCE RESULTS

The network and application performance of the IRIS NGGS network was evaluated under various network configurations and traffic loading conditions.

Network Performance

Network performance was assessed through measurements of data throughput at various network interfaces, round-trip delay from host to host, bandwidth allocation to each ground terminal, and overall overhead introduced by the IRIS network.

Data Throughput

Figure 7 illustrates data throughput results obtained at Node-2 during the on-orbit tests. Each colored line in the graph represents a different destination IP address of the traffic flowing out of a node. Under heavy loading, the total throughput was about 100% greater than under medium loading. The peak rate was near its maximum capacity (4.23 Mbps).

As a result of the small number of terminals used during the on-orbit tests, congestion conditions could be created only at individual terminal uplinks, not at the transponder level. The performance impacts due to transponder congestion can be evaluated only when a sufficient number of terminals are deployed, and each terminal generates enough traffic to cause overall tran-

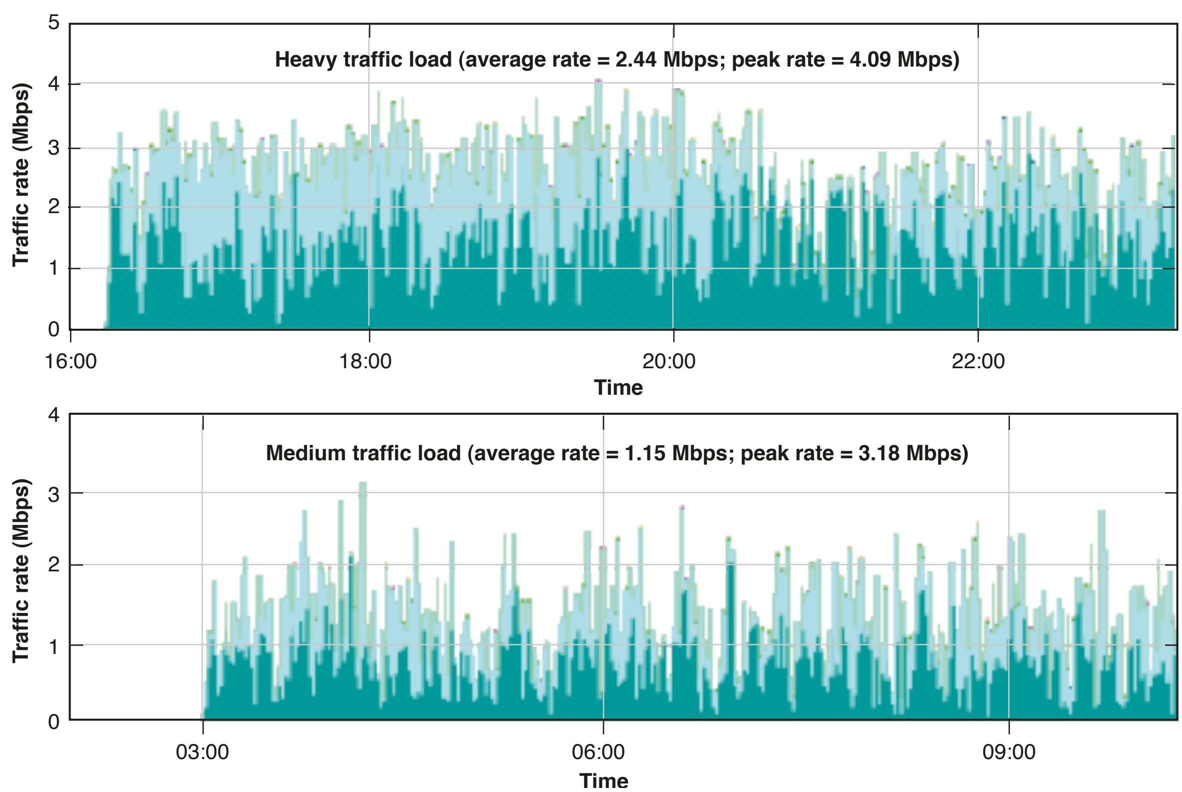

Figure 7. Total throughput at Node-2 under medium and heavy traffic loading.

sponder congestion. This condition was demonstrated during the laboratory-based tests, which included a total of 32 emulated terminal nodes, as shown in Fig. 6.

Round-Trip Delay

Round-trip delay was measured by sending ping (Internet Control Message Protocol) packets marked with one of four DSCP settings (i.e., EF, AF41, AF21, or BE).

Table 3 summarizes the round-trip delay statistics obtained at Node-1. Packets marked EF had the smallest average delay and smallest standard deviation compared with all other classes; BE packets performed the worst and had the largest standard deviation; and the AF41 and AF21 packets were somewhere in between. The results under heavy loading show that the average round-trip delay and distribution spread changed very little for the EF class, increased somewhat for the AF41 and AF21 classes, and increased significantly for the BE class.

The results obtained show that the marked traffic was handled adequately and the QoS solution implemented worked effectively.

Bandwidth Resource Allocation

The bandwidth management function in IRIS is provided by Linkway's Network Control Center. The Network Control Center runs a proprietary BoD algorithm designed to dynamically allocate the bandwidth available from each set of channels within a transponder and with "fairness" among all active terminals that request bandwidth. Terminals with specified CIRs are accommodated first. Then, the Network Control Center allocates any excess bandwidth to all remaining terminals on an as-available basis. During the on-orbit assessment demonstration, all bandwidth requests were 100% allocated under both medium and heavy traffic loading. This resulted from the small number of terminals (three) and the consequent relatively low total traffic volume, which did not load the PSIM. However, the results for the laboratory emulation tests, with a network loaded with 32 ground terminals, are more representative. For example, under light traffic loading, P3-service-grade terminals got 90–100% of the requested bandwidth, whereas under heavy loading the resource allocation dropped to 67%. Higher-service-grade terminals (P0, P1, and P2) got better allocations than P3 terminals.

Overhead

The combined overhead introduced by the IRIS network was estimated by measuring the layer-2 bandwidth assigned by the Network Control Center to carry a measured amount of ingress CGR traffic. The total overhead includes that added by the CGR (IP security encryption, management and control messages), layer-2 (segmentation, TDMA framing, encoding, etc.), and BoD algorithm implementation. (Again, note that the Network Control Center control messages are not part of the overhead because these messages are transmitted over a separate dedicated signaling channel, common to all terminals within a control group.) This definition of overhead provides a good estimate of the link bandwidth a user needs to subscribe to so as to be able to transmit a specified average user payload. The overhead was calculated from measured data averaged over 1-h intervals as follows:

$$\text{Overhead} = \frac{(\text{Allocated Link Bandwidth} - \text{Ingress CGR Traffic})}{\text{Allocated Link Bandwidth}}.$$

The results obtained for FTP-only traffic show that the overall overhead stayed in a range of approximately 55–60%. However, the overhead may be different when the network is loaded with other applications and other traffic mixes.

Applications Performance Under Various Traffic Loading Conditions

This section presents the performance results of VoIP, VTC, web, and chat applications obtained during

Table 3. Round-trip delay measurements at Node-1.

DSCP	Average (ms)	Standard Deviation (ms)	Minimum (ms)	Maximum (ms)
Medium traffic loading				
EF	771.0	15.7	741.3	883.5
AF41	790.4	53.8	742.2	1912.2
AF21	817.0	127.2	741.7	3715.8
BE	902.7	282.3	741.7	3946.8
Heavy traffic loading				
EF	771.4	15.8	741.0	869.6
AF41	796.8	62.9	741.5	2493.9
AF21	814.5	108.6	741.9	3474.1
BE	957.3	339.5	743.1	3960.9

the on-orbit demonstration. All instrumented application packets were marked with appropriate DSCPs as defined in the QoS scheme. The class marking was as follows: VoIP (EF), VTC (AF41), chat (AF21), FTP (BE), and web (BE).

VoIP Performance

Listening quality and conversation quality of VoIP calls were measured by the "R-factor" and its corresponding mean opinion score (MOS). (The R-factor is measured on a scale of 1–100, the MOS on a scale of 1–5.) According to International Telecommunication Union (ITU) Recommendation G.107,[6] R-factor scores are mapped to user satisfaction as follows: 60–70 (many dissatisfied), 70–80 (some dissatisfied), 80–90 (satisfied), and 90–100 (very satisfied). The VoIP application used the ITU-defined G.729A voice codec.[7] Table 4 summarizes the performance results of VoIP calls generated by DVQattest under both medium and heavy traffic loading conditions.

The results show that the one-way delay (mostly propagation delay) was the major determinant of VoIP performance quality. Furthermore, under heavy traffic loading, VoIP quality was affected by higher packet loss rates, packet discard rates, and protocol packet delay variation.

Upon investigation, it was determined that the unexpected low performance in the heavy traffic case was due to overloading of the traffic generator rather than overloading of the network. The expected results should have shown similar performance for both traffic loading conditions, because VoIP packets were marked with the highest EF class. Overall, the VoIP results are considered "fair" (on the MOS scale) and acceptable to satellite users. (Note that the ITU[6] has adopted a provisional advantage factor of 20 for satellite connections. Hence the resulting R-factor values and MOS ratings should be adjusted 20% higher than the measured values.)

Table 4. Average VoIP performance under medium and heavy traffic loading.

VoIP Performance Metrics	Traffic Loading: Medium	Traffic Loading: Heavy
R-factor (listening quality)	81.9	75.63
R-factor (conversation quality)	48.3	39.84
MOS (listening quality)	3.90	3.63
MOS (conversation quality)	2.37	2.08
Packet loss rate (%)	0.03	2.64
Packet discard rate (%)	0.00	0.94
Protocol packet delay variation (ms)	10.23	31.53
One-way delay (ms)	435.55	517.77

Table 5. Average VTC performance under medium and heavy traffic loading.

VTC Performance Metrics	Traffic Loading: Medium	Traffic Loading: Heavy
VSMQ	28.69	29.72
VSTQ	76.56	82.11
Packet loss rate (%)	0.01	0.03
Packet discard rate (%)	0.35	0.23
Packet to packet delay variation (ms)	10.34	9.31
One-way delay (ms)	454.56	451.75

VTC Performance

VTC performance was measured by the Video Service Multimedia Quality (VSMQ) and Video Service Transmission Quality (VSTQ) scores.[8] (VSMQ is measured on a scale of 0–50, VSTQ on a scale of 0–100.) The VSMQ considers the effect of picture and audio quality and audio–video synchronization on overall user experience, whereas VSTQ measures the ability of a network to carry reliable video applications. DVQattest generated all VTC applications using the ITU-defined H.264 video codec.[9] A theoretical data rate of 156.8 kbps per VTC session was predicted based on frame size and data rate. The VTC performance results shown in Table 5 were calculated for sessions that were successfully set up during the on-orbit assessment demonstration.

The results show virtually the same performance under medium and heavy traffic loading. (The slight differences observed in the packet loss rate and the packet discard rate are not statistically significant.) One-way delay and codec type are the two greatest determinants of VTC performance quality. QoS implementation provided the appropriate quality for AF41-marked traffic, and the performance of VTC was acceptable.

Web Performance

The performance of web page browsing is measured by its session throughput. During the test, the same web page was downloaded multiple times. Because the Wide Area Application Services units were enabled and included caching, all repeated web page downloads were removed from the calculations to avoid any skewing of the data. Figure 8 shows the average session throughput versus web page size. The results show that web browsing (marked as BE class) was directly affected by traffic loading:

- Under heavy traffic loading, the throughput of large web pages (>50 KB) was worse than under medium traffic loading. The larger the web page, the greater the degradation.
- Under both traffic loading conditions, the larger the file size, the greater the session throughput.

- No significant difference in throughput was observed for the small web pages (<50 KB) between medium and heavy traffic loading conditions. (Because FTP runs on top of TCP, the slow-start algorithm of TCP initially limits data throughput to avoid creating congestion. The TCP connections never reach the maximum window size, and hence small data files will generally result in low data throughput in high bandwidth-delay product networks, such as in IRIS.)

Chat

The performance of chat sessions was measured by the latency of each message in reaching its destination. Table 6 summarizes the performance results of chat:

- Under heavy traffic loads chat experienced high jitter.
- No messages were missed or duplicated with any of the traffic loads.

Chat was marked as AF21 class, and it was combined with network management traffic generated by the IRIS network. The combined AF21 traffic under heavy loading was greater than under medium loading. However, the combined AF21 traffic was relatively low compared with the overall traffic.

Application Performance With and Without PEP

Two tests were performed to assess the impact stemming from the use of PEP (Cisco's Wide Area Application Services) in the IRIS network. The first test was run with all three PEP modules enabled; the second test was run with the PEP modules disabled. Both tests were run with a traffic profile containing only FTP traffic consisting of four different file sizes. Figure 9 shows the average session throughput versus the file size of FTP traffic measured with and without PEP.

We conclude that PEP devices improved the performance of large FTP files (>100 KB) but offered little improvement (and even some degradation) for small- and medium-sized files. Through other measurements with randomly generated FTP files, it was verified that the Wide Area Application Services compression and caching combined with the PEP functions provided even higher throughputs and thereby reduced even further the consumption of satellite bandwidth.

Table 6. Chat performance under medium and heavy traffic loading.

Chat Performance Metrics	Traffic Loading: Medium	Traffic Loading: Heavy
Average latency (ms)	1,606.7	1,634.5
Standard deviation of latency (ms)	247.2	345.0
Number of undelivered messages	0	0
Number of duplicated messages	0	0
Average size of received messages (bytes)	90.5	96.8
Total number of received messages	97,129	237,020

Cross-Band, Interbeam, and Intrabeam Performance

Cross-band, interbeam, and intrabeam network configurations were assessed for differences in performance. We measured data throughput between user nodes and also round-trip delay per DSCP. Similarly, we compared the measured application performance results for VoIP, VTC, FTP, web, and chat applications. The results showed virtually identical performance among these configurations.

Operational Factors that Impacted Performance

In contrast with laboratory-based emulation tests, which are controlled events during which system conditions are created to replicate what can be expected in a field operation, on-orbit tests provide a significant amount of new information. Not only is the actual equipment used, but also other external elements (human

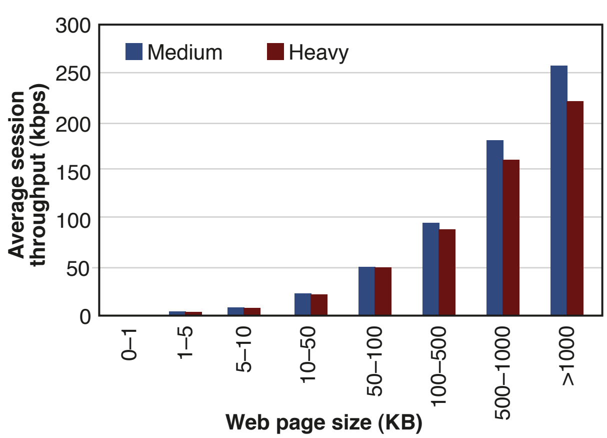

Figure 8. Web performance under medium and heavy traffic.

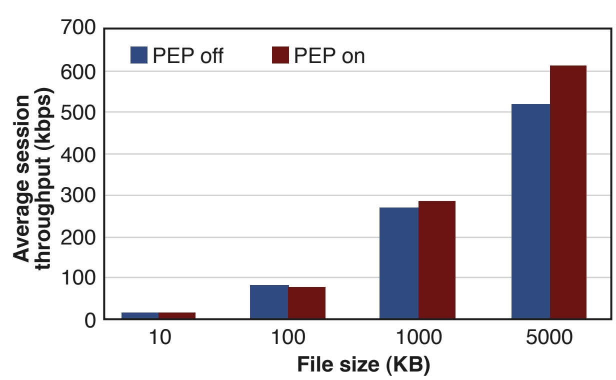

Figure 9. FTP performance with and without PEP devices.

operators, atmospheric events, etc.) that characterize a real operational network are present. The operational factors that were observed in the on-orbit demonstrations include power failures, RF equipment failures, and network equipment and user application misconfigurations. We also observed propagation-related effects (rainstorms, sun outages) and cross-polarization interference; nevertheless, these did not significantly affect the performance of the network. One major network anomaly, however, did impact network performance. The anomaly was attributed to a PSIM timer rollover, which caused the system to lose synchronization and hence caused service disruptions that lasted about 3 minutes. These events occurred somewhat periodically, a few days apart. The root causes of this problem and potential long-term solutions are being investigated by Cisco.

ON-ORBIT OPERATIONAL DEMONSTRATION

The on-orbit operational demonstration (the fourth such event for IRIS JCTD) was conducted with the Joint Interagency Task Force South (JIATF-S) and Royal Netherlands Navy (RNLN) in support of Caribbean counterdrug operations on 8–18 March 2010. This was the final operational demonstration and used the on-orbit capability and the ground infrastructure enabled by Cisco, who was supporting the event as the IRIS service provider. A key objective of the operational event was to assess the operational impact of extending Combined Enterprise Regional Information Exchange System (CENTRIXS) Multi-Lateral Enduring Contingency (MLEC) secured network onto an afloat unit supporting JIATF-S counterdrug operations.

Two distinct scenarios were conducted during the on-orbit operational demonstration. The first scenario comprised actual real-world counterdrug operations conducted by JIATF-S and RNLN. The IRIS capability was leveraged by extending the CENTRIXS MLEC onto a maritime node using approved High-Assurance IP Encryptor devices to encrypt the IP packets between the end users and MLEC services. The second scenario was a notional counter-narcoterrorism scenario conducted by role players. The role players executed specific net-centric operations to exercise the capabilities of the on-orbit operational demonstration network by using collaboration tools to develop situational awareness and to support decision making.

Figure 10 shows the types of applications available during operational demonstration in supporting JIATF-S and RNLN counterdrug operations. The RNLN frigate *Van Speijk* (F828) was able to conduct enhanced net-centric operations by using both real-time and high-bandwidth-intense communications with JIATF-S Headquarters and Commander Task Group 4.4 (CTG 4.4) at Curaçao by leveraging IRIS. With the capabilities available with IRIS, the CENTRIXS MLEC network was fully operational on the *Van Speijk*. This allowed the *Van Speijk* to coordinate and gain situational awareness by using large data files previously available only to fixed ground units.

Microsoft Communicator and Adobe Connect Pro were two collaboration tools specifically incorporated into the operational demonstration to allow the two application suites to be compared. Adobe Connect Pro is an Internet-based collaboration tool that provides ease of setup and use. However, it does not support

Figure 10. CENTRIXS MLEC. LNO, Naval Liaison Officer.

DiffServ and operates all its collaboration services at a single QoS. Microsoft Communicator, on the other hand, is a server-based program that has the capability to mark real-time packets in accordance with DiffServ, but the default mapping of voice and video packets implemented by Microsoft Communicator was different from the mapping required by the service provider's QoS plan. Additional modification and installation of Microsoft hotfixes were required, and some interoperability issues were encountered during the event. Even so, the quality of real-time applications such as voice and video (when it was able to stream) was significantly better than with Adobe Connect Pro, which could not differentiate real-time application packets from other traffic. Figure 11 provides a network overview of the two collaboration tools used during the on-orbit operational demonstration.

OVERALL ASSESSMENT

On the basis of the results obtained primarily during the final on-orbit assessment, APL prepared the *Operational Utility Assessment*[10] by addressing each of the four major COIs identified for the IRIS JCTD. The following sections describe the major findings for each COI.

Functionality and System Performance

IRIS provided direct connectivity to different user groups, terminal types, and user nodes located in distinct geographic areas. Cross-band, interbeam, and intrabeam connectivity were seamlessly achieved once the user nodes and satellite ground terminals were properly configured. The network supported multiple private enterprise networks, Internet access, and connectivity to the Public Switch Telephone Network (PSTN). The BoD functionality for managing the uplink bandwidth demonstrated the ability to allocate resources dynamically, upon request, to all terminal nodes. The laboratory emulation tests, which provided the necessary scale to load the network and create congestion conditions, showed that IRIS adequately handled any temporary surges of traffic by rapidly reassigning resources. The end-to-end QoS architecture leveraged DiffServ and effectively demonstrated interoperability of QoS features, providing clear benefits to real-time applications. The quality of VoIP and VTC, which were carried as high-priority services, was determined to be acceptable and remained consistent under various traffic conditions. The performance of nonprioritized packets (FTP, web applications, and chat), which were running at a BE level of service, varied widely and correlated well with network utilization conditions. However, as experienced in the on-orbit operational demonstration, the ability to utilize the IRIS QoS features with certain workstation applications was limited, because many of these applications do not natively support DiffServ or do not support them very well. In addition, the response to sudden surges of bandwidth was not always satisfactory. The Cisco Wide Area Application Services units improved the performance of only large FTP files but offered little improvement (and even some degradation) for small- and medium-sized FTP file transfers.

Operational Impact

During the operational demonstration, the ability to conduct multimedia collaboration by using voice, video, desktop sharing, and chat was effectively demonstrated.

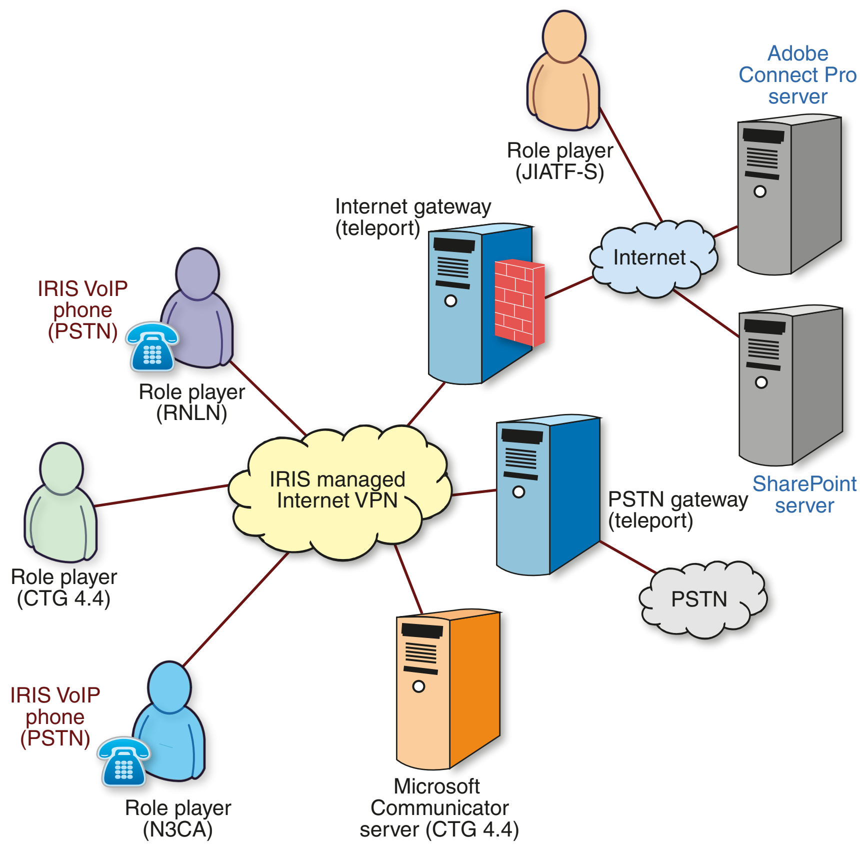

Figure 11. Network overview of on-orbit operational demonstration collaboration tools. NC3A, NATO Consultation, Command, and Control Agency.

The ability to share information among the different user nodes that were geographically dispersed was demonstrated between the Hague, CTG 4.4 Curaçao, and the RNLN frigate *Van Speijk*.

The ability to reach out and pull classified information to support situational awareness and decision making was also demonstrated by using the MLEC system onboard the *Van Speijk*. Users aboard the *Van Speijk* could chat with and send e-mail to any other operational user on the MLEC system. The *Van Speijk* was able to call any MLEC telephone and communicate in real time to support timely decision making. In addition, the *Van Speijk* had the ability to share briefings and intelligence products with critical command and control and support nodes.

Interoperability

A demonstration of interoperability with Defense Information System Network services was not conducted during the on-orbit operational demonstration. However, the CENTRIXS MLEC capability was integrated on two user nodes and on an operational Strategic Tactical Entry Point node. The CENTRIXS MLEC is an approved Secret Releasable Classified network supported by the U.S. Southern Command. CENTRIXS MLEC was extended to the RNLN frigate *Van Speijk*, which represented a maritime node. Existing CENTRIXS MLEC connectivity with CTG 4.4 was reconfigured and demonstrated over IRIS. In addition, an IRIS Earth terminal was installed at the network access point of the Americas facility so that a direct downlink into the MLEC hub could enable improved performance and eliminate potential interoperability issues.

The integration of CENTRIXS MLEC capability was fully demonstrated during the on-orbit operational demonstration. No significant issues were revealed during the operational demonstration that would preclude other CENTRIXS networks from leveraging IRIS. Considering the potential technical and policy issues that could have arisen, the integration of the CENTRIXS MLEC capability onto the RNLN *Van Speijk* went smoothly; no significant operational or integration issues were observed.

Suitability

The network architecture implemented for the on-orbit operational demonstration provided the capability to transmit to any user host on any terminal on the network over a single satellite communication hop. The ability to transmit and receive large data files supporting situational awareness at high data throughput was made possible by the reduced round-trip delay, as compared with a double-hop architecture, and through the Wide Area Application Services capabilities enabled on the CGR. Observations during the on-orbit operational demonstration reinforced the dependency on communications systems, especially hardware, supported by full-time staff or civilian contractors organic to the organization, as was the case for JIATF-S and U.S. Southern Command. The IRIS concept provided opportunities to demonstrate remote technical and troubleshooting support that could be suitable for JIIM users.

CONCLUSIONS

The overall assessment showed that the IRIS network capabilities available for the on-orbit operational demonstration performed adequately, according to the intended design. The quantitative results, together with qualitative observations obtained from the operational demonstrations, were generally acceptable in the areas of functionality and performance, interoperability, suitability, and operational impact. However, the PSIM network anomaly, which disrupted the demonstrations for short periods, remains of concern. It must be resolved before IRIS is ready for service. Finally, the issues on network reliability and equipment configuration identified during the demonstrations highlight the need for robust, real-time network management capabilities.

Although the IRIS JCTD Operational Manager will provide the final recommendation on whether the current IRIS capability is suitable for the needs of the DoD user, the successful on-orbit demonstration of IRIS represents the beginning of a new generation of commercial communication satellites.

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