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FUTURE INTEGRATED ARCHITECTURE (FIA): A PROPOSED SPACE INTERNETWORKING ARCHITECTURE FOR FUTURE OPERATIONS

by

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September 2008

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13. ABSTRACT (maximum 200 words)

In order for the U.S. military to adjust to asymmetrical warfare and fight a Global War on Terror, military leaders have had to dramatically increase the quantity and quality of information flowing across the communications networks which has strained limited network resources. Yet, increased information requirements only begin to describe the current issue. An elusive enemy and multiple theatres of conflict have increased the operational distances between front-line units and command structures increasing the demand for satellite communications. However, deployed forces currently depend on multiple satellite systems which may not always support interoperability, connectivity, and net-centricity required for enemy engagement.

This thesis begins with discussion of several current efforts attempting to address this issue as well as several enabling technologies and concepts. Key capabilities extracted from these efforts form the basis for the initial evaluation of the proposed architecture supported by the software modeling tool same here OpNet. For operational applicability, recent Marine Corps operations, concepts, and lessons learned provide basis for further evaluation. Findings support internetworking in space capabilities and a recommended modification of current architectural strategies and policies.

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FUTURE INTEGRATED ARCHITECTURE (FIA): A PROPOSED SPACE INTERNETWORKING ARCHITECTURE FOR FUTURE OPERATIONS

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LIST OF ACRONYMS AND ABBREVIATIONS

AEHF	Advanced Extremely High Frequency
AISR	Airborne Intelligence, Surveillance, Reconnaissance
AOR	Area of Responsibility
ASD/NII	Assistant Secretary of Defense / Networks and Information Integration
BEM	Bandwidth Efficient Modulation
BGP	Border Gateway Protocol
CCSDS	Consultative Committee on Space Data Systems
COI	Community Of Interest
DAMA	Demand Assigned Multiple Access
DBRA	Dynamic Bandwidth Resource Allocation
DHCP	Dynamic Host Control Protocol
DNS	Domain Name Service
DO	Distributed Operations
DSCS	Defense Satellite Communications System
DSN	Defense Switched Network
FOB	Forward Operating Base
FSO	Free Space Optics
GEO	Geosynchronous
GIG	Global Information Grid
GWOT	Global War on Terror
IEEE	Institute of Electrical and Electronics Engineers
IER	Information Exchange Requirements
IETF	Internet Engineering Task Force
IP	Internet Protocol
IRIS	Internet Routing in Space
ISL	InterSatellite Link
ISR	Intelligence, Surveillance, Reconnaissance
JCS	Joint Chiefs of Staff
JCTD	Joint Communications Technology Demonstration

LAN	Local Area Network
LEO	Low Earth Orbiting
MUOS	Mobile User Objective System
NCTAMS	Naval Computer and Telecommunications Area Master Station
NIPRnet	Non-Classified Internet Router Protocol Network
NSSO	National Security Space Office
OBP	Onboard Processing
OEF	Operation Enduring Freedom
OSI	Open Systems Interconnection
OTH	Over the Horizon
QoS	Quality of Service
RIP	Routing Information Protocol
SATCOM	Satellite Communications
SBLAN	Space-Based Local Area Network
SIPRnet	Secret Internet Router Protocol Network
STK	Satellite Toolkit
SWAP	Size, Weight, and Power
TCA	Transformational Communications Architecture
TCP	Transmission Control Protocol
TSAT	Transformational Satellite
VPN	Virtual Private Network
WAN	Wide Area Network
WiMaX	Worldwide Interoperability for Microwave Access
WGS	Wideband Global Satellite Communications

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I. INTRODUCTION

A. BACKGROUND

> Our goal is to create an "Internet in the Sky" – making it possible for U.S. Marines in a Humvee … in the middle of a rainstorm to open up their laptops, request imagery, and get it downloaded within seconds.
>
> [Teets, 2004]

September 11, 2001, forever changed the environment within which the United States conducts military operations. Our enemy now maneuvers in a global, non-state battlefield forcing us into a protracted war referred to by some leaders as "The Long War." Recent discussions amongst military leaders have characterized this future combat as irregular warfare, whereby the individual warfighter will operate with a greater knowledge of cultural sensitivities and will employ non-traditional military skills. Irregular warfare will also require forces to operate across greater distances while maintaining the required situational awareness provided by distributed intelligence sources, and remaining under the command and control of higher headquarters. This paradigm shift is accelerating a demand for information that is beginning to surpass the capacity of existing satellite communication (SATCOM) systems. As this trend continues, a better "system of systems" will be required to support more intense information demands across disparate platforms: naval, air, and ground.

However, many current satellite systems remain stovepiped; they are designed for single-purpose missions and are not fully optimized across any type of networked architecture. As the demand for bandwidth intensive information, such as imagery, continues to increase, current systems support only a small portion of these requirements, forcing heavy use of commercial systems. Furthermore, the war on terror will potentially consume U.S. operations for decades and will demand an architecture that is truly global, networked, and with a level of responsiveness not seen in today's architectures. That being said, the only way to provide this level of responsiveness is to significantly enhance capabilities of the current architecture and adopt a different paradigm in communications. This new paradigm should include a much closer and integrated partnership with the commercial satellite communications industry.

The Department of Defense recognizes this capability gap, and has validated an operational requirement to provide a true Internet-like, networked, backbone in space. Much of this recognition was developed from lessons learned and feedback from deployed operating forces as will be discussed later. The importance of this requirement was further articulated to national leadership in Congress by the previous DoD Executive Agent for Space, Mr. Peter Teets, highlighting its importance for national security. A portion of his testimony was provided at the beginning of this thesis. Therefore, a challenge has been presented to the United States and the space community to deliver the required future space architecture. The solution to this challenge will result only from a dramatic change in how space architectures are engineered. Although future uncertainty may reduce creativity and hinder any departure from status quo, a vision must be established and maintained. The vision of future space and satellite communications architectures must reflect and extend Internet capabilities, and connect disparate satellite systems across the space layer, if the United States desires to satisfy the challenge for adequate support to deployed operating forces.

B. OBJECTIVES AND CORE TENETS

The primary objective of this research is to propose a future space and satellite communications architecture that is multi-mission and multi-organization, and supports the vision as stated. Further discussion will show how the proposed architecture may improve military operations. Some current satellite communications programs of record will be analyzed, and their technologies and concepts of operations may be incorporated as they will realistically form the foundation for the future architecture. However, this research will focus on the final architecture product, or several courses of action, and to a lesser degree on the spiral development or evolution to arrive at that architecture. The bottom line is identifying the architecture which will provide the maximum level of capabilities to the operational forces while meeting key or core tenets initially articulated and defined in the research questions.

As conducting architectural studies may spin off in any number of directions, such a study requires a certain level of focus. Several attributes or tenets will become a baseline for discussion and analysis. The attributes, accompanied with the appropriate definition, are as follows:

- Connectedness: The holistic communications architecture supporting every aspect of U.S. military operations is called the Global Information Grid, or GIG. The visionary document for the GIG provides extensive discussion regarding connectivity which may be simplified as network availability at all levels of command. The GIG visionary document further states that "even at the tactical 'edge,' users have access to sufficient bandwidth which enables those users to 'pull' or 'post' important bandwidth intensive information such as high-resolution video with acceptable latency [DoD, 2007]." Any future space architecture must be viewed as an extension of the GIG. Therefore, further clarification of the GIG definition will be that connectedness which provides network availability for all users, with minimal interruptions, with any satellite communications terminal, and supports the information exchange requirements (IER).
- Interoperability: The ability of diverse systems and organizations to work together. Interoperability may also be defined as the ability of a collection of communicating entities to (a) share specified information and (b) operate on that information according to an agreed operational semantics [Grace, 2008]. Additionally, the DoD defines interoperability as "the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together [JCS, 2005]." The future space architecture will be required to provide interoperability by allowing the exchange of information and services between disparate satellite terminals, and across all levels of organization and command.
- Net-centricity: This term has been loosely referred to across the military community and may lead to a number of definitions. A general definition as stated by the Joint Chiefs of Staff (JCS), could be "a framework for full human and technical connectivity and interoperability that allows all DoD users and mission

partners to share the information they need, when they need it, in a form they can understand and act on with confidence [JCS, 2005].” A specific definition of net-centricity for this architecture will be that each satellite will leverage a common body of technical standards, or technical framework, while providing all users access to the same network and information resources with minimal training. The training aspect reflects the human element which cannot be overstated in importance. As common technical standards are vital for this architecture, they cannot impose any additional burden to the user. Technical capabilities must function in the background and support the most inexperienced user as articulated by the current Marine Corps Chief Information Officer: “He doesn’t care how it works, just as long as it works [Allen, personal communication, 2007].” Net-centricity must support cutting edge technologies and standards as well as user friendliness.

C. RESEARCH QUESTIONS

1. What space architecture should be developed to provide robustness and responsiveness for multiple missions and applications, and to support common tenets such as, connectedness, interoperability, and net-centricity?

2. How can space architectures be developed that integrate, and standardize, terrestrial Internet protocols and standards?

3. What technologies unique to the space environment could become standardized or agreed upon across the global user community?

4. How will this architecture improve operations?

D. SCOPE

The scope of this thesis will include:

- An analysis and information gathering of past, present, and future space architectures employing IRIS and Internet like capabilities.
- A study of enabling technologies.
- Modeling of key enabling technologies into a cohesive architecture.

- Analyzing the performance of the identified technologies against a Marine Corps distributed operational scenario.
- A recommendation for areas of further study and research

E. METHODOLOGY

1. Research current space communications plans and concepts supporting networking capabilities through government and industry

2. Research and analyze technologies that could best support the future space architecture.

3. Integrate plans and concepts with the identified technologies resulting in an objective architecture.

4. Model the objective architecture with OpNet and Satellite ToolKit (STK).

5. Conduct a validation of architecture in the context of a Marine Corps distributed operation.

F. ORGANIZATION OF THESIS

CHAPTER I. This chapter discusses the context, background, and justification for further research into networking space assets, leveraging core technologies such as Internet routing. This background information addresses the reasons for conducting this research, and provides a framework and foundation for further research in this area.

CHAPTER II. This chapter uncovers efforts, plans, and projects by government and industry that would contribute to and leverage this architectural concept and capability. The details of several discussions and consultations are provided in this chapter. The focus here is to discuss details of past, present, and future space networking architectures and provide a foundation for additional study and modeling.

CHAPTER III. This chapter will delve into the technical parameters of the proposed architecture, and the candidate technologies that will promote the networking aspect of space communications. The choice of these technologies is driven by information discovered during the previous chapter, and, additional technologies discovered during technology forecasting which might become architecture enablers.

CHAPTER IV. This chapter will show an integrated and complete proposed architecture. Modeling and simulation is focused on architecture performance, such as Information Exchange Requirements (IERs), using tools such as OpNet and STK. The intent here is to show a basic picture and provide a foundation for further analysis.

CHAPTER V. This chapter discusses an operational analysis of the architecture in context of the Marine Corps distributed operations concept and a recent deployment to Afghanistan. The analysis will answer the "So What?" question for making such drastic changes to future spacecraft and space communications architectures.

CHAPTER VI. This chapter provides a conclusion to the research study as well as recommends areas for further analysis and research.

II. SPACE NETWORKING IMPLEMENTATIONS AND PLANS

A. OVERVIEW

Many current government programs and commercial entities propose solutions that could improve future space architectures. This chapter will provide further discussion of these solutions as important capabilities of these solutions could support the proposed architecture to be discussed later. Each government and commercial program was measured against the previously discussed attributes: Connectedness, Interoperability, and Net-Centricity**.** These attributes became the “benchmark” by which the author chose these projects for analysis and priority of effort to approach the respective experts within each organization.

Although each program to be discussed here proposes a solution that could possibly satisfy some of the attribute definitions, no current program will fully support all of the attribute qualities as will be discussed in more detail in subsequent chapters. This is a bold statement as many of these programs maintain very large budgets and are being developed from requirements approved by senior government and commercial leadership. However, the programs discussed here highlight critically needed capabilities to be integrated into the proposed space architecture. These capabilities will be further discussed in the following chapter, and then engineered into the Future Integrated Architecture (FIA) for operational analysis.

More importantly, since there may be a shortfall in the current space architecture to fully support these attributes, a requirement may exist for government and commercial entities, national and international, to work more closely together. This teamwork could be considered similar to the current Internet whereby all nations adhere to a body of standards and protocols for seamless networking capability. The space architecture should be considered an extension of the Internet and should adhere to similar or agreed upon standards and protocols within a community of intended and authorized users.

Furthermore, since the space architecture could leverage the Internet as a model architecture as well as becoming a seamless extension of the Internet, the space segment should employ the single technology that appears pervasive and commonly applied throughout many modern networks — Internet Protocol (IP) routing. IP routing provides the core dynamic quality of Internet networks and will provide the same quality to future space networks.

B. WIDEBAND GLOBAL SATCOM (WGS)

Current military satellite communications have been categorized in three areas: wideband, narrowband, and protected. WGS will be the wideband system supporting military and government users for the next two decades, replacing the aging Defense Satellite Communications Systems (DSCS) system and providing bandwidth orders of magnitude greater than the DSCS constellation. WGS will also introduce the employment of full-duplex Ka satellite communications in addition to X band operations currently provided by DSCS. Similar to commercial systems, WGS will continue to be a bent pipe system providing point to point communications between ground nodes [Brozo, 2007].

However, a unique feature introduced by WGS is called the Channelizer. The Channelizer will provide a cross-banding capability between the X and Ka frequency bands, and will add a much needed level of interoperability and connectedness between disparate ground terminals. Many ground terminals employed throughout the military continue to operate in the X band only mode since the previous wideband satellite, DSCS, provided services only within the X band range.

The Channelizer may be considered a layer 2 switching device by providing a circuit switched capability between frequencies. Users will have to request Channelizer services configuration prior to operations via the normal Satellite Access Request/Gateway Access Request (SAR/GAR) process. The Channelizer will provide a superb networking capability in that it will allow information to traverse frequency bands between the X band and Ka band similar to current teleport and Naval Computer and Telecommunication Area Master Station (NCTAMS) capabilities. Providing space-based cross-banding will improve connectivity across all coverage areas regardless of frequency and will add a level of redundancy across the entire GIG architecture. However, it is not dynamic in nature compared to IP routing. Network and satellite controllers require a certain timeframe to validate and configure these requests so as to not interrupt current and ongoing services. WGS transponders will operate in 125 MHz mode with up to 400 Mhz in RF bypass mode as compared to commercial satellites which provide services in 36 MHz increments. Increasing transponder throughput in this manner will provide tremendous improvements in bandwidth supporting ground terminals and will support the extreme demands of the Airborne Intelligence Surveillance Reconnaissance (AISR) platforms [Brozo, 2007].

C. TRANSFORMATIONAL COMMUNICATIONS ARCHITECTURE / TRANSFORMATIONAL SATELLITE (TSAT)

As an attempt to pursue and support the goal of "Net-centricity," the National Security Space Office (NSSO), under guidance by the former Assistant Secretary of Defense for Networks and Information Integration (ASD/NII), Mr. John Stenbit, began development of an effort titled Transformational Communications Architecture (TCA) to establish an architectural roadmap to dramatically enhance the Global Information Grid with a more comprehensive integration of the space layer. The vision of TCA is an integrated global satellite communications architecture to improve data transfer capability across several large Communities of Interest (COI), to include Department of Defense, Intelligence Community, and NASA. Figure 1 illustrates the high-level view of how TCA will attempt to fulfill requirements across several military, intelligence, and civilian government communities and organizations. This figure also highlights the extension of terrestrial networking capabilities into the space architecture. However, what is not included in TCA, and not depicted in this figure, is the integration of commercial communications satellite architectures. As such, the TCA will become a government communications backbone, not unlike the existing terrestrial Internet, that will integrate other mission type satellites as well as ground infrastructure and airborne layer assets, such as Unmanned Aerial Systems (UAS) [NSSO, 2008].

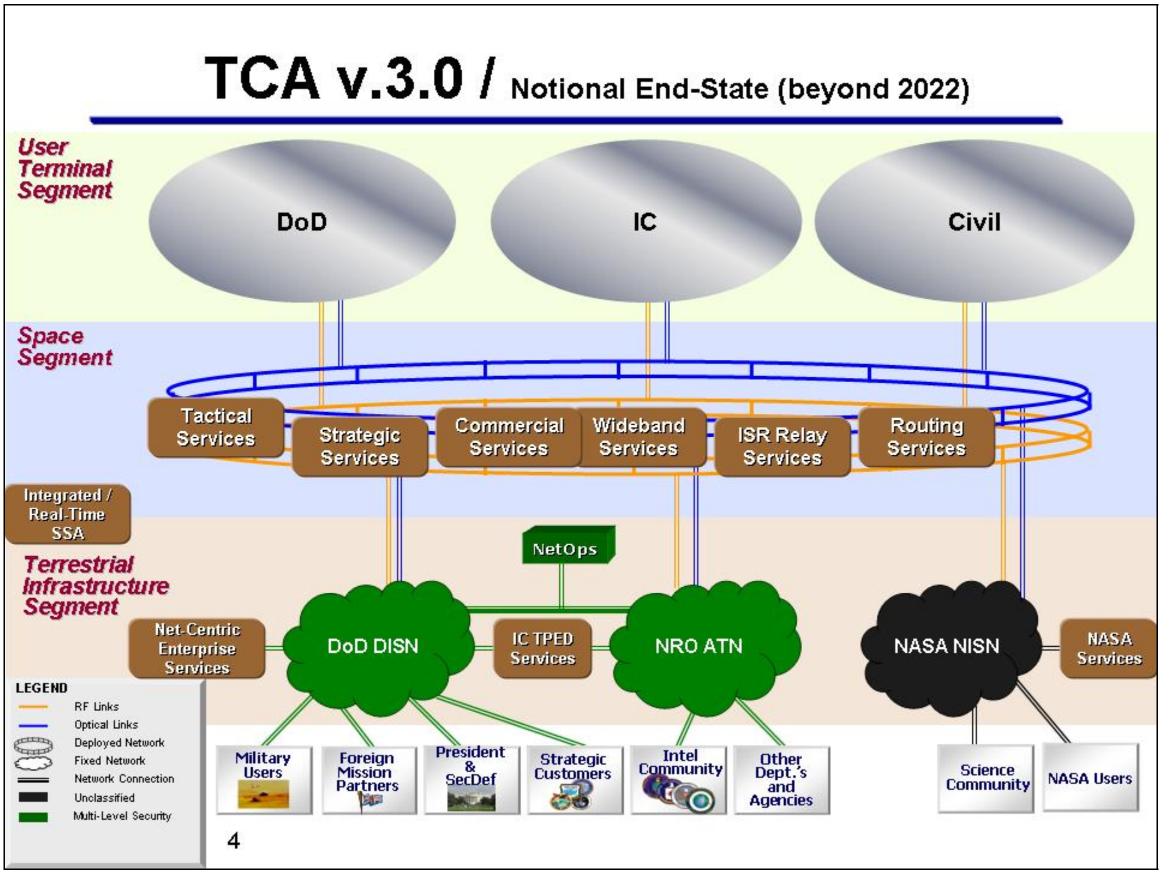

Figure 1. Transformational Communications Architecture (From: TCA)

Several variations of TCA have been produced over the past seven or eight years. The National Security Space Office Communications Functional Integration Office (NSSO Comm FIO) develops and maintains this living document, and facilitates cross-community involvement which includes all Services, OSD offices, Intelligence Community organizations, Program Offices such as TSAT, research facilities such as Massachusetts Institute of Technology (MIT) Lincoln Labs and Johns Hopkins University Applied Physics Laboratory (JHU APL), and other interested parties and stakeholders.

TCA has introduced several interesting technologies which will support future networked satellites and will be introduced and discussed here. These technologies include Dynamic Bandwidth Resource Allocation (DBRA), Bandwidth Efficient Modulation (BEM), Internet Routing in Space (IRIS), Inter-Satellite Crosslinks (ISLs), extremely high gain antenna technology, and space-based server applications such as

Dynamic Host Control Protocol (DHCP) and Domain Name Service (DNS). Although these specific applications may be new, some previous satellite communications systems have provided what is called onboard processing (OBP). OBP is a method whereby data or information entering the satellite is modified, repackaged, and sometimes compressed prior to retransmission to another station or node, such as a ground station [M. Regan, personal communication, 2004].

Although TCA will integrate several excellent capabilities, a core capability provided by TCA, as articulated in the TSAT Technical Requirements Document (TRD) is IP routing. IP routing, also known as Internet Routing in Space (IRIS), will provide a backbone infrastructure just as it has for the Internet and will provide connectivity and interoperability expected of future architectures. It is this capability, IP routing, to which Mr. Teets refers in his quote at the beginning of Chapter I. The Internet has become an autonomous, re-configurable, and self-healing network supporting millions of global users, and the future space architecture should become the space extension with IP routing as its core capability. The value of extending IP routing to the space architecture cannot be overstated. Several other efforts have or will employ IP routing and will be discussed next.

D. SPACE-BASED GROUP

SBG is another program that resides within the NSSO, and was borne from the need to increase the dynamic and flexible qualities of the future space network supporting missile defense and early warning capabilities. The other government programs representing these capabilities were seeking to pursue solutions that were different than business as usual, but with greater adaptability and affordability. Recent discussions with NSSO personnel also show an objective to develop more of a "plug and play" architecture that employs commercial and/or standardized communication protocols. In other words, the objective would be to integrate standard technologies and protocols into a number of satellites allowing the dynamic reconfiguration of network connections across the many satellites. This would be similar to an Internet user logging on and off the Internet using common, "plug and play" technologies such as 802.11, Digital

Subscriber Line (DSL), or cable connectivity. The NSSO SBG team is currently working with Air Force Space and Missile Systems Center to further study space based networking capabilities with similar plug and play qualities [NSSO, 2007].

SBG introduces a few relevant technologies and concepts referred to as Space as an Internet / Communications Backbone (SIB) and Space Based Local Area Network (SBLAN). SBLAN is a recently adopted term and acronym to show networking of assets in space, and the focus of future study. The goal of the SBLAN study is to solicit solutions from commercial satellite companies that could provide a space plug and play capability in support of an early warning or weather-sensing satellite, known generically as mission satellites, which would be positioned near the communications satellite. The communications satellite would become a point of presence as termed in the Internet community, thus providing ready and available network access for the sensing or mission satellite. Figure 2 illustrates the SBG concept by showing the communications satellite, depicted by the larger satellites, with the mission satellites, as depicted by the small satellites, positioned nearby. As other mission satellites are launched and positioned, plug and play technologies would allow these new satellites to quickly join the network. Wireless technologies, such as IEEE 802.16, would provide the required connectivity and could be visualized in this diagram with a virtual line across or though all satellites in the network. The communications satellites would be similar to an Internet Service Provider (ISP), in space.

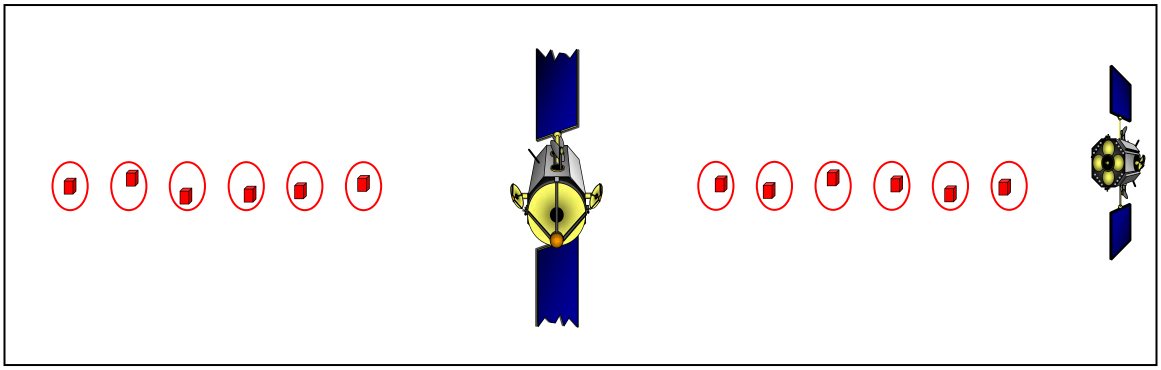

Figure 2. Space Based Group OV [From: NSSO]

There are several savings resulting from the SBG architecture configuration. With respect to size, weight, and power (SWAP), the communications subsystem of the mission satellites would only be concerned with transmission over a much shorter distance in the space environment, such as 15 km vice 36,000 km to a ground station. Additionally, the link budget would be improved not only from the reduction in free space path loss but from the reduced atmospheric attenuation. An improved link budget from the data source, or the sensing satellite, could greatly improve bandwidth performance while also leveraging the high bandwidth connectivity between the communications satellites and ground stations.

However, another point brought to attention after further discussion with the NSSO SBG team is the "origination" of data and information that suits this type of architecture. The team feels that data that is generated in space, or near space such as from UAS/UAV systems, would be most appropriate for this type of architecture. The employment of additional communications assets within this concept would, in their opinion, further require another communications satellite with the majority of similar subsystems as required in a communications satellite [J. Cosby, personal communication, 2008]. However, the author disagrees with this position. A communications relay satellite could serve as a mission satellite and could provide an additional point of presence and a common interface between government and commercial communications satellites. As was discussed with TCA, commercial communications satellites are not fully integrated into the existing space networking vision. However, commercial communications satellites have supported up to 80% of bandwidth in recent operations such as Operation Iraqi Freedom (OIF) [Allen, 2003]. As such, a communications mission satellite could provide the level of connectivity, interoperability, and net-centricity required for integrated government and commercial architectures.

E. NASA

Future space exploration will provide a venue for tremendous changes in space communications networks. In anticipation and preparation for increased activity within the Moon and Mars environment, NASA has been developing concepts and plans for a robust network. The organizational vision that has been driving this architecture development is called Vision for Space Exploration (VSE). This includes the retirement of the Space Shuttle and the introduction of the Crew Exploration Vehicle (CEV) leading manned and robotic missions to the Moon, Mars, and other areas of the Solar System. But, more importantly for this discussion, NASA experts have been diligently working on the future networked space communications architecture.

NASA formed a Space Communication Architecture Working Group (SCAWG) which produced an initial and formal baseline for future communications systems and architecture development supporting Deep Space Operations. This group developed an architecture that encompasses several networking capabilities across several operational phases and user segments. Unlike past space exploration missions, this future space network will be required to support multiple types of information and data such as HTML, FTP, email, TTC data, and real time services such as voice and video. COTS technologies will be leveraged to the maximum extent possible so as to reduce integration costs and increase potential for future international interoperability.

The future Deep Space Network (DSN) will be segmented into several components and phases for management and security. The first segment comprises the ground and near earth network elements, consisting of the ground based network between NASA locations, satellite gateways, and near Earth satellite relays, such as with the current TDRSS system. The current TDRSS system is a layer 2 relay which is also known as Bent Pipe similar to current GEO communications satellites. What is interesting is that the replacement for the current TDRSS system will be similar in capabilities and will not employ any Layer 3 technologies. The justification for the lack of layer 3 technologies is that the current data relay system provides excellent communications support to current missions, and is deemed worthy and adequate for future missions. Additionally, NASA believes the ground segment is less expensive and easier to configure than the space segment.

The other network segments will support Lunar and Martian missions. For many reasons, to include the lack of a robust ground segment, these segments will have integrated layer 3 IP routing at almost every network node. The first phase will show the development of the lunar network and will integrate a number of currently employed technologies and protocols such as array antenna technology, Demand Assigned Multiple Access (DAMA) and QOS networking techniques, Internet routing, and wireless technologies such as IEEE 802.16. One of the key attributes of this network is the dynamic quality inherent at all nodes which includes Lunar Orbiters (similar to Earth GEO and LEO satellites), LOS point to point using 802.16 (similar to commercial terrestrial cellular networks), and long haul microwave links to the Earth networks, Earth orbiting satellites, or LaGrange point relays [NASA,2006].

The Martian network will prove quite challenging. Similar to the Earth and Lunar networks, the Mars network will utilize constellations of LEO and GEO satellites providing coverage across every point of the Martian surface. However, despite the challenges, the integration of IP core technologies will provide the basis for network robustness which is the key attribute of the deep space network supporting human safety. Given the extreme distances, the Martian network will also employ a technology called DTN, Delay Tolerant Networking [Schier, 2007].

Figure 3 illustrates the high-level view of the entire Deep Space Network. The Earth network will provide the baseline architecture and primary node for all DSN networks. The Moon and Mars will act as critical nodes and will support Local Area Networks (LAN) with cross-links between the major nodes as Wide Area Network (WAN) connectivity.

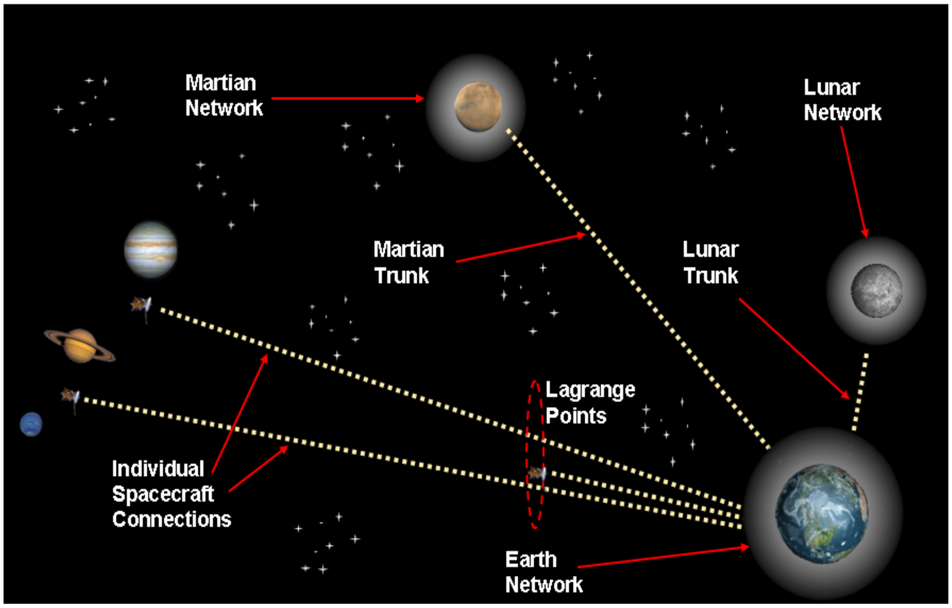

Figure 3. Deep Space Network OV [From: NASA]

Significant similarities exist between planetary networks and the Earth LEO and GEO communications and ground networks, which is why the NASA DSN is briefly discussed in this chapter. Future DSN and other planetary satellite communications systems will leverage successes and lessons learned from Earth GEO and LEO networks. Additionally, similar to other programs and efforts discussed, COTS and Internet technologies will be employed to the maximum extent possible to maintain affordability and leverage technological development previously completed. Employing standards could also encourage partnerships with other space-faring nations. The Deep Space Network should provide a strong baseline for future interoperability with Internet based networks employed not only by other international government's space programs, but with future commercial ventures as well.

F. INTERNET ROUTING IN SPACE (IRIS) JOINT CAPABILITIES TECHNOLOGY DEMONSTRATION (JCTD)

Although IP routing / Internet Routing in Space (IRIS) was previously discussed in the TCA section as a core capability, the IRIS Joint Capabilities Technology Demonstration (JCTD) is currently underway to provide additional focus and experimentation regarding this capability. As the overall TCA effort has experienced delays and setbacks, the Commander of Strategic Command was approached with an opportunity to show a “proof of concept” for integration of IP routing, and routers, into future communications satellites. Intelsat, along with the Strategic Command staff, briefed General Cartwright regarding the employment of IRIS in the IS-14 Ku and C band satellite scheduled to be launched during FY-09. Understanding that this capability has yet to be proven in space across the network, and current programs of record will not deliver for some time, the General directed his staff to pursue IP routing in space as a 2009 JCTD [Florio, 2007].

IRIS will provide a tremendous opportunity to operationally test the impact of extending Internet like capabilities into the space layer. The satellite, IS-14, will integrate a Cisco router behind, or as an IP backplane to, the Ku and C band portions of the satellite. As such, incoming information and signals will be demodulated prior to routing, and then remodulated for transmission via the downlinks. This will provide the ability to multicast to any number of users and terminals within the IS-14 beam coverage and network. Additionally, since the signal is de-modulated and re-modulated, signal gains are experienced allowing even better support for small or disadvantaged terminals. The other feature is the dynamic environment this creates due to the nature of IP, which also creates additional management and security concerns. Intelsat and Strategic Command will support a three-month operational test and evaluation period providing valuable data for future IRIS networks. Following this evaluation period, the satellite will be completely returned to the control of Intelsat for normal operations. Furthermore, the IRIS only supports three of the many transponders aboard IS-14 [Florio, 2007].

Figure 4 illustrates the IRIS architecture which shows the IRIS router as an extension of the terrestrial network unlike current implementations of IP routing only in ground networks

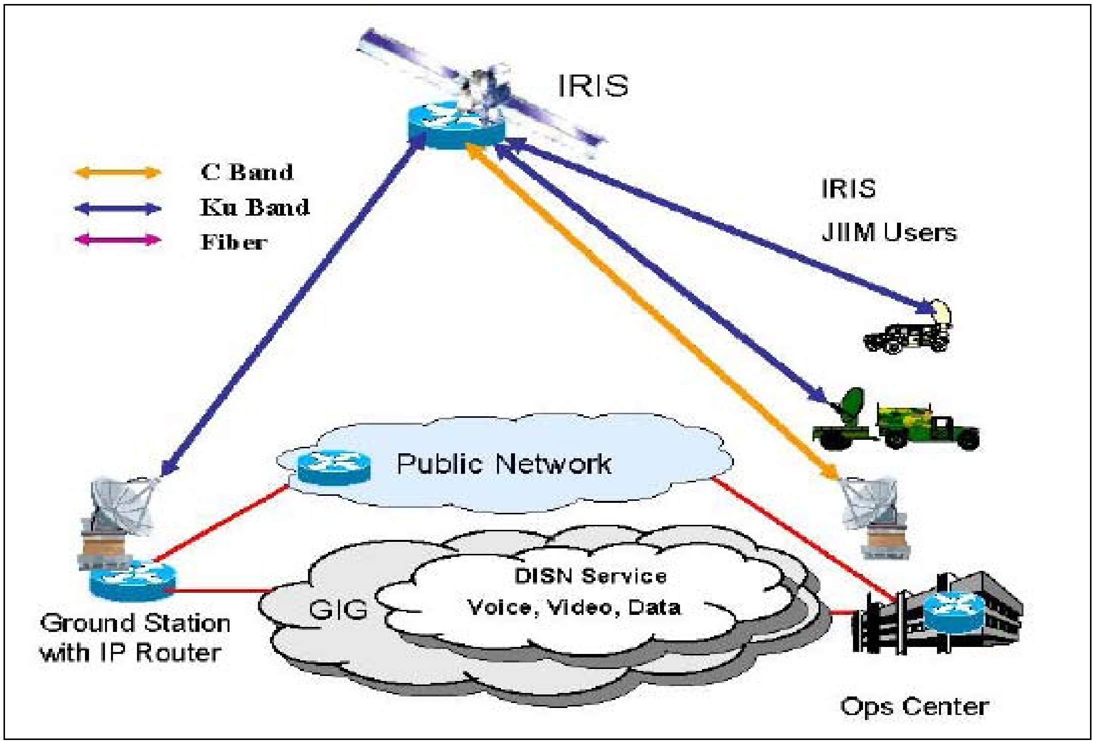

Figure 4. IRIS OV [From: Florio]

G. INTELSAT

As just discussed, Intelsat will provide the initial proof of concept for IRIS capabilities. However, future corporate plans show additional and expanded capabilities. Similar to SBG, Intelsat has been exploring the capability or option for "Near Field Wireless." The concept here is for a communications satellite to provide a wireless "access point" for other types and categories of satellites. For example, sensing satellites, such as Environmental Monitoring, could be positioned in near proximity (i.e., 15 KM) to the communications satellite and experience a reduction in size, weight, power, and link budget due to the requirement to communicate over the short distance vice the 36,000+ km directly to an Earth gateway. In a sense, the space-based LAN will provide an Internet WAN connection across the GEO layer if employed by many communications satellites [J. Cosby, personal communication, 2008].

Figure 5 highlights the capability with the communications satellite acting as a point of presence in space. In this example, the IEEE 802.16 standard dynamically connects the sister satellite with the communications satellite. The sister satellite may be considered synonymous with the mission satellite discussed in Space-Based Group. The enabling capability for this architecture is the IP router integrated within the communications satellite. Similar to the IRIS JCTD, the IP router will allow dynamic integration of any type of sister or mission satellite while also providing a space extension to the Internet or terrestrial networks. Again, the value of IP routing cannot be overstated and will be further analyzed within the Future Integrated Architecture.

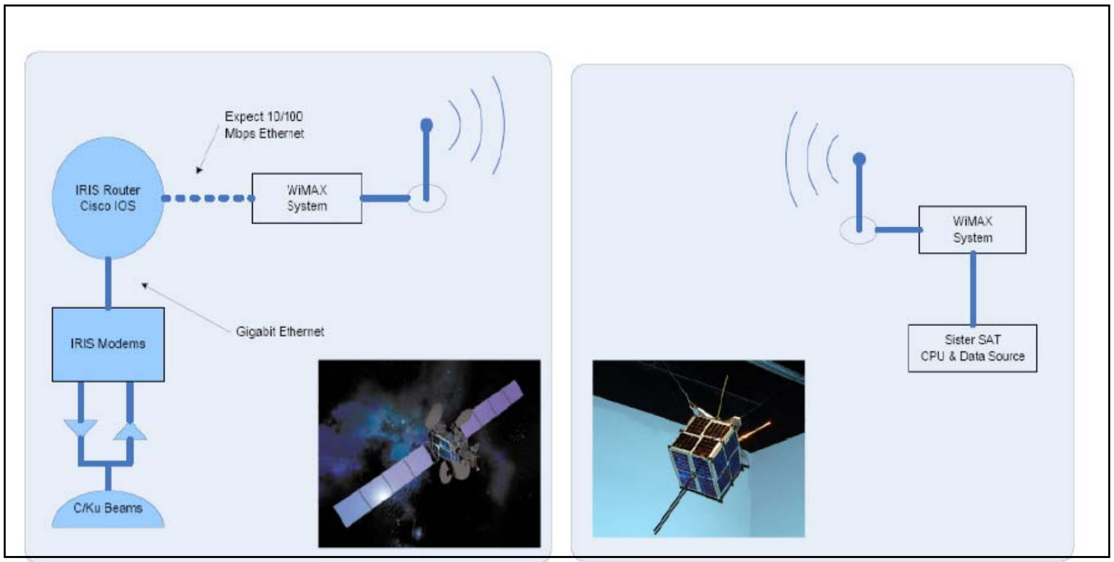

Figure 5. GEO Near Field Wireless / Space-Based LAN [From: Caulfield]

H. SURREY SATELLITE U.K.

Surrey Satellite, from the United Kingdom, was one of first satellite providers to employ a true IP router. Surry partnered with Cisco in 2003 for IP router integration into a Surrey LEO Disaster Monitoring Constellation (DMC) satellite. As an earlier implementation of space based routing, there were lessons learned regarding the space qualification of a COTS router. For example, terrestrial routers employ certain metallic substances, such as Tin, that when exposed to a space environment will significantly degrade performance and reduce system lifetimes. Therefore, Tin components may have to be replaced by Lead components.

The overall DMC experiment was successful as it proved that a small, mobile router could be integrated into spacecraft allowing for IP addressable sub-systems, and for a potential virtual control capability across terrestrial data networks such as the Internet. So, very simply stated, the DMC satellite became an extension of the terrestrial network and operated within the same simple, powerful demonstration. The Cisco mobile router aboard operated as any other routed node on the Internet today [Wood, 2005].

The Surrey experiment also provided other interesting points with respect to space data communications at other Open Systems Interconnection (OSI) layers. As the International Engineering Task Force (IETF) provides a body of standards for the Internet, Consultative Committee for Space Data Systems (CCSDS) provides a body of standards for space data communications. However, the CCSDS recommends certain data standards that may or may not be similar and/or interoperable with IETF standards. One of these standards involves file transfer protocols. CCSDS shows a recommended standard called File Delivery Protocol (FDP) while terrestrial networks may employ a User Datagram Protocol (UDP) based file transfer protocol. Results from the Surry experiment show that employment of the UDP based protocol actually improved performance during image transfers as compared to FDP due to reduced packet size [B. Maskell, personal communication, 2008].

Surry DMC provided an excellent venue with IP router/networking integration into a LEO spacecraft. However, as we discussed during GEO programs employing similar capabilities, the power of a networking capability may surface when connecting numerous spacecraft. The next section discussing Iridium will provide some insight into LEO networking.

I. IRIDIUM

As one of the few LEO communications constellations, Iridium has provided a wide variety of customers with space based cell phone like services. In particular, military users have successfully integrated this capability into their respective architectures. Many of the younger military personnel have found the Iridium terminal/handset very much like the terrestrial cellular phone. The only difference between Iridium and terrestrial cellular is that the “cell tower” is the Iridium satellite which provides over-the-horizon (OTH) communications beyond that of current terrestrial military systems such as with SINCGARS or UHF.

Another feature, and maybe one of the most important, is information flow throughout the Iridium constellation while interfacing with terrestrial networks (i.e., DISN) via only one gateway. The current Iridium constellation employs layer 2 switching capability leveraging the Asynchronous Transfer Mode (ATM) technology. Routes are pre-defined across ISLs which travel North/South across the same plane, or orbital altitude, and East/West with other planes. Recent discussions with Iridium show that the East/West ISLs communicate or connect between approximately 50 degrees South and North latitude due to the gimbaling requirements of ISL antennas. Due the polar orbit of the Iridium constellation, all satellites quickly converge closer to the poles making it challenging for differing planes and altitudes to communicate. However, since satellites are connected via a number of ISLs, data and information quickly transit across the network to the gateway for call setup and terrestrial network interface. The ISLs, combined with the space to ground links, allow for data exchange with existing IP networks such as NIPRNet and the Internet albeit at the much lower data rate than GEO satellites due to the LEO design characteristics.

The future Iridium constellation promises to show even greater capabilities. A recent discussion with George Xenakis, lead project manager for Iridium’s future follow on constellation, dubbed as NEXT, revealed that they are currently in source selection at this point in time with three different companies: Loral, Thales, and Lockheed Martin. Over the course of the coming year, the source selection process will produce a winning vendor and will also shape the specific technologies and characteristics of the NEXT satellites. However, discussions revealed that although there will be some level of IP routing aboard the satellite and across the constellation. But, the future network cannot afford a full IP capability as employed by terrestrial networks due to available bandwidth constraints and overhead requirements. So, for example, NEXT may employ and integrate a Cisco router but with much reduced capability. One feature of terrestrial routers is the ability to constantly exchange routing tables which provides the very dynamic quality of IP networks. For NEXT, instead of employing this capability, routes will maintain a more static form similar to current Iridium constellation. Due to the dynamic quality of the LEO constellation, exchanging of routing tables would pose a significant level of overhead across the network and degrade needed bandwidth and performance. Additionally, future terminals, or handsets, will become IP addressable. In summary, "we will not employ a full IP capability, but a much reduced level of routing while integrating more of a Virtual Private Network (VPN) quality by encapsulating IP packets from external networks" [Xenakis, personal communication, 2008].

And, with respect to hosting other payloads, Iridium is currently reviewing candidate payloads for host applications aboard NEXT satellites. However, the hosted payload may not exceed 10% of the dry mass of the NEXT satellite, and may not degrade the core communications services across the NEXT network. The Iridium team was not at liberty to disclose specific payload candidates due to the current stage of source selection and payload sensitivities [Xenakis, personal communication, 2008].

J. DARPA F6

The space industry continues to become increasingly competitive, striving for improvements with respect to delivering space capabilities and supporting future operations. Dissatisfaction across the industry has led to experimental efforts to better address programmatic challenges, future threats, and uncertainty. Operationally Responsive Space has become a key concept as the need for quicker and more efficient launch capabilities providing ad hoc like assets during major operations, or as the need arises. Regardless of the approach, the future of space architectures is uncertain.

In order to mitigate uncertainty and continue improvement of future capabilities, DARPA stood up a program titled F6 – Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft – that will provide one solution or course of action to address the uncertainty of future architectures. The premise behind F6 is "to demonstrate the feasibility and benefits of a satellite architecture wherein the functionality of a traditional ('monolithic') spacecraft is replaced by a cluster of wirelessly-interconnected spacecraft modules [DARPA, 2007]." Present and past spacecraft have been monolithic, whereby all subsystems are physically docked or connected to each other across a common bus and structure. F6 will produce spacecraft that contain subsystems operating with each other, just as today, however with no physical connectivity. This lack of physical connectivity will require advancements in several areas of technology that are not currently employed in current architectures.

After analysis by the F6 team, several technology areas were identified to support fractionated spacecraft including: networking, wireless communication, distributed computing, wireless power transfer, cluster navigation, and distributed payload operation. However, there may be an assumption of a "common" communications backbone or infrastructure that would support disparate systems. No specific or "must have" orbital parameters are discussed, but it appears that a majority of the work and research has been focused upon LEO spacecraft with some level of interoperability with GEO spacecraft [DARPA, 2007].

The networking and wireless technology focus areas require a self-healing, robust, flexible, net centric infrastructure for robust inter and intra-spacecraft communications. Information exchange requirements will include all TT&C and subsystem management commands, payload support operations, and cross-network support. In other words, the combination of these capability areas should behave similar to terrestrial wireless networks which support multiple forms of data such as voice, video, email, etc., [E. Sundberg, personal communication, 2008].

F6 becomes an interesting study of future uncertainty. Many government programs and efforts experience uncertainty in funding, requirements definition, technology readiness, leadership preferences and turnover, and political atmosphere. As a result, programmed capabilities may never achieve or fully support user's requirements leaving commercial augmentation as a necessary architectural element. This program leverages this uncertainty into ongoing research of future space architectures.

K. SIMILARITIES ACROSS EFFORTS

What do these efforts have in common? What is the relevance to the thesis discussion? Additional studies modeling the environment of networked spacecraft may show dramatic and positive results for user applications, as will be further discussed in Future Integrated Architecture. The collective research efforts show that government and commercial organizations are committed to networking the future space architecture. Satellite developers, providers, and program managers have initiated a change in how satellite communications are employed. Much of this desire may be attributed to the successful implementation of a data network called the Internet. Research and discussions with the experts have shown that a key reason for this change or shift in visions is the desire for more efficient space networks, and greater value for both providers and customers. The next chapter will discuss many of the potential technologies in some detail.

III. ENABLING TECHNOLOGIES, STANDARDS, AND CONCEPTS

A. OVERVIEW

This chapter will provide a discussion regarding candidate and potential technologies and standards that could enable a powerful space-based networked architecture. The entire breadth or detail of space and/or data networking standards is not proposed. Instead, the intent is to briefly discuss certain capabilities that could further enable the extension of internetworking into space, or have been considered by international bodies. The majority of these technologies will be taken from the efforts discussed in Chapter II, and will form the core discussion as to how they would best provide the future satellite communications architecture for a variety of operations. Specifics of the operations and applications will be discussed in following chapters. The technologies to be analyzed are: Internet Routing in Space (IRIS), other networking technologies such as CCSDS standards, wireless communications such as 802.16 and optical/Free Space Optics (FSO) technologies, and network/resource management schemes.

B. INTERNET ROUTING IN SPACE (IRIS)

The modern Internet provides an excellent model into a nodal architecture that is extremely dynamic, robust, and flexible. It is this technology that best supports the network attributes stated earlier in this thesis: connectedness, interoperability, and net-centricity. And, like the Internet, government networks will be required to support a multitude of user communities while the information exchange requirements between the communities changes on a daily basis. Many users across the community mistakenly interchange layer 2, switching, and layer 3, routing. A more detailed discussion will help to clarify the unique capabilities provided by IP routing and IRIS.

The individual nodes must be capable of constant change without apparent disruption or change to these user communities. Since space networks should further extend the terrestrial and airborne networks as discussed in Chapter I, IP packet routing and switching seems to be a logical choice for advancing network capabilities. The GIG Vision compares all future networks, to include space networks, to the Internet, because

> like the Internet, the target GIGs scalable, robust, and highly available communication infrastructure is based on packet switching to interconnect anyone, anywhere, at any time with any type of information such as voice, video, images, or text. With this common Internet Protocol (IP)-based packet communications layer, an information transfer through an EHF MilSatCom terminal to an UHF terminal or to a wired device is transparent to users. Also transparent is an information transfer from an Army brigade to a nearby Marine unit [DoD, 2007].

What makes the router dynamic and able to best serve this architecture? First, what is routing? Routing dynamically manages IP packets across the network by employing software algorithms at each node, or router, to determine a unique path for the packets. Figure 6 provides a visual description to support this discussion. As shown, the packet will contain a source address which will allow intermediate nodes and routers to decide the most efficient transmission path for the packet. Routing is a layer 3 technology which is different than layer 2 switching technologies. As was mentioned, many users across the community confuse layer 2 and layer 3 with respect to satellite communications. Layer 2 defines a more static, connected capability rather than a dynamically routed capability. Routing involves two basic activities: determining optimal routing paths and transporting information groups (typically called packets) through an internetwork. In the context of the routing process, the latter of these is referred to as packet switching. Although packet switching is relatively straightforward, path determination can be very complex [Cisco, 2008]. IP routing as defined here will provide the core capability for FIA.

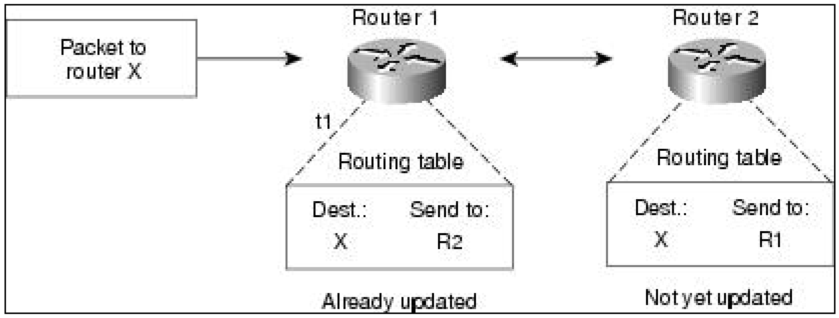

Figure 6. Sample routing configuration [From: Cisco]

For clarity, several additional terms require definition: OSI reference model, and internetworking. OSI stands for The Open Systems Interconnection Basic Reference Model (OSI Reference Model or OSI Model) is a layered, abstract description for communications and computer network protocol design. It was developed as part of the Open Systems Interconnection (OSI) initiative and is sometimes known as the OSI seven layer model. From top to bottom, the OSI Model consists of the Application, Presentation, Session, Transport, Network, Data Link, and Physical layers. A layer is a collection of related functions that provides services to the layer above it and receives service from the layer below it. For example, a layer that provides error-free communications across a network provides the path needed by applications above it, while it calls the next lower layer to send and receive packets that make up the contents of the path.

The OSI model provides for a type of network connection called connectionless-mode transmission. This mode of transmission allows disparate and logically separated networks and nodes to send a single data unit across the network, via several "service-access-points," without established a firm connection. Previous networks were engineered to establish a true physical connection and might have been known as circuit switched. However, with the connectionless-mode, the sending node may initiate transmission by invoking a single network access request. It will be connectionless-mode operation that will provide the true dynamic and flexible qualities required to further extend data networks into space [ISO, 1996].

The OSI layer that is most known and commonly referenced for such a network, and for IRIS, is Layer 3, the Network layer. This layer provides the functional and procedural means for connectionless-mode, or connection-mode, transmission between nodes and introduces routing and data relay independence. For readers familiar with the Internet, IP addresses are contained in this layer and provide the addressing scheme across the entire network, similar to the Postal Service for traditional “snail-mail” services. The IP addressing scheme provides the basis for IP routing, which may also be known as Internet routing. Internet routing services provide gateway functions which may be confused with application layer translations. IP routing is a very dynamic capability. Dynamic routing requires that routes, or connectionless-mode pathways between nodes, be calculated automatically at regular intervals by software in routing devices, or routers. The routers maintain what is called an IP routing table which consists of destination addresses and next hop addresses. Please visit the Cisco Internetworking Handbook website for further details into this process. Finally, IP routing requires that IP packets traverse the network, or internetworks, one hop/router/node at a time. Each node invokes algorithms which determine the next route.

As such, the combination of IP routing and OSI capabilities discussed form what is called an internetwork. An internetwork is a collection of individual networks, connected by intermediate networking devices, that functions as a single large network. Internetworking refers to the industry, products, and procedures that meet the challenge of creating and administering internetworks. The OSI reference model, Layer 3 protocols, and IP routing will provide the foundation for future space networks, or space internetworks [Cisco, 2008]. Figure 7 provides the traditional terrestrial view of an internetwork. Each computer and client is connected with every other client across the WAN, or Wide Area Network, through the connectionless-mode and routed architecture. Routing becomes a common networking language that interconnects many physical mediums such as Ethernet and Fiber as illustrated in this figure. The future space network will be required to be an extension of this network. And, for the remainder of this discussion, networks could be considered synonymous with space internetworks.

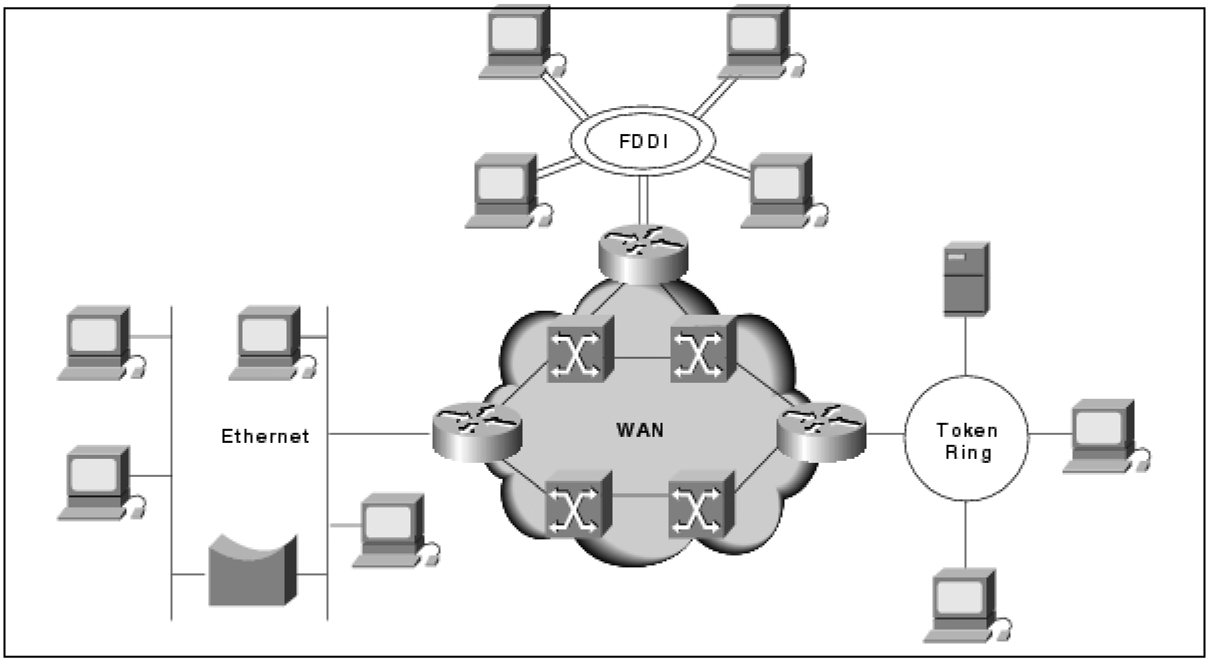

Figure 7. Example of generic internetwork [From: Cisco]

C. OTHER NETWORKING TECHNOLOGIES

Other technologies that are very much related to IP networking and routing, however may require separate discussions. Further detail into the OSI and TCP/IP protocol stacks is not provided here. However, further discussion is required regarding the capabilities that are a part of, or similar to, these families and require consideration in future space internetworks. These technologies are as follows: Dynamic Host Configuration Protocol (DHCP) and CCSDS Standards / Space Internetworking Standards (SIS).

1. Dynamic Host Control Protocol

As an Application Layer protocol, "Dynamic Host Configuration Protocol (DHCP) is a protocol used by networked devices (clients) to obtain the parameters necessary for operation in an Internet Protocol network. This protocol reduces system administration workload, allowing devices to be added to the network with little or no manual configurations [Cisco, 2008]." DHCP provides a partial network management capability from a single DHCP server, or a group of DHCP servers. DHCP adds new machines to the local network regardless of network size. When a DHCP-configured client connects to a network, the DHCP client sends a broadcast query requesting necessary information from a DHCP server. The DHCP server manages a pool of IP addresses and information about client configuration parameters such as the default gateway, the domain name, the DNS servers, other servers such as time servers, and so forth. Upon receipt of a valid request, the server will assign an IP address to the requesting user or node such as a satellite terminal. In the case of a satellite terminal, the request for DHCP services could be made immediately but must be completed before the terminal can initiate IP-based communication with other terminals. The best-known mode is dynamic, in which the terminal is provided a "lease" on an IP address for a period of time. At any time before the lease expires, the terminal can request renewal of the lease on the current IP address. In this model, the DHCP server could reside onboard the satellite and be used as a terminal authentication process [Cisco, 2008].

2. Consultative Committee for Space Data Systems: Space Internetworking Services (SIS)

CCSDS stands for the Consultative Committee for Space Data Systems and is a multi-national, multi-member organization intended to address standardization for space communications and space data systems. “The Consultative Committee for Space Data Systems (CCSDS) was formed in 1982 by the major space agencies of the world to provide a forum for discussion of common problems in the development and operation of space data systems. It is currently composed of ten member agencies, twenty-two observer agencies, and over 100 industrial associates [CCSDS, 2008].” CCSDS standards are categorized in the following areas: Mission Operations and Information Management Services, Spacecraft Onboard Interface Services, System Engineering, Cross Support Services, Space Link Services, and Space Internetworking Services (SIS). The areas of most interest here are Space Internetworking Services.

CCSDS “bins” the standards within several categories. Organized by color, they are as follows: Blue documents show recommended and currently employed standards, magenta documents show recommended standards, green documents show informational standards, and orange documents show experimental and future standards/topics for further discussion. This discussion will focus on Blue standards, with some reference to Orange/experimental standards as they may become relevant for future networks [CCSDS, 2003, 2006, 2007, 2008].

Within SIS, we find several standard protocols on the retired list, or soon to be discontinued as an international standard, for a number of reasons which include wider adoption and employment of OSI and TCP/IP protocols. However, the following SIS standards remain valid and considered for space internetworking: Space Packet Protocol and Space Communications Protocol Specification (SCPS)—Transport Protocol (SCPS-TP). The Space Packet Protocol articulates requirements for efficient data transfer of various types and characteristics over a space network involving multiple ground and space nodes. Figure 8 highlights the location of the Space Packet Protocol within the protocol stack. The Space Packet Protocol provides a half-duplex traffic flow from a single node to multiple nodes through multiple subnetworks, or subnets. The path from the source user application to the destination user application(s) through the subnetwork(s) is called a Logical Data Path (LDP) and will be assumed later in our Opnet simulation discussions [CCSDS, 2003].

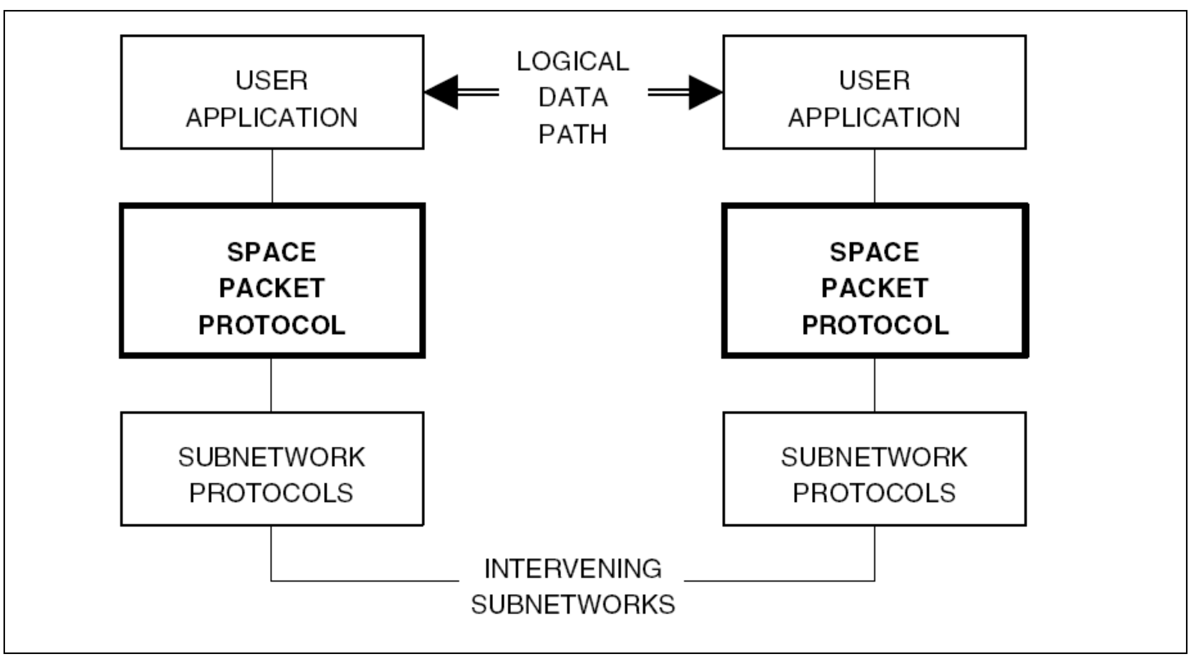

Figure 8. SIS Protocol Stack [From: CCSDS]

Throughout the traffic flow, packets are subject to other protocols, such as IP routing, provided by each subnet and are independent of SIS protocol stack. This may also be known as connection-less mode transmission, and is similar behavior to IP routers as they employ algorithms to determine the next best route. Although this protocol is very similar to TCP/IP protocols and addressing employed by terrestrial networks, in order to continue integration of this protocol, IP packets would have to be encapsulated [CCSDS,2003].

The other SIS protocol recommended for space networks is SCPS-TP. As other CCSDS networking standards are retired and networks become increasingly based upon OSI and TCP/IP standards, the SCPS Transport Protocol maintains its presence and usefulness. The majority of IP networks employ Transmission Control Protocols, TCP, for a variety of applications. TCP employs a 3-handshake algorithm that insures reliable delivery of information to the destination. Intermediate nodes may not have impact to TCP performance as they simply relay the packet towards the destination while only the source and destination nodes employ the algorithm. As such, TCP supports connectionless-mode networks as dedicated circuits, or connected-mode, are not required leading to a dynamic and flexible network capability. UDP may be employed to support Real Time Services, such as voice and video, as this protocol avoids the overhead and potential latency provided by the multiple acknowledgments of TCP.

SCPS-TP adds extensions to TCP and UDP for use in spacecraft communications environments which may show long delays as compared to terrestrial networks. Other characteristics of space communications that SCPS-TP attempts to address are the unbalanced forward- and return-link data rates, and the potentially high error rates. Therefore, SCPS-TP adopts the existing Transmission Control Protocol (TCP) standard as employed by the current Internet, and refers collectively to the protocols that provide the full reliability, best-effort reliability, and minimal reliability services. The full reliability service is provided by TCP. The best-effort service is provided by TCP with minor modifications. The minimal reliability service is provided by UDP. For the remainder of our discussion, we will articulate TCP standards and extensions as these become the most challenging in the space environment [CCSDS, 2006].

D. WIRELESS TECHNOLOGIES

1. IEEE 802.16

The 802.16 standard is most commonly known as WiMax which stands for Worldwide Interoperability for Microwave Access. WiMax is an IEEE standard providing guidance for wireless deployment for WANs for point-to-point or multipoint and beyond line of site wireless network access. The industry trade group WiMax Forum TM has defined WiMax "as a 'last mile' broadband wireless access (BWA) alternative to cable modem service, telephone company Digital Subscriber Line (DSL) or T1/E1 service [WiMax Forum, 2008]." WiMax is designed for broadband wireless access for increased range, up to 30 or so miles, and capable to support multiple data types including voice and video. This standard is also very flexible in the methodology used to support users connecting and disconnecting from the network in an ad hoc environment. Figure 9 shows a basic terrestrial model of WiMax deployment in an urban environment.

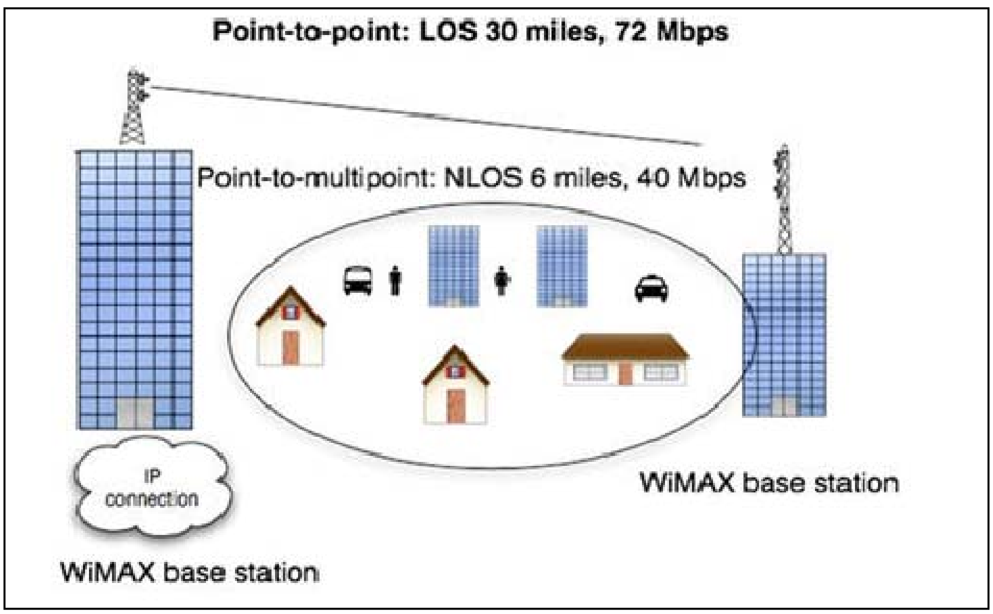

Figure 9. WiMax terrestrial model [From: WiMax Forum]

WiMax provides capability through the bottom two layers of the OSI model: physical and data link layers. The physical layer specifies frequency range of 10 – 60 GHz operation and supports ad hoc communications due to advanced packet framing and coding techniques. RF codes supported include time division and frequency division multiple access schemes. Additionally, another coding scheme under consideration is called Orthogonal Frequency Division Multiple Access (OFDMA) which could provide an added layer of interoperability and enhance existing IP QoS techniques [IEEE, 2003]. The MAC maps and manages clients to the main node with some level of guarantee or quality of service. While connected, a traffic or service flow is established which provides somewhat of a permanent circuit allowing for high bandwidth data flow of up to 72 Mbps. Bandwidth may be aggregated or channelized based upon the MAC layer configuration [IEEE, 2007, p. 630] [WiMax, 2008]. However, the MAC is also connection-oriented which can become problematic for the bursty IP traffic. As we discussed, IP networks support a connectionless-mode architecture. Several issues arise when transmitting IP over WiMax networks to include address resolution and next hop route discovery. This issue is currently under research by an IETF working group with the first goal of providing the successful point-to-point link model for the IP convergence sublayer over the WiMax layers [Jee, 2008]. The IEEE has defined several wireless standards addressed in the 802.xx family under which WiMax, 802.16, falls. Figure 10 shows high-level relationships across this family of standards.

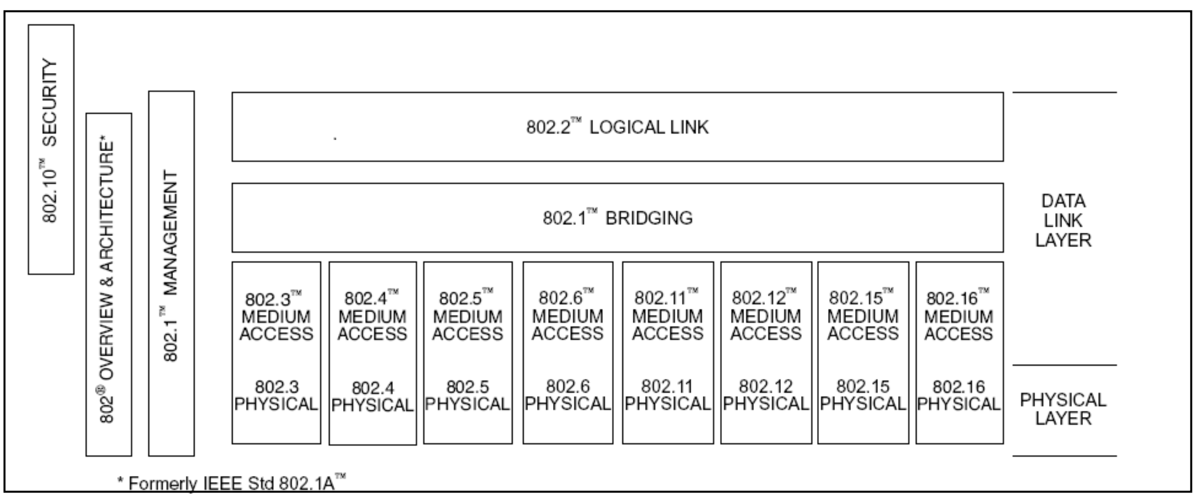

Figure 10. IEEE 802.xx Standards Family [From: IEEE]

The features that allows the 802.16 standard a candidate for space communications is the maturity of development, ability to provision resources, and wide adoption across existing international networks. The author feels that WiMax could be employed as a common air interface between communications satellites and mission satellites due to the protocol standardization within the International Association of Electricians and Electrical Engineers (IEEE) and the technology readiness level (TRL). The mission satellite concept and its role in future architectures will be explained later. However, many efforts to include Space-Based Group continue to model and study WiMax integration into space communications networks.

2. Free Space Optics (FSO)

FSO in space, also known as laser communications, has been a topic of discussion within the international space community for decades. FSO employs high frequency lightwaves - normally infrared frequencies, in place of RF [Schier, 2007]. A mature form of FSO may offer transmission distances up to 10 KM or more in terrestrial networks, but the distance and data rate of connection is highly dependent on atmospheric conditions and available power.[fSONA, 2008] FSO attracts network developers for a number of reasons which include a very large increase in bandwidth, reduced frequency interference, and greatly improved bit error rates (BER). However, since atmospheric conditions will not pose such an obstacle across space-based networks, FSO capabilities may experience far greater distances as demonstrated in past studies and efforts. Additionally, if FSO technology is used to support ISLs, bandwidth will increase over RF links by orders of magnitude thereby mitigating the growing demand for information. Sample link budgets may show data rates up to 50+ Gbps which will support a tremendous amount of data exchange across an FSO ISL [Iida, 2003]. The potential of FSO technology has been one of many driving reasons for the validated requirement of a global satellite communications ring to augment and provide redundancy to the terrestrial Internet and GIG as articulated in the TCA document [NSSO/TCA, 2007].

E. NETWORK/RESOURCE MANAGEMENT TECHNOLOGIES

1. Quality of Service (QoS)

As user requirements demand greater quantities of real time services such as voice and video, networks may not provide the level of user satisfaction as currently configured. There needs to be some way to prioritize certain types of IP traffic flows to minimize latency and complete degradation of critical services. There are many protocols and standards to accomplish this task. However, in an all IP environment, IP quality of service provides the greatest promise for future converged networks. As defined by a leading network vendor, "Quality of Service (QoS) refers to the capability of a network to provide better service to selected network traffic over various technologies [Cisco, 2008]." QoS leverages the existing IP packet by encapsulating the packet with additional instructions for handling within each router regardless of the lower OSI layers such as Frame Relay, Asynchronous Transfer Mode (ATM), Ethernet and 802.1 networks. As stated, the result is better service and priority to certain types of data in order to reserve minimum bandwidth or reduce latency and delay. For example, voice packets traveling over an IP network cannot tolerate delay and require a certain bandwidth leading to a higher level QoS. QoS settings are configured for each data type such as Hypertext Transfer Protocol (HTTP or web), File Transfer Protocol (FTP), and video [Cisco, 2008].

QoS may be implemented in the router configuration by establishing bit configurations within the IP packet header. This bit configuration is called Type of Service (TOS). TOS bits provide a precedence level and are assigned to specific data. Up to six classes of precedence are offered for configuration and will provide priority for data flows that require little or no latency. Figure 11 shows a typical model of TOS bit heading for IPv4 packets [Cisco, 2008], which will be used for modeling and simulation later in this discussion.

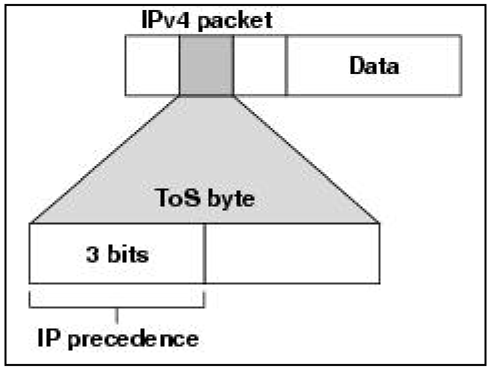

Figure 11. TOS Bit configuration for IPv4 packet [From: Cisco]

A key point to remember regarding QOS is that all routers are required to implement not only QoS, but the same TOS bit settings, or else QoS becomes ineffective. Although IP traffic flows inherently operate in connectionless-mode operations, they still require end to end configuration for successful QoS configuration. As such, TOS bit settings are configured and said to define the service level of the traffic flow. When configuring a router, several service levels are identified and equate to the TOS bit setting. These service levels are as follows:

- Best Effort Service: No QoS settings have been configured and all traffic competes with available bandwidth.
- Differentiated Service: A percentage of the traffic flow, per data type, receives some higher-level priority as related to processing speed, bandwidth, and packet loss.
- Guaranteed Service: Network resources are reserved for a specific data type regardless of impact to other applications.[Cisco, 2008]

Both of these last two levels will be modeled and simulated later during Opnet configurations.

2. Dynamic Bandwidth Resource Allocation (DBRA)

DBRA defines an additional method to improve number of users, link availability, and the link data rate by offering a unique process interaction between the network layer, link access layer, and physical layer as well as the satellite resources. DBRA consists of two functions: Dynamic Coding and Modulation (DCM) and Demand Assigned Multiple

Access (DAMA). "DCM improves link availability and data rate based on the link state condition, while DAMA optimizes the system throughput based on user traffic needs [TCA, 2003]."

DCM performs under the assumption that the satellite links are consistently variable resulting from environmental changes such as cloud cover, rain, and the mobility of ground terminals. This function monitors link parameters and settings such as symbol rate, modulation scheme, error correction, and power. A dedicated subsystem component will operate via the satellite LAN and onboard routing functions. Past analysis and simulations have shown that the DCM function alone could result in a 2x-8x improvement in link performance [TCA, 2003]. The second function of DBRA, DAMA, will provide user management based upon demand, priority settings, time slots, and traffic load similar to that of the current UHF satellite systems [Grayver, 2007].

F. SUMMARY

This section focused on consideration of core technologies for Future Integrated Architecture (FIA). The next portion of this FIA study will focus on the final architecture, or a version of FIA. Following an initial presentation of the high-level architectural view, the architecture will be analyzed in context of an operational scenario and will include many of the technologies presented in this section.

IV. THE PROPOSED FUTURE SPACE ARCHITECTURE

A. OVERVIEW

The development of satellite communications architectures involves analyzing a seemingly endless number of possible configurations. In this chapter, the development of one instantiation of the future space architecture is examined. The methodology here continues to leverage previous discussions of current efforts and technologies, standards, and concepts. But, more importantly, this notional architecture will support the core attributes of this discussion. Several elements of current and future efforts are proposed that could provide tremendous service for ground users, of which we will discuss operational details in the next chapter.

B. THE PROPOSED ARCHITECTURE

What should the final architecture look like? There are a number of common themes observed within current efforts and developments. The first theme seen is the use of Internet Protocol to provide an extension of Internet capabilities. IP routing as a core technology appears pervasive throughout the future plans. As such, the extension of existing bent-pipe, transponded geostationary communications satellites with an IP backplane is required by the Future Integrated Architecture. Integrating IP routing within all satellite communications platforms will provide FIA a common baseline suite of protocols. The employment of IP appears to be pervasive throughout all existing efforts, programs, and plans.

Another common theme highlighted is the employment of links between satellites called Inter-Satellite Links (ISL). Traditional bent-pipe communications provides connectivity between the satellite and ground users only. Interoperability arrives only within the ground infrastructure which could increase latency and reduce performance for real time applications such as video and packetized voice as well as inefficient use of finite satellite resources due to the extra “hops” necessary. Other types of terminals will not be directly interoperable with the terminals attached or connected to this satellite. However, with the introduction of ISLs and space-based IP routing, any number of satellites can be connected across the space layer while adding another point of connection within the architecture beyond the existing terrestrial networks.

The next theme or concept that will be integrated is a combination of mission satellites and a fractionated architecture, as presented by SBG and DARPA. Although ISL's are critical for a space networking system, integration of all capabilities into a single spacecraft will continue to be challenging and provide less flexibility. As such, an additional proposal would be that a relay mission satellite be positioned near any communications satellite in order to provide the relay and ISL service. Yet, this relay satellite would also act as an extension of the communications satellite subsystems by integrating into the subsystem IP subnet and receive TT&C commands via the parent communications satellite. The flexibility of this capability is the ability to move and re-position any relay satellite near any government and commercial communications satellite provided certain key assumptions are satisfied.

Therefore, in addition to current capabilities of GEO communications satellites, assumptions for this proposed architecture are:

1. All satellite communications platforms have a Layer 3, IP router to support the majority of onboard processing demands.

2. All platforms adhere to a common and agreed to near field wireless standard not unlike the terrestrial cellular industry.

3. All ground terminals will become IP addressable.

Figure 12 shows an instantiation of this architecture, or an Operational View-1 (OV-1). Satellite Toolkit (STK) was used to analyze coverage and access of terminals to be used later for the operational discussions. Figure 12 shows the STK physical layer connectivity between all satellites and terminals. Provided technical parameters of communications satellites and terminals, such as antennas, frequencies, throughput parameters, modulation schemes, STK analysis provides a "go/no-go" situation with respect to ability to connect between platforms. In this case, the blue lines show adequate coverage and connectivity between all terminals.

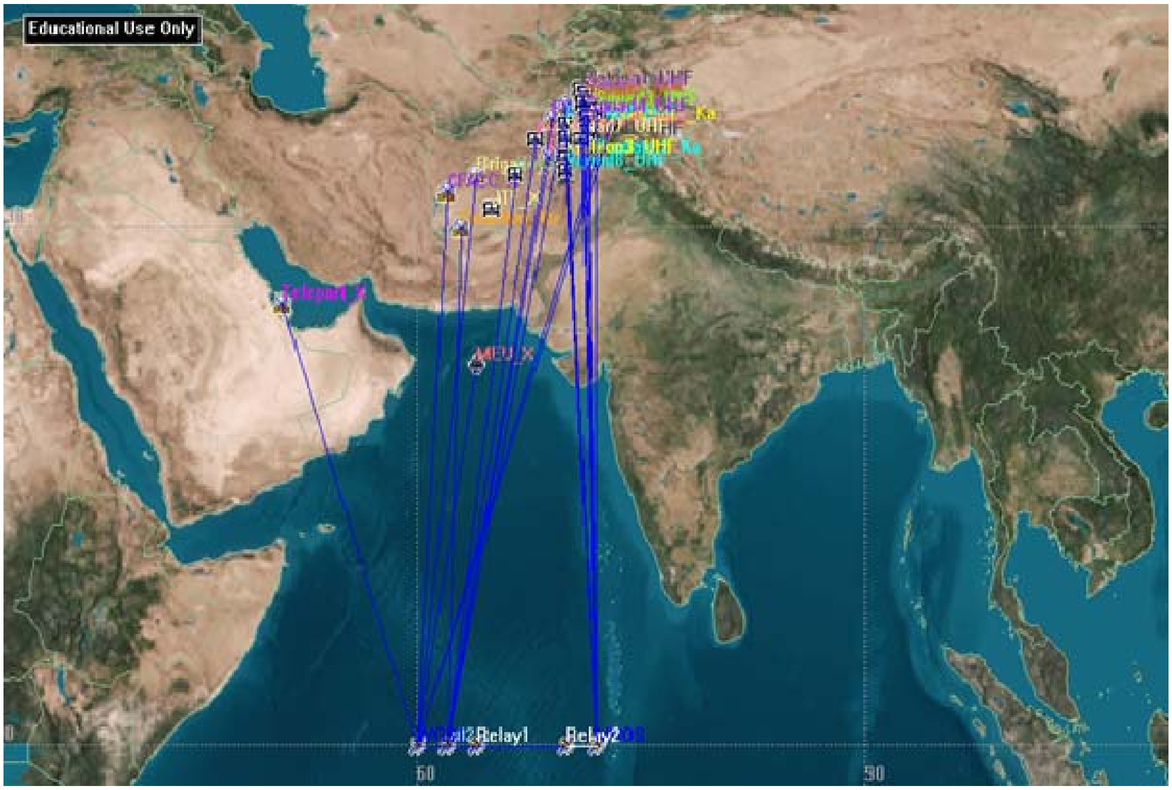

Figure 12. Space Architecture OV-1 using STK

Figure 13 shows a closer view of the architecture and the ISL. This view depicts several familiar program names requiring some explanation. In this instantiation, some current programs of record are integrated for modeling and analysis. Wideband Global SATCOM (WGS), Intelsat 902, and Mobile User Objective Systems (MUOS) are used as examples of differing “types" of communications satellites, and represent the majority of capabilities employed, or to be employed, by operational forces: WGS for government wideband services, Intelsat for commercial wideband services and MUOS for government narrowband/tactical services.

Figure 13. GEO layer of space architecture using STK

What STK might not show is the OSI layer 2 / 3 and higher capabilities across this architecture. To gain insight, OPNET was used to provide a deeper level of analysis given the network assumptions previously discussed. Figure 14 shows a similar view of connectivity but with IP routers as the core of these platforms or nodes.

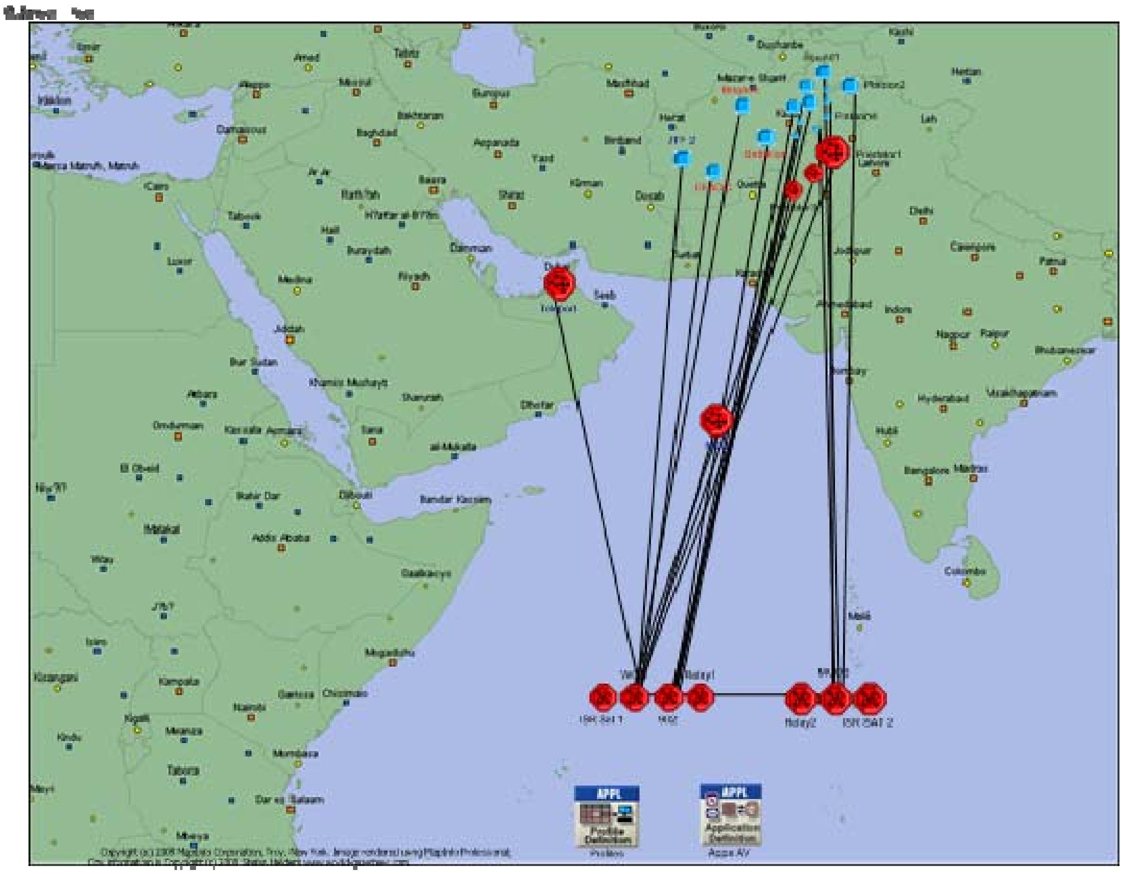

Figure 14. Architecture OV using Opnet

OPNET analytical models provided the majority of analysis as it facilitated further study of performance data of an all-IP architecture. However, the value of integrated routing for onboard processing may not be revealed so much from this initial view. Another look at the differing elements of this architecture, and then a revisit to the All View (AV), will show the purpose of routing. In addition, this discussion will provide a further look at the justification for the other network elements and thesis assumptions previously mentioned. As was also articulated, there are several types of communications satellites represented in this architecture. For each satellite type or category discussed in this chapter, both an STK and OPNET model will be displayed.

First, government wideband services are depicted by WGS which is both X and Ka band. A recent loading analysis by the space community as led by Air Force Space Command (AFSPC) recommended that Airborne Intelligence, Surveillance, and Reconnaissance (AISR) requirements, such as Predator, leverage Ka services while all other users leverage X band services. This model implementation integrated this recommendation by prioritizing the larger ground users or nodes, such as the JTF HQ and teleport, over the X band services and the Predator services over Ka frequencies. Figure 15 shows this WGS laydown developed for this model.

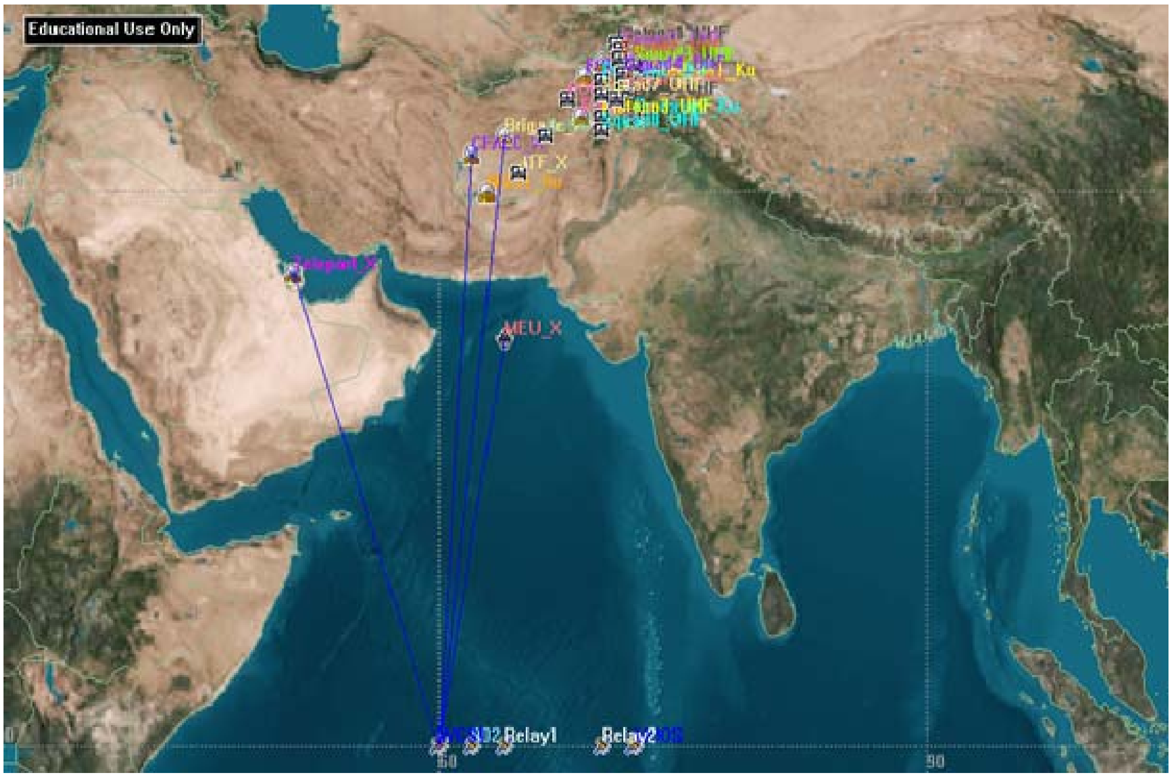

Figure 15. WGS-2 X-Band Coverage OV using STK

Government narrowband services connect UHF ground terminals such as field radios (AN/PRC-117) employed by tactical units, i.e., platoons. The current UHF constellation is called UHF Follow On (UFO). However, for this architecture, we will employ the MUOS system as it is the near term future UHF constellation to support small, disadvantaged, tactical users. MUOS will offer bandwidths with a threshold of 64 Kbps per terminal link, and provide greater Effective Isotropic Radiated Power (EIRP) from the satellite to support very small terminals such as handhelds. The size of the MUOS ground, man-pack terminals and bandwidth configurations may become an issue when connecting the MUOS system, by an ISL, to the entire space architecture. As seen in our operational discussion, satellite terminals add additional weight load to ground troops which supports the requirement for very small terminals. Figure 16 illustrates the MUOS coverage for this architecture.

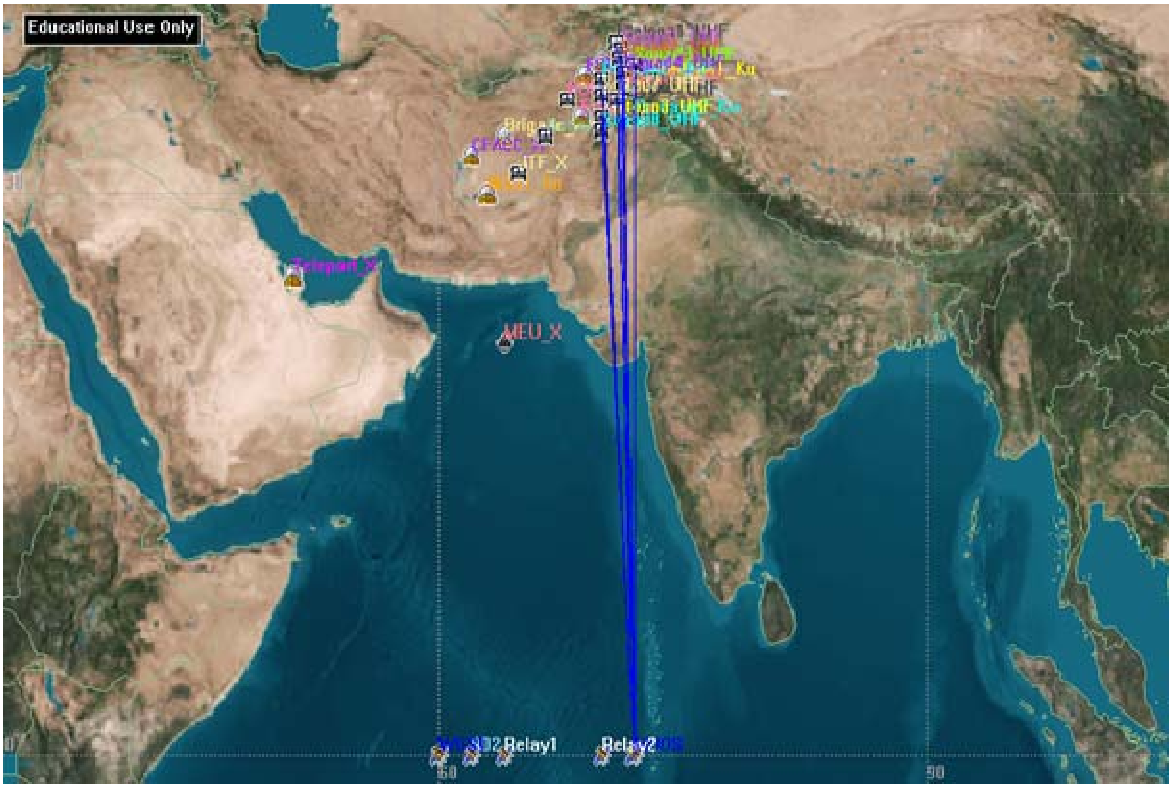

Figure 16. MUOS UHF Coverage OV using STK

Given the exponentially increasing demand for bandwidth by the U.S. military and coalition forces combined with the disparities in the U.S. government acquisition process as compared to the commercial sector, commercial satellite communications provides up to 80% of total throughput. Any discussion of future space architecture must consider the integration of commercial assets. Additionally, during the formative years of Operational Enduring Freedom (OEF), Congress passed Supplemental Defense budgets which provided the increase and modernization of important assets such as VSAT satellite terminals. However, the majority of available VSAT terminals during these years were designed for commercial Ku frequencies. Thus, another assumption will be that commercial satellite communications will be a part of the space architecture for many years to come. Figure 17 highlights the commercial Ku coverage for this architecture.

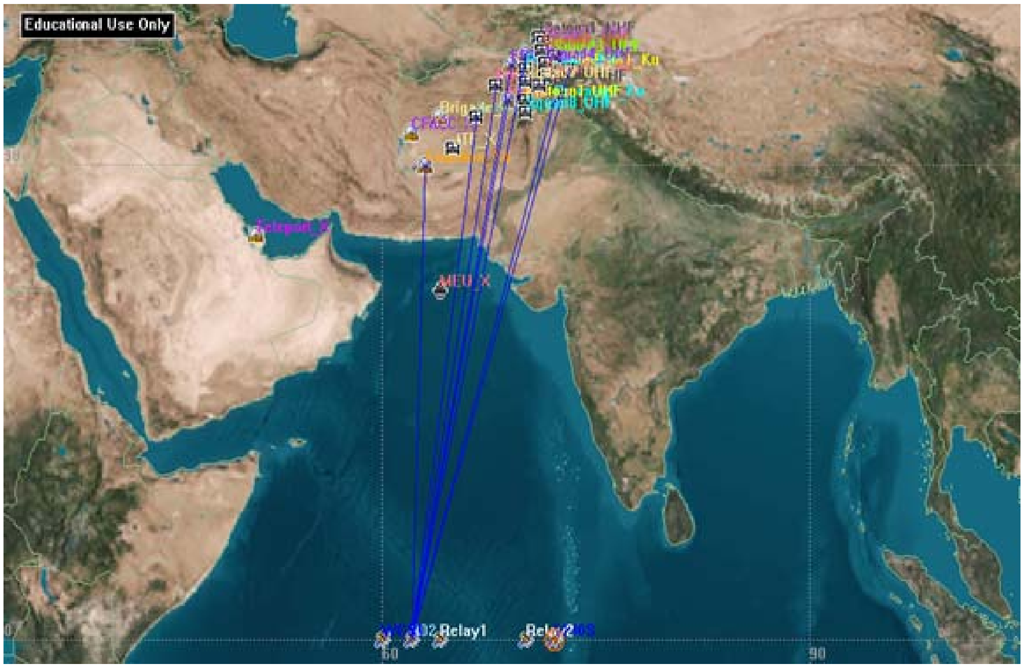

Figure 17. Intelsat 902 Ku Coverage OV using STK

C. SUMMARY

Up to this point, three different categories of communications satellite have been considered. Users of these services experience a great deal of interoperability as long as they are communicating through the same satellite, i.e., MUOS terminal to MUOS terminal. However, as currently proposed, a MUOS terminal is not able to directly communicate with an X, Ku, or Ka band terminal. So, how is this lack of interoperability corrected? One capability employed by a small number of other constellations, such as Iridium, has been with ISLs as previously mentioned. Certain assumptions were previously articulated in this architecture to include a common air interface for near field wireless and leveraging a fractionated architecture. Therefore, along with IP routing, this architecture will introduce the concept of a mission relay satellite for interface between the common air interface of the communications satellite and the ISL technology such as Free Space Optics (FSO). This will become the core or backbone infrastructure for this architecture and will provide interoperability and connectivity between all ground terminals and frequencies.

V. OPERATIONAL APPLICABILITY OF THE FUTURE INTEGRATED ARCHITECTURE USMC DISTRIBUTED OPERATIONS

A. OVERVIEW

Accurate assessment of any networked architecture is best evaluated in the operational context, and in the most demanding of scenarios. In order to include some historical context in this discussion, FIA will incorporate the Marine Corps' concept of distributed operations. Distributed Operations (DO) has been a concept heavily discussed over the past several years with significant debate. The execution of Distributed Operations requires dramatic changes in tactics, techniques, procedures, and capabilities, to include an increase in communications and networking infrastructure. As such, the basics of DO are applied to FIA in consideration of the historical context and after-action report from a Marine infantry battalion deployment to Afghanistan.

Distributed Operations has seen much debate among military experts and historians. Many feel that this concept does not introduce any new operational tactics and is just another name for the aged concept of Maneuver Warfare or "Light Infantry." However, some of the "basics" of this concept are evaluated here. DO may be defined as a form of maneuver warfare. The core capability of DO shows small units or teams of Marines operating independently but connected virtually. Each team will be capable of operating independently of direct command of higher echelons yet will maintain the ability to rejoin other teams and reform traditional command structure as required by the enemy actions. This flexible command structure allows each team, whether it is a fire team, squad, or platoon, to possess greater capabilities for fire support, logistics, intelligence, and overall exchange of command and control (C2) information. Tactical commanders, such as battalion commanders, will experience a greater level of challenge to maintain situational awareness and ability to adjust operations quickly as required due to increased distance and terrain challenges. But, more importantly, communications and networking infrastructure requirements will greatly increase by connecting all levels of command which has been a primary tenet of the Net-Centric Warfare (NCW) concept development. Figures 19 and 20 illustrate a high-level conceptual and architectural view of the DO concept.

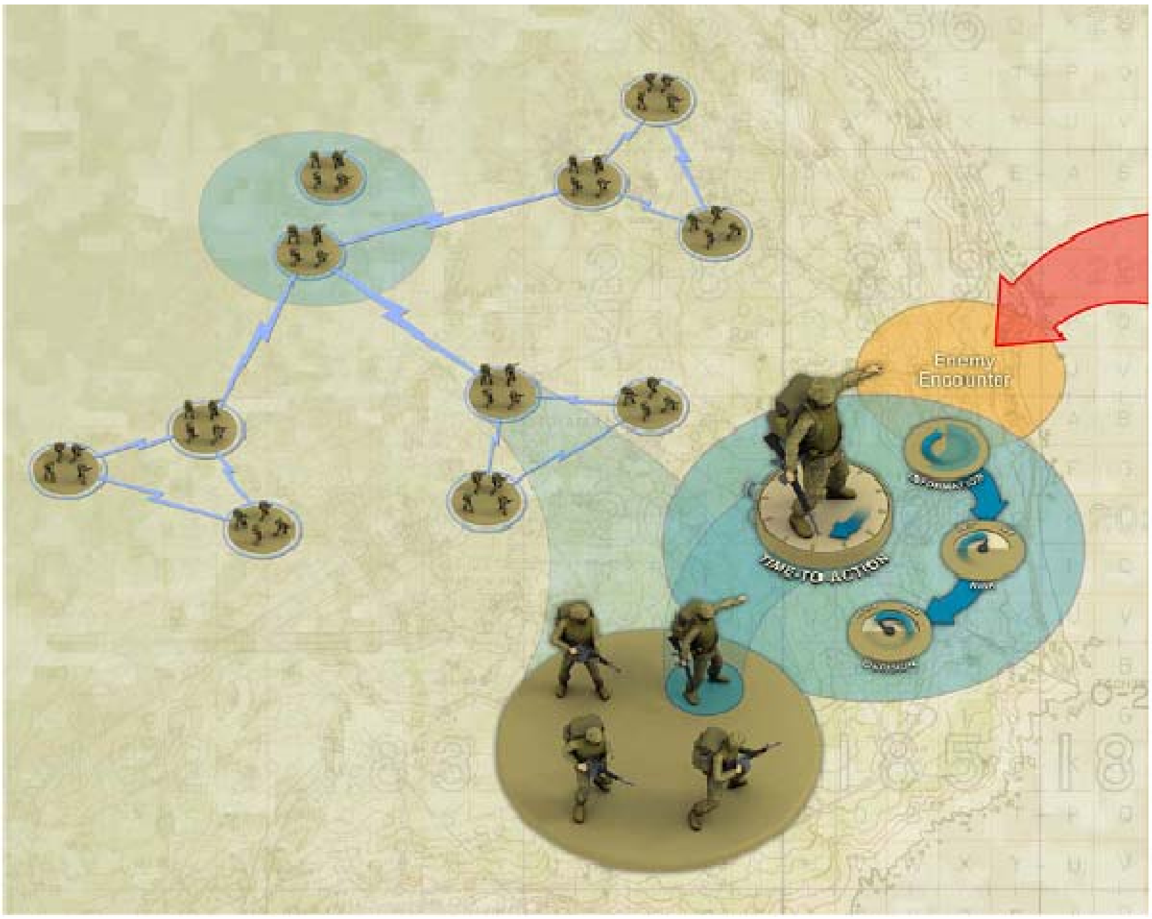

Figure 18. Distributed Operations Conceptual View – “Proliferation of Decision Makers” [From: USMC]

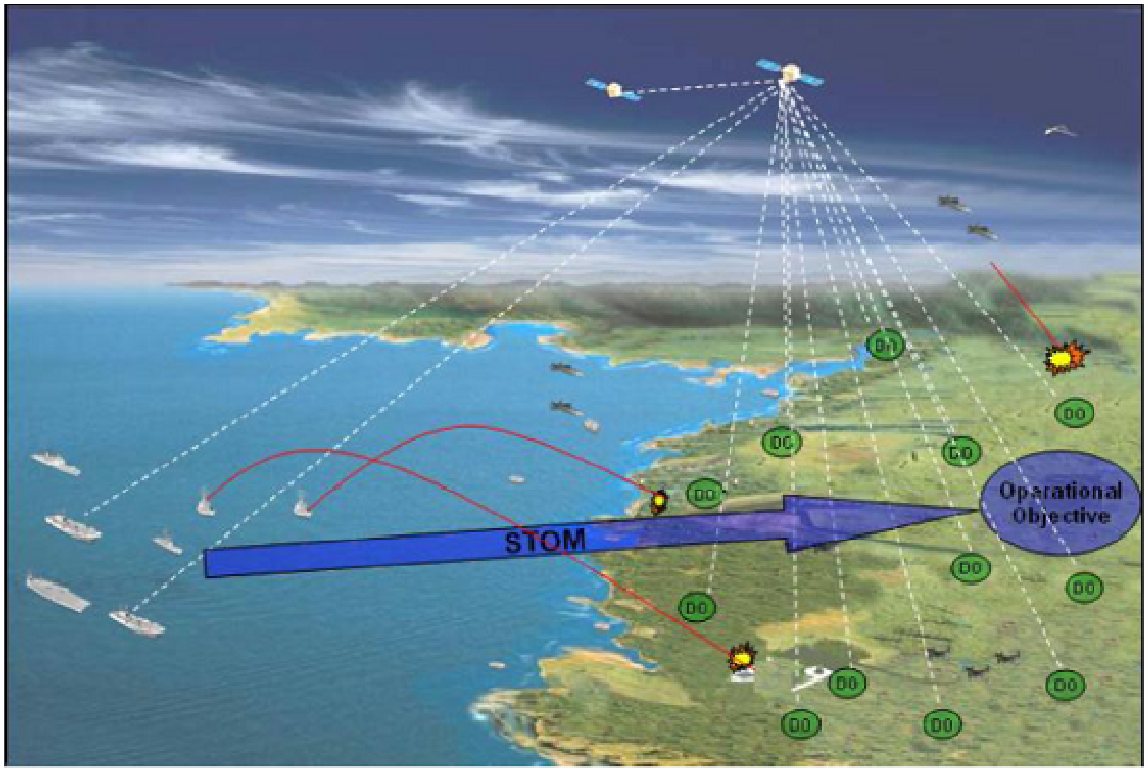

Figure 19. Distributed Operations Architecture OV [From: MCWL]

Critical for D.O. operational support is the communications architecture as depicted by Figure 20. Each node of the architecture must be able to exchange information in a mesh or networked environment with all teams operating well beyond line of sight of each other. This level of networking will require increased employment of over-the-horizon (OTH) capabilities such as satellite communications which may require more systems than currently maintained by Marine units. However, in order to maintain the mobility of these small teams, the network must not add burden to the individual Marine, and must be capable of operation by any number of military specialties [MCWL, 2006]. Additionally, as seen later, Marines don't operate in a vacuum; operations will encompass interoperability with other services, coalition, and possibly other governmental agencies. So, now a common understanding of this concept is provided, DO is reviewed in recent operations and analyzed within the FIA architecture.

B. FIA ANALYSIS WITHIN HISTORICAL CONTEXT: 1/3 DEPLOYMENT TO AFGHANISTAN

For further operational context, this discussion will focus on Global War on Terrorism (GWOT) efforts in Afghanistan. In addition to recent deployments of the United States Marine Corps in coordination with U.S. Army and NATO, Afghanistan may have added relevance for future operations. Taliban activity has shown increased efforts in this area of responsibility (AOR) while both U.S. Presidential presumptive nominees, Senators Barak Obama and John McCain [Fox News, 2008], have articulated a desire for increased U.S. presence and operations in the AOR once elected to office. Therefore, we will study one recent deployment to Afghanistan by a Marine unit [MCCLL, 2006].

In support of Operation Enduring Freedom, from December 2005, to July 2006, 1st Bn, 3rd Marines deployed to Afghanistan and executed what some might consider distributed operations. The battalion was tasked to cover an AOR of over 12,000 square miles. Figure 21 shows the 1/3 AOR.

Figure 20. 1/3 Area of Responsibility [From: MCCLL]

Afghanistan topology is marked by rugged mountains with peaks in excess of 12,000 feet elevation. Furthermore, in order to support maneuver throughout the AOR, the battalion had to establish six forward operating bases (FOB) which were separated from each other, higher headquarters, supporting units from U.S. Army and Air Force, and supported Afghan National Army (ANA) positions by hundreds of miles [MCCLL, 2006].

The only available method of communications between all sites was satellite communications. Each FOB employed a VSAT using commercial Ku wideband satellite communications to support non-classified internet protocol routing network (NIPRNet) and secret internet protocol routing network (SIPRNet) services. However, as these were semi-permanent staging areas for anti-Taliban patrols, many platoons and squads operated the majority of time "outside the wire" throughout the AOR and beyond line of site of the FOBs. This required the employment of the AN/PRC-117 tactical radio for UHF satellite communications. Operating with over the horizon (OTH) constraints added to the increased burden to exchange greater amounts of information, including critical and timely intelligence.

Historically, real time intelligence information from the Marine operated Dragon Eye UAV has provided an excellent picture of the battlefield. However, high winds and elevation precluded the use of Dragon Eye in the Afghan AOR leading to the reliance upon the much larger Predator UAV. Although the Predator was employed with a direct video feed, certain terrain features may prohibit direct video feed and require greater reliance upon satellite communications. The Predator is currently equipped with commercial Ku satellite communications. However, the near term deployment of the WGS constellation will allow the Predator to send information via the government Ka frequencies. For this discussion, Predator use of the Ka band for video dissemination is assumed. The deployment of different satellite systems results in a stovepipe architecture with at least three different satellite communications networks. 1/3 also used the commercial Iridium satellite system; however, this discussion will maintain focus on the GEO satellite layer [MCCLL, 2006, p. 14].

First battalion, 3rd Marine Infantry Regiment (1/3) articulated many after action issues pertaining to lack of adequate network connectivity between all locations and levels of command. A good portion of this deficiency resulted from differing satellite communications systems, inadequate bandwidth, and competing application demands [MCCLL, 2006, p. 14]. The remainder of this discussion will illustrate how FIA could provide a solution to these issues.

The high-level view of FIA was presented in Chapter IV. The frequency bands discussed are equivalent to those employed by 1/3. However, as was mentioned, the differing satellite terminals are not interoperable which adds to the burden of increasing Information Exchange Requirements (IER). FIA provides a method that will provide connectedness, interoperability, and net-centricity while meeting operational requirements in a regional context.

1. Single Traffic Flow Simulation

To further model and prove this architecture, OPNET was used to simulate differing types of IP data flows from sites within the laydown of the 1/3 AOR. OPNET provides the ability to analyze single IP traffic flows, full mesh IP traffic flows, or the ability to configure similar client/server/application architecture as deployed by 1/3. For this discussion, a "snapshot" of each OPNET instantiation will be presented to show nodal connectivity. A Cisco 7200 series router was configured in each satellite and terminal platform with default routing protocol settings such as routing information protocol (RIP) and border gateway protocol (BGP). No quality of service was configured, so traffic flow was modeled at Best Effort similar to the Internet and currently deployed tactical networks.

Intelligence and video information was critical during 1/3 deployment, and quite often was demanded on very short notice. Assuming that a continuous combat air patrol (CAP) of the Predator UAV is in support, a video feed from a Predator UAV to several 1/3 locations was first modeled. For further clarification, OPNET was configured with realistic bandwidths supported by the various ground terminals as follows: AN/PRC-

117/MUOS capable – 56 Kbps, VSAT/Ku terminal – 1.4 Mbps, DKET/X band – 40 Mbps, Pheonix/X band – 40 Mbps, and the Predator/Ka band terminal – 3 Mbps [NSSO/TCA, 2007].

The following figures provide a more detailed view of data flow. For further clarification, OPNET was configured in a hierarchical construct with all IP subnets, such as ground terminals which are designated in red, imbedded within either the WGS subnet or MUOS subnet. With the exception of the MUOS subnet, all subnets were connected with an IP cloud. Each subnet was configured with an IP router so that IP communications is accomplished between layer 3 routing devices. Standard routing protocols, such as Routing Information Protocol (RIP) and Border Gateway Protocol (BGP), were used. The flow of information is identified with a thick black line and arrow to mark the direction of data flow for analysis.

To analyze data flow for this configuration, only streaming video data simulating Predator video feeds was used. Figure 22 shows the beginning of a multicast IP data flow with Predator 1 transmitting a 6 Mpbs video stream via a Ka band frequency through WGS and across the ISL to both Intelsat 902 and the Relay satellite.

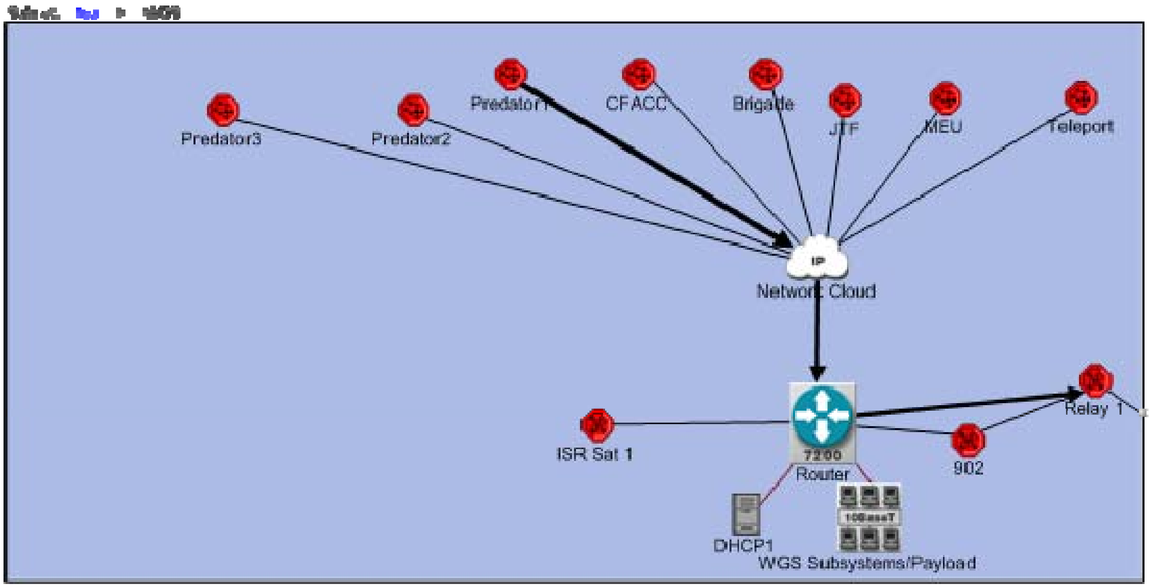

Figure 21. WGS Simulation Traffic Flow

At this point, the IP stream enters both the Intelsat 902 router for transmission to FOB1, and the Relay 1 router for transmission via the ISL to the MUOS router. Figure 23 shows the MUOS specific architectures with highlighted data flows with the final destination subnets for the Predator video feeds.

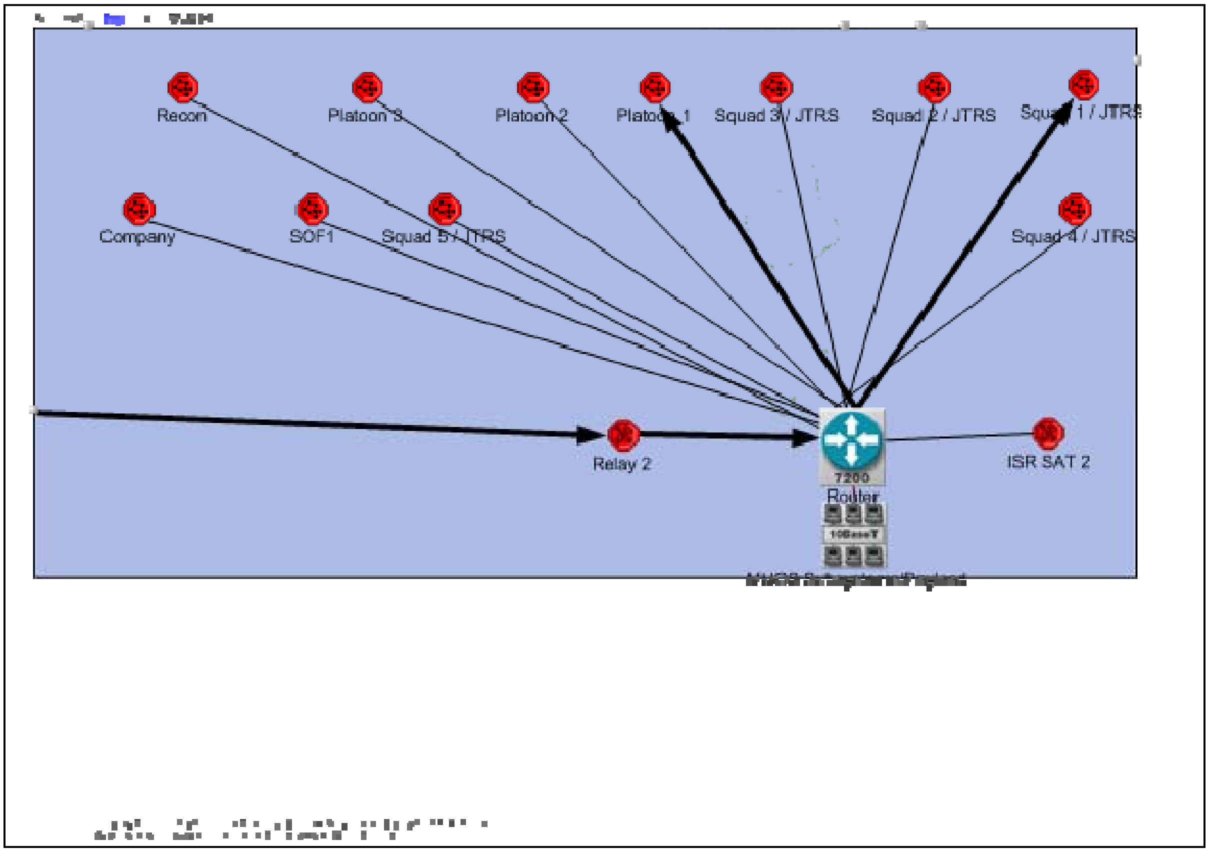

Figure 22. MUOS Simulation Traffic Flow.

Table 1 shows the packet flow results from this model with configured link and packet settings resulting in approximately of 10 Gbps of video packets successfully transmitted across FIA. For this single traffic flow simulation, OPNET was configured with 6 Mbps of Predator video to FOB 1 web server, FOB 2 web server, Platoon 1 leader, and Squad 1 leader, with 100 packets per second, and during a simulated timeframe of 60 minutes. The OPNET model was not configured with satellite specific restrictions or physical layer characteristics such as frequency except for bandwidth settings. However, bandwidth may be a limiting factor in FIA given the disparity of bandwidth settings across all satellite systems. The most restrictive element of the architecture could be MUOS. Although MUOS will support data rates of 64 Kbps threshold and 128 Kbps objective, OPNET only supports a narrowband link of 56 Kbps. After several modeling attempts with the goal of inducing packet loss and degradation of service, no significant loss of data was experienced according to the OPNET results in this simulation.

However, in reality, OPNET did not account for other external conditions such as atmospheric attenuation and interference that would lead to packet loss.

The results in Table 1 further illustrate that an IP and ISL enabled space architecture, such as FIA, could potentially support the future demands of video and imagery currently measured by Mbps and even Kbps bandwidths. Performance improvements resulting from an all IP space network to include narrowband links could be referred to as IP Gain and could support data-rate intensive applications such as video where before it might have not supported that application. IP Gain will be further discussed later. However, previous studies have shown that a typical 128 Kbps link supporting by IP routing in the satellite and ground terminals could experience an approximate 59% improvement in link performance [TCO, 2003].

Flow Simulated Time Span	60 minutes
Total Volume	10.058 Gbps
Average Volume per Flow	2.515 Gbps
Number of Flows	4

Table 1. Predator IP Video Traffic Analysis across FIA

2. Full Mesh Traffic Flow Simulation

The next simulation modeled was a full mesh of IP traffic from every node to every node. This model represents all types of data while simulating the quantity of IP traffic capable of traversing FIA. Not previously mentioned as a piece of this architecture are the two ISR satellites transmitting imagery data into the network via WGS and MUOS, respectively. The ISR satellites were included in the full mesh simulation. Table 2 shows the results from this simulation with a total packet flow of approximately 830 Gbps and an average flow of approximately 51 Mbps. Similar to the previous simulation, this OpNet simulation does not provide for lost packets.

Flow Simulated Time Span	60 minutes
Total Volume	830.4 Gbps
Average Volume per Flow	51.5 Mbps
Number of Flows	16512

Table 2. Simulation Results from Full Mesh / All Nodes

3. Discrete Event Simulation – Full Application Deployment

So far, simulation results showing FIA support for 1/3 deployment, as well as any future deployments to Afghanistan, have been provided. From a network perspective, these models show connectivity and interoperability between all ground terminals to include UHF, Ku, Ka, and X frequency bands. This configuration could provide a true internetworking presence at the GEO layer. However, each simulation was shown with only a single traffic flow or a complete full mesh, both of which might not be as indicative of true operational conditions. As such, the last OPNET simulation provided is called a Discrete Event Simulation (DES) whereby simulations were provided with a closer modeling of actual applications and network load with a simulated time of 30 minutes. The applications for this simulation were as follows: VOIP, Email, FTP, HTTP, video conferencing to simulate the Predator video feeds, and ISR to simulate imagery data from the ISR satellites. For successful DES simulation, OPNET requires the configuration of Application Definitions and Profile Definitions. The FIA application definitions were configured with the applications just listed with a "medium load" setting. The FIA profile definition was configured with three primary profiles, Operations, Intelligence, and Logistics, with the following traffic flows:

<u>Operations:</u>

-VOIP between MUOS Platoon 1, Platoon2, Squad 1, Squad 2, and WGS FOB2 VOIP server.

- Email between same users and FOB2 email server

Intelligence:

- Video Dissemination from Predator 1 video processing server to MUOS Company Commander and WGS Teleport Video server.

Logistics:

- Email and FTP between WGS FOB 1 Web Server, WGS FOB 2 Web Server, WGS Teleport FTP server, and WGS Teleport Email server.

Figure 23 shows the IP traffic Received results from this simulation with the results focused on a very demanding application across the network: streaming video. In this case, Predator multicasts the video feed two times to the company commander and to a server at the teleport for further storage in addition to competition with other traffic flows.

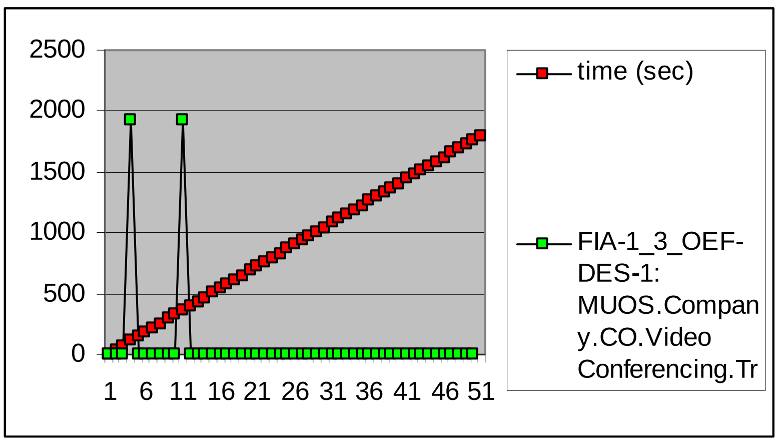

Figure 23. IP Traffic Received (Bytes/sec) by MUOS Company Commander

However, an issue with deploying such a demanding and real time application across a network with a variety of bandwidth settings is packet delay. Packet delay can significantly degrade the quality of information resulting in unusable information to the user. Figure 24 shows the packet delay for the video streaming traffic flow will increase linearly over time. This will eventually result in unusable video and intelligence information to the company commander, and degrade his intelligence picture.

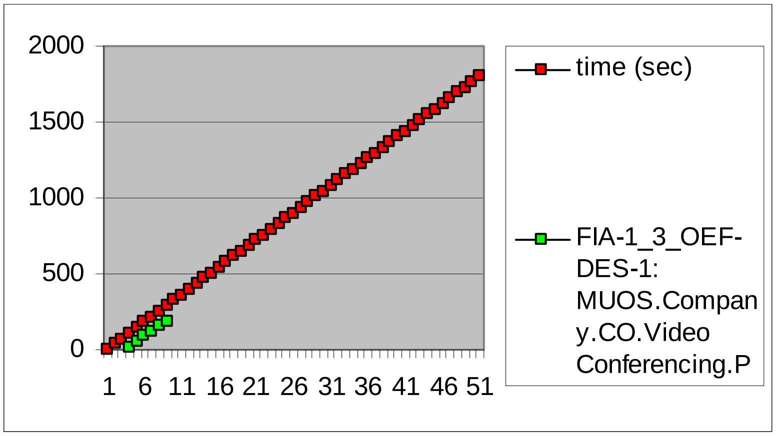

Figure 24. Packet Delay (Bytes/sec) to MUOS Company Commander: No QOS

As was discussed in Chapter II, current terrestrial IP networks have been required to support increasing real time traffic demands such as voice and video. And, a way to manage the differing types of data is through QoS, as was discussed in more detail in Chapter II. OPNET provides the ability to simulate IP traffic flows throughout the network or for selected links. In this case, FIA was re-configured with QoS on the Predator video feed links to the MUOS Company Commander with results as shown in Figures 25 and 26. Both simulations were configured with QoS with slightly different implementations. Initial observation will show that QoS would be required across FIA to provide adequate support for real time applications, links with a variety of bandwidths, and disadvantaged users.

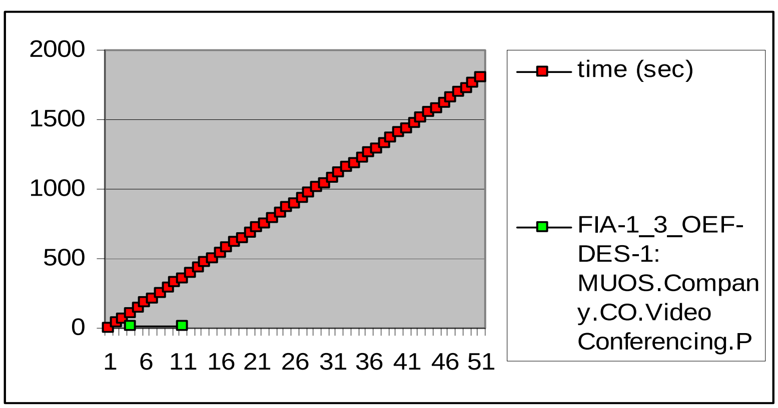

Figure 25. Packet Delay (Bytes/sec) to MUOS Company Commander: QOS set to First In / First Out on Predator links using Type of Service (TOS) bits

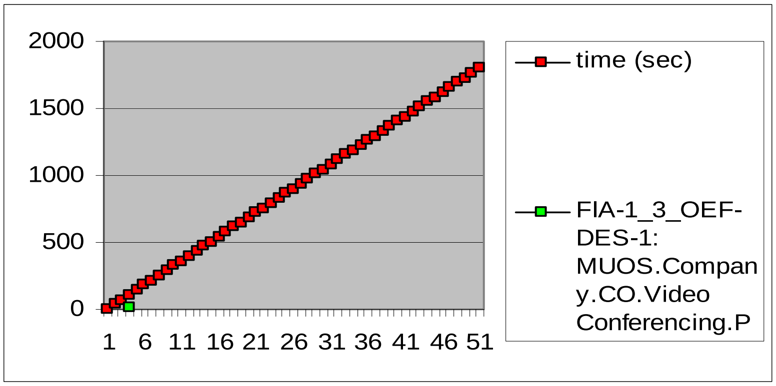

Figure 26. Packet Delay (Bytes/sec) to MUOS Company Commander: Priority Queuing

C. FIA IMPROVEMENT OF TCA

As was briefly discussed, FIA could potentially offer capability enhancements to the current TCA vision, currently deployed systems such as WGS, MUOS, and Milstar, and also to the ground infrastructure such as teleports. The current systems offer tremendous capability and future systems, such as TSAT, will improve the architecture exponentially. However, FIA could enable the TCA to provide far greater support to the attributes of connectivity, interoperability, and net-centricity. The specific aspect of FIA not found in TCA is IP routing integrated on all satellite platforms, near field wireless standardization, and an isolated 2–3 degrees ISL deployment. Many network performance improvements will result from this level of integration and can be categorized as IP gain, survivability, architectural flexibility, and latency improvements for real-time services. These specific areas should be considered improvements of the TCA.

1. Improved Link Efficiency (IP Gain)

Current systems employ circuit switched configurations since IP routers have not yet been integrated onboard the satellite except for certain experiments. However, future TCA systems, specifically TSAT, will integrate IP routers for space-based layer 3 networking capabilities. To further validate this architectural approach, the Transformational Communications Office was tasked to study IP routing and determine improvements over circuit switched implementations. This improvement was referred to as IP gain or more formally as Statistical Multiplexing (Stat-Mux). Circuit based information on WGS and other commercial systems are categorized as “bursty” leading to underutilization of the link. Bandwidth is wasted while circuits are dedicated to idle individual networks or applications. IP routing will leverage the concept of stat-mux and produce higher link utilization and efficiency.

Downlinks experience higher gains that uplinks due to the satellite becoming the single point of aggregation and managing the entire link for all types of applications. Studies by Boeing and Lockheed have resulted in downlink IP gains of up to five times as compared to circuit-based links. Downlink gains become critical for this configuration of FIA due to the Predator video streaming across the ISL to MUOS and then down to a disadvantaged user. MUOS, as configured and programmed today, may not support video feeds. WGS offers cross-banding capabilities from the satellite but is still circuit-based. To further illustrate the advantages of IP or Statistical Multiplexing gains, Figure 27 offers the results from a TCO analysis of downlink IP gains based upon Operational Iraqi Freedom (OIF) network results. This figure also shows tremendous gains across even the lower bandwidth links that MUOS will provide to users and the overall TCA [TCO, 2003].

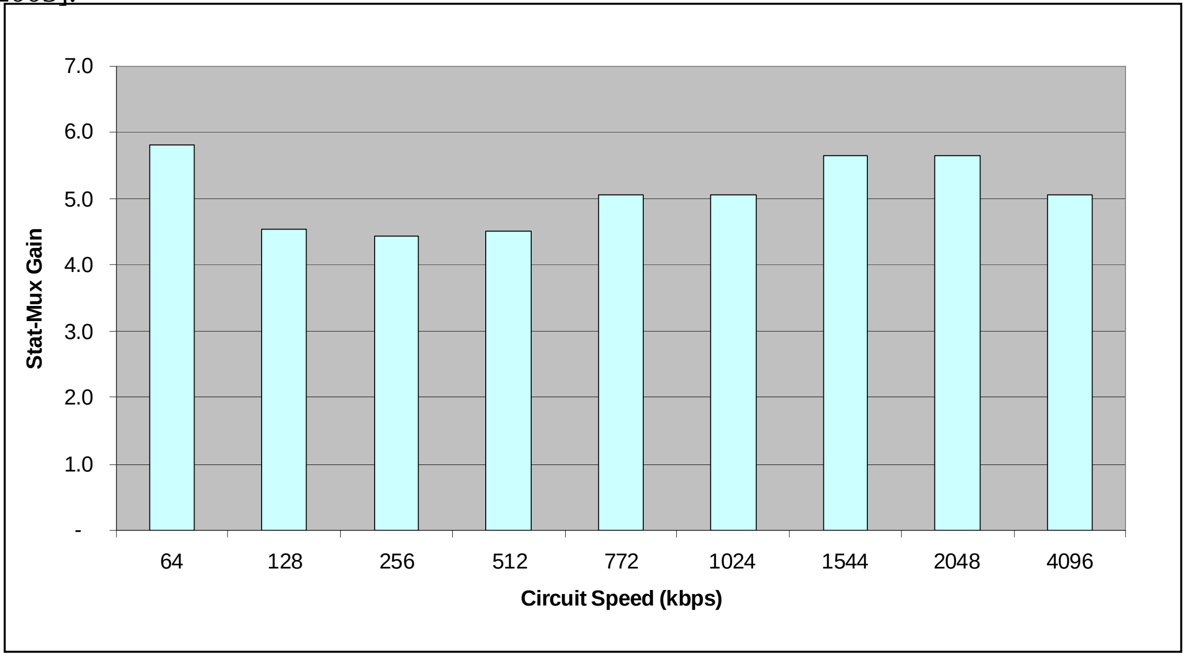

Figure 27. Downlink IP Gains [From: TCO]

Furthermore, TCA will introduce IP routing and IP gains through only one program of record, TSAT. FIA could introduce IP gains across the entire government and commercial architecture leading to even greater link utilization and IP gain for future users. Future analysis of FIA could potentially result in even higher IP gain results across the entire architecture.

2. Survivability

All future space systems could potentially face new and more dangerous threats such as improvements in RF jamming. Similar to the jamming of terrestrial radio signals, jamming of satellite links is accomplished when there is enough RF noise somewhere within the link to significantly degrade the link budget. As such, IP packets could become prohibited from traversing the satellite to their destination. Today's wideband systems, such as WGS and commercial systems without ISLs, may offer little to mitigate this issue. Current and future protected systems, such as Milstar and Advanced Extremely High Frequency (AEHF) systems, offer protection but lack the adequate bandwidth to support all users and bandwidth intensive applications. However, the FIA configuration offers a potential solution to this issue. Onboard IP routers could be assigned to transponders so that when the interference occurs, the router may choose a default route to destination similar to terrestrial routers. And, since every satellite will also employ ISLs, the router could have several paths to send the IP packets to their destination.

3. Reduced Frequency Interference

Geostationary orbital slots have become a premium and competitive opportunity due to limitations as frequency interference and Power Flux Density (PFD). The International Telecommunications Union (ITU) and Federal Communications Commission (FCC) set limits on PFD and minimum angular distance - currently 2 degrees - between any two communications satellites to control several consequences such as frequency interference. Furthermore, as the quantity of terminals accessing the space segment grows, RF conflicts will potentially rise. Past studies have shown that ISLs employed in a regional context, such as FIA, could assist in mitigation of frequency interference. Specifically, information traversing the ISL in the regional configuration, such as with FIA, could potentially reduce the use of simultaneous uplinks and downlinks resulting in reduced intersystem interference (COMSAT, 1986).

As currently configured, TCA will employ ISLs only in a global ring construct, and will not employ ISLs within the near term wideband system, WGS. However, FIA would provide cross-banding across multiple frequency domains with improved bandwidth utilization leading to even greater spectral efficiency and reduced interference. For example, the FIA configuration discussed here shows a single WGS and MUOS satellite. However, the deployment of a second IP and ISL enabled WGS or MUOS satellite within the same region or AOR could greatly improve the number of AISR platforms having access to the network and support the growing demand for ISR information.

4. Latency Improvements for Real Time Services

The current teleports and NCTAMS provide satellite users the capability to cross-band and multiple hop (M-hop) to other satellite constellations. This capability has worked very well for circuit based voice and data networks. However, current operations and future concepts are driving the demand for high bandwidth and low latency tolerant applications such as video and imagery over an IP network similar to the Internet while extended to the satellite architecture. In this environment, ground networks may impose an unacceptable level of delay for these services. For example, a packetized voice datagram may experience up to 555 ms of delay by traversing the teleport or NCTAMS which may degrade the quality of that voice packet to an unintelligible level. However, the same voice packet traversing an ISL between communications satellites in the FIA regional context may experience a delay as low as 300 ms between source and destination nodes. This improvement shows an approximately 50% improvement over the currently deployed satellite communications architecture [COMSAT, 1986].

D. SUMMARY

A recent operation employing the Marine Corps distributed operations concept in a real world environment was discussed. That this is an AOR that will undoubtedly see future activity from U.S. military forces adds relevancy to this discussion, and leads to the conclusion that the studies, analysis, and recommendations in this thesis require serious consideration by the National Security Space community. The National Security Space community shows an increasing disparity in synchronization across the enterprise space architecture, particularly between ground terminals and the space segment. Disparity across the architecture has led to a variety of terminals operating in different frequency bands yet not interoperable. Several efforts, such as TCA, attempt to address issue such as this through plans for advanced networked space architectures in a global context. However, the current approach leaves deployed units with a disparate menu of capabilities.

Specific capability areas where FIA could improve the Transformational Communications Architecture were discussed. As was shown, an all IP routed architecture combined with ISLs could potentially provide a tremendous performance improvement over the existing TCA configuration. Future Marine Corps distributed operations will require a similar space network as provided by FIA. The 2006 deployment by 1st Bn, 3rd Infantry Regiment was analyzed for operational context. But, more importantly, this operation highlights the growing capability gaps that only FIA could fulfill.

VI. RECOMMENDATIONS, FUTURE RESEARCH, AND SUMMARY

A. OVERVIEW

This thesis covered several aspects of a future space networked architecture, which has been named Future Integrated Architecture, and will hopefully contribute to the overall development of future space architectures. Although an architecture was proposed in this thesis, this discussion was not exhaustive in nature. Several other areas of study will require a more detailed discussion and further research. Therefore, this chapter will provide recommended research areas and thesis conclusions.

B. RECOMMENDATIONS

The following specific recommendations are proposed for future research to provide a more connected and interoperable space architecture to support operations such as that seen in Afghanistan. These recommendations also highlight the most critical points revealed from this analysis.

1. Transformational Communications Architecture

The first recommendation might be considered a very bold statement, and that is to integrate FIA, as it was discussed here, into the Transformational Communications Architecture (TCA). TCA will not become fully capable until approximately 2020. However, when it does, it should provide a level of networking in space not unlike the current Internet capabilities and will provide tremendous net-centric capabilities to the warfighter. However, there are potential single points of failure in TCA that could be mitigated by incorporating FIA capabilities as was discussed in the previous chapter. All the IP networking capabilities exist in a single satellite program of record. Any ISL connectivity exists only across government owned systems, and predominately within a single program of record. FIA could provide a distributed architecture across all government and commercial satellite systems without having to always leverage gateways, and provide a foundation for networking and wireless standardization.

As was shown through analysis, this capability might provide tremendous utility to the lower levels of the operating forces. Although TCA will provide capability to the majority of the National Security Space requirements, it might not provide the full capability that is required for the Marine Corps distributed operations concept. Nor will TCA provide the full capability required by almost any tactical ground operations.

2. Intersatellite Links

Based on the analysis in this discussion, interconnection between satellites with ISLs could allow or provide a networked space layer to support connectivity between varieties of ground terminals. This analysis showed successful modeling of traffic flows across a variety of satellite systems and a variety of bandwidths. In this case, the distributed operations environment demands a reliable and efficient exchange of information across all echelons of command. An efficient and effective method to meet this requirement is connectivity and interoperability across the GEO satellite communications assets.

Near term efforts for IRIS and space-based near field wireless / LAN capabilities show that these critical capabilities could be employed within the near future such as within five years. It is important this capability be considered given the impending increase of troop rotations within the Afghanistan AOR in support the war on terrorism.

3. Fractionated Architectures and Mission Satellites

Space acquisition efforts appear to show that extremely complex, monolithic spacecraft add years to the development lifecycle. This degrades the ability to provide a responsive and flexible architecture. The GWOT will demand an architecture that can provide flexibility and support to a variety of missions. A method to provide this flexibility is to insert technology without total spacecraft or architecture replacement.

The Mission Satellite concept could provide a flexible method for the common tenets of the networked architecture. A separate satellite could be re-positioned for virtual and logical integration within a space network but be limited by becoming the physical subsystem of another GEO satellite.

4. IP Routing with Multicasting and QoS

As an extension of the terrestrial networking infrastructure, FIA should integrate the core technologies successfully employed by the Internet. Specifically, IP routers were modeled to show the excellent flexibility and connectivity across the architecture. Future operations will demand greater levels of real time services supported by current networks. The uncertainty and pace of operations will require services such as streaming video to be produced in a very short timeframe, often within seconds. IP networks can provide this flexibility, but may still restrict extreme traffic flows. Resource management techniques such as Quality of Service will be the norm across future networks although QoS is not configured on current terrestrial networks such as the GIG and Internet.

5. Standard Air Interface(s) amongst GEO Communications Satellites

As was shown and analyzed, mission satellites will require a level of interoperability with any government or commercial communications satellite. This will require agreement and standardization with wireless protocols. In this discussion, IEEE 802.16 was assumed as the agreed to and integrated standard. Yet, standardization in this area will be absolutely required to support adequate levels of connectedness, interoperability, and net-centricity across the entire space architecture, both government and commercial.

6. OPNET

Additional results were observed specifically from OPNET models that deserve explicit attention. Future studies which leverage OPNET should consider several issues. The first issue concerns real time services and the strain or impact on the network such as heavy use of VOIP. Several simulations not discussed here included employment of VOIP by all users and nodes which may not always be realistic. However, the DES simulation was successful due to exceeding memory limit either at the server hosting the application or a pre-configured limit set by OPNET. It is unknown if the disparity in bandwidth and low bandwidth circuits aggravated this situation. Another issue for further study should be the mechanics of OPNET simulations and how they appear to show that network performance may be limited by the "lowest common denominator." In other words, with respect to overall network performance/end to end, data moves as fast as the lowest bandwidth circuit. For example, one simulation created an IP data flow from an FTP server, to a Ku satellite at about 1.4 Mpbs, across an OC-48 ISL, and down MUOS at 56k, shows results similar to another simulation with different circuit configurations. Analysis presented in this thesis shows adequate efficiency across the network despite a great disparity in bandwidth configurations.

C. AREAS FOR FURTHER RESEARCH

Many areas of technology were investigated during this research effort. However, due to current research constraints, many areas and topics were not included and will be mentioned here as potential items of research by future students.

1. IP Traffic Streaming of Real Time Services in a High Latency Environment

A review of expert sources such as IETF will show great advances with respect to IP traffic flow. However, throughput requirements for transmission of voice and video over all IP architectures may exceed even improved capabilities. Current video formats, such as High Definition (HD), travel over dedicated circuit or Asynchronous Transfer Mode (ATM) architectures and deliver quality products to the user. Further student research, as well as participation in international user forums such as with IETF, would provide a solid foundation for further research. Advanced QoS configurations and IPv6 should be included in these studies [C. Laurvik, personal communication, 2008].

2. A Networked LEO Satellite Communications with Picosatellites / Cubesats

Recent studies showed the realm of the possible with respect to picosatellites with the development of a cubesat design, sized 10 x 10 x 50 cm, that could successfully support a LEO ISR mission. A future study should take this configuration and modify for networked communications at the LEO layer. Wireless LAN protocols, such as with 802.16 discussed here, requires consideration. Additionally, the value and method of LEO to GEO communications should be included as well as partnering with current efforts in this area. For example, the DARPA F6 communications study could consider the transmission of ISR generated at the LEO layer to a GEO communications satellite. [Nelson et al., 2007].

3. Information Assurance Concerns

All IP architectures raise new concerns. The terrestrial model, the Internet, has highlighted the issues and vulnerabilities that come with the IP gain and advantage. Information Assurance and network security could provide discussion for a multiple thesis effort. However, beyond just the technical issues are the organizational issues, such as with Designated Approval Authority (DAA) relationships [Nelson et al., 2008].

4. Fractionated Satellites and Space Architectures

The DARPA F6 program has provided a tremendous opportunity for the space community to deliver true transformation of future spacecraft and architectures. The concept of spacecraft subsystems flying in a formation connected only by wireless might be considered science fiction at this point, but an area for further research none the less. This area could overlap with future space LAN studies. Additionally, the concept of wireless power transfer, as currently presented by F6, has great merit for further research as power becomes a firm limitation in the space environment [DARPA, 2007].

5. IRIS vs. Ground Based Routing Architectures

During research for this thesis, it came to light that many in the space community feel that routing capabilities may not be required within the space segment and that ground infrastructure can provide the necessary networked capabilities for the overall architecture. A further study should focus on the performance characteristics of both configurations using OPNET, STK, Matlab or other modeling tools [M. Regan and J. Schier, personal communications, 2007 and 2008].

6. Improvement in Spacecraft Acquisition and Impact to Technology Insertion

Criticism has abounded regarding the government spacecraft acquisition processes. Cost overruns and requirements “creep” have pushed critical programs beyond original timelines. Although satellites are designed to support each payload, there may be common subsystem and structural configurations that could be applied across different programs and capabilities sets, i.e., ISR vs. communications. Progress in this area is critical to the future efficiency of U.S. military space capabilities. A potential endstate to such a study, as was recommended by an expert in the field, is to develop a matrix or template. This template would show sizes of spacecraft on one axis, i.e., small/medium/large, and mission areas across a different axis, i.e., ISR/PNT/communications. A common component to begin this evaluation could be the structural bus [M. Regan, personal communication, 2007].

D. CONCLUSION

Future Integrated Architecture presents a solution for increased connectivity, interoperability, and net-centricity. The analysis and discussions show several critical capabilities that must be integrated into the future space architecture. IP routing will form the core capability across the architecture and within each satellite. However, as was seen with the success of the Internet and the Internet Engineering Task Force (IETF), network standards require concurrence across the entire enterprise to include all government and commercial organizations. Standardization should include agreement of a common air interface to support inter-satellite links between any set of communications satellites. The previous assumptions going into the STK and OPNET analysis can be re-stated as premises for FIA network requirements.

This discussion of FIA is one of the many possible configurations for future space networked architectures. A goal of this thesis was to hopefully provide a foundation for further space architecture studies and encourage research by future students. Yet, the focus of research is not for the sake of research; the focus of research is to provide better support for our deployed forces. Our military personnel frequently find themselves in harm’s way and they expect a communications network that is responsive and robust, and delivers the connectivity and interoperability required to defeat the enemy. We should conduct research with a context in mind and the face of the user who requires it. As such, the face of future research is found with the 19-year-old private on patrol in enemy territory. Or, his squad leader who is trying to bring his Marines home alive. The author is reminded of this when visiting the Marine Corps War Memorial in Arlington, VA and hears the faint voices of those Marines, and sailors, who fought that incredible battle. We should not forget why we do what we do. This should be our focus and our passion!

Figure 28. Iwo Jima Flag raising [From: www.iwojima.com]

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