TECHNOLOGY READINESS OF FUTURE GENERATION NETWORKS LEVERAGING REGENERATIVE SATELLITE MESH ARCHITECTURE – A SPACEWAY PERSPECTIVE

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ABSTRACT

Satellite network capacity, adaptability, and responsiveness are enhanced with onboard capabilities for packet switching, bandwidth allocation, and spot-beams which facilitate uplink and downlink spectral reuse. A recent over-the-air (OTA) test of the SPACEWAY™ system, a Ka-band regenerative satellite mesh network supporting IP packet services, provides definitive demonstration of key capabilities in the areas of quality-of-service, routing for unicast and multicast (both best-effort and guaranteed service) traffic, dynamic bandwidth resource allocation, security, and configurable satellite uplink and downlink components. Leveraging SPACEWAY system technologies and operational capabilities serves as a pragmatic step toward the development of future multi-satellite networks with more advanced features including onboard packet routing, multi-mode radio transmission, and inter-satellite links, which are now being considered for transformational satellite networks.

INTRODUCTION

Satellite networks have been widely deployed worldwide for supporting a variety of defense, governmental and commercial applications. A complete spectrum of web, data, voice, video, multicast, and broadcast services are now available to the end users interfacing with these networks through satellite terminals. The terminals provide a wide range of protocols and associated inter-networking functions between the user networks and the satellite domain. So far, support for user applications has largely been achieved with a steady stream of innovations embedded in satellite terminals and the supporting network operations control centers (NOCC) comprising the *ground segment*. The satellites, belonging to the *space segment*, have largely retained their "bent-pipe" payloads providing analog signal (from a source transmitting terminal) amplification and re-transmission, without any higher layer digital processing, to the downlink to reach the destination terminals. This simplistic physical layer-centric design of satellite payloads has now started limiting the full potential of the satellite networks with respect to their capacity, geographic coverage, configurability, responsiveness, policy based security, and support for rapidly evolving peer to peer applications with demanding transport needs.

Recently new satellite systems such as SPACEWAY [1] have started incorporating many digital processing functions in the satellite payload. SPACEWAY has many similarities with the transformational satellite systems being defined today and the associated risk mitigation is summarized in Figure 1 and described later in this paper.

Transformational Satellite Networking Risk Areas	SPACEWAY Feature OTA Testing
Routing	✓
Quality of Service	✓
Network Security	✓
Uplink and Downlink Components	✓
Dynamic Bandwidth Resource Allocation	✓
Multicast	✓

Figure 1. SPACEWAY Risk Mitigation for Transformational Satellite Networks

SPACEWAY design includes support for packet processing, uplink and downlink configurable spot beams, and adaptive dynamic bandwidth resource allocation. Packetization provides a much desired capacity gain, compared to a circuit-based architecture, for bursty traffic that can benefit from statistical multiplexing. A regenerative satellite payload, as shown in Figure 2, receives packets from the source terminal on the uplink and switches them to a particular downlink spot beam location that include the destination terminal. This packet processing in the satellite is supported by demodulation of the uplink digital signal, packet switching within the payload, and then re-modulation for the downlink digital signal. With this capability, such regenerative satellite system can provide full mesh single hop services based on international satellite communication standards [2].

In these regenerative satellite network architectures, the overall system capacity is further enhanced because of the spectral reuse possible with the support for multiple spot beams in both downlink and uplink, as shown with four different patterns for uplink cells Figure 3. A dynamic bandwidth resource allocation function implemented in the payload can provide bandwidth-on-demand and adaptive coding and modulation support to better handle changing weather conditions and mobility that can compromise radio transmission through the atmosphere. The satellite-based resource allocation function can respond faster by providing bandwidth to a terminal based on the combination of current traffic, service level agreement, and resource availability without requiring additional hops that would be necessary if the terminal would have to interact with a ground-based resource control function.

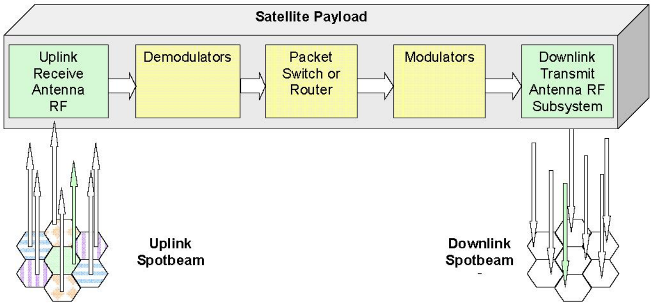

Figure 2. Regenerative Digital Processing Satellite Payloads

The innovative satellite networking technologies summarized above can significantly enhance both capacity and responsiveness of planned transformational satellite systems for defense use [3,4,9]. Because of the magnitude and complexity of the associated system design, development, and integration effort, especially with respect to these advanced satellite payload functions, it is prudent to take a systematic approach toward risk reduction and acquisition phases of these procurements. As part of the standard risk mitigation and technical readiness process normally utilized in these programs, the acquisition programs typically sponsor the development of key technologies on the ground first which will eventually be placed on the satellite. The availability of an in-flight satellite system with similar technologies during the technology demonstration phase can significantly enhance technology readiness of complex satellite systems under development. A recent over-the-air testing and demonstration of the SPACEWAY satellite system is very timely in providing technical data directly demonstrating mitigated risks in the space adaptation of key packet routing, security, dynamic bandwidth resource allocation, uplink, downlink, and multicast technologies.

A systematic use of the SPACEWAY OTA test and demonstration information for technical risk reduction of future defense satellite communication systems is the key theme of this paper. It includes an overview of the SPACEWAY architecture and the current status of development and integration testing culminating in the OTA.

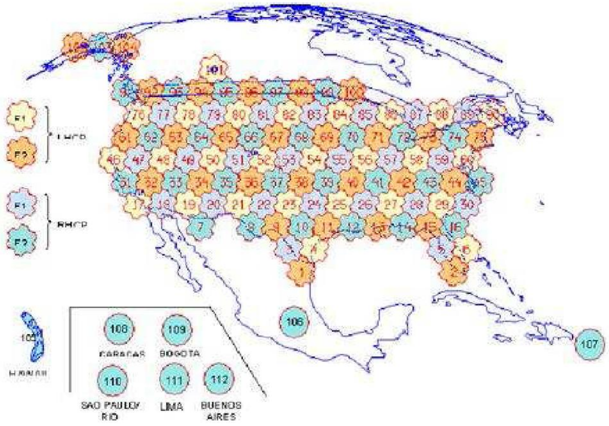

Figure 3. SPACEWAY Uplink Spot Beams for CONUS

The paper describes how the critical risks associated with future generation satellite systems are mitigated by leveraging the SPACEWAY tests across multiple facets of packet networking. Each risk area is analyzed with respect to an operational scenario describing a specific use of the various network functions and components with an integrated end to end perspective covering various technologies and implementations.

The rest of the paper is organized as follows. The next section provides an architectural summary of the SPACEWAY system and the current status of development and testing. This is followed by multiple sections, each analyzing key design and operational features of the SPACEWAY system in the areas of packet routing, security, dynamic bandwidth resource allocation, point-to-point unicast, and multicast with hopping downlink beams. These areas were specially selected for the OTA demonstration for their technical importance with respect to future defense satellite systems.

This comparative analysis with respect to SPACEWAY provides a better understanding of the technological readiness of the relevant technologies needed in next generation systems. In the concluding remarks section, an overall assessment of the relevance of SPACEWAY system development and testing is made and some networking extensions proposed to further leverage the use of future SPACEWAY operations in risk reduction. Specific areas of SPACEWAY development, testing, and operations process are also identified that can be adapted and reused during the system definition phase of future defense satellite systems.

SPACEWAY SATELLITE SYSTEM

SPACEWAY is a packet satellite system designed to provide full mesh IP-based network services using small size, starting at 74 cm, Ka band terminals with data rates into multi Mbps. Packet switching and dynamic bandwidth resource allocation in the satellite payload, coupled with uplink and downlink spot beams provides multi Gbps capacity to the system. Developed by Hughes (providing NOCC and terminals) with Boeing (providing the space segment), the system went through an over-the-air test in early 2006 thus completing the final phase of an elaborate multi-year pre-service system test campaign. The OTA testing comprised a carefully selected subset (about 5%) of the thousands of system integration tests that were already executed in the system reference test-bed environment prior to the OTA. The reference test-bed had used an actual engineering model of the payload, actual NOCC, and terminals connected over a simulated air interface.

Besides the launch of a satellite with a packet processing payload, SPACEWAY also included the development of a highly scalable NOCC for supporting a comprehensive suite of capacity planning, network management, service management, terminal management, payload management, and network control functions for potentially millions of terminals. Multiple models of terminals with compact form factor and power efficient designs were developed. These terminals support dynamic IP packet routing, at multi-Mbps receive and transmit data rates, capabilities in Ka band and use the RSM-A standard for the air interface.

The OTA testing used the following test equipment: (1) Production NOCC at Germantown, Maryland, (2) System and user terminals in a variety of configurations (512 kbps, 2 Mbps, 16 Mbps) distributed over the continental USA, and (3) Gateways in Las Vegas, Nevada and in Germantown. After this successful OTA test campaign, several commercial, consumer, and enterprise services are planned to be launched in the year 2007. In this paper, only a subset of the SPACEWAY features relevant for specific risk mitigation is included. A more detailed overview of the SPACEWAY system, its architecture, and various capabilities can be found in [1,5].

PACKET ROUTING

Packet routing is a key feature of next generation satellite network systems. From an end user perspective, an external network interfaces with a satellite network via a terminal. Figure 4 shows how a laptop communicates with a server over SPACEWAY, connected to the network via terminals. The Gateway and terminals engage in full dynamic routing with the external networks using terrestrial IGP protocols.

In SPACEWAY, multiple Virtual Private Networks (VPN) can be supported over a common physical infrastructure, each with its own set of terminals and route servers. Thus a terminal can maintain an up-to-date dynamic routing table reflecting the best path to the destination. The satellite itself switches each packet to the right downlink beam and the destination terminal using the terminal's Layer 2 MAC address carried in the packet header. A NOCC-based address resolution server ensures the proper mapping between the Layer 3 IP address and the Layer 2 MAC address cached in the terminal.

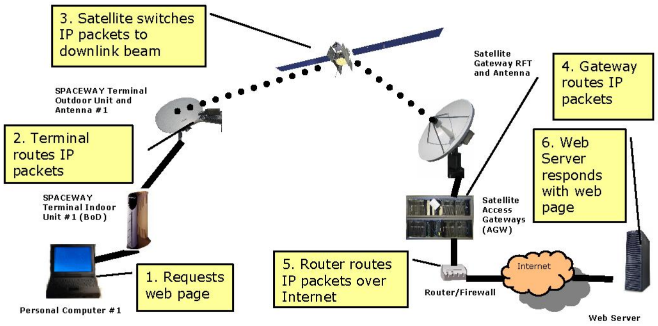

Figure 4. Packet Routing in SPACEWAY Network

A satellite network's unique topology, with a large fanout from the satellite network device to all terminals, provides an opportunity to improve upon traditional terrestrial routing protocols. For example, OSPF routing protocol requires $O(n^2)$ messages, n being number of routers, so that all link states are propagated to every router in the domain and then each router performs a shortest path calculation based on the Dijsktra algorithm. In SPACEWAY, only one node needs to collect route updates, perform the satellite domain routing calculations (add, delete, modify), and then distribute the route updates to all other nodes leading to an $O(n)$ implementation of OSPF for the satellite domain. Terminals can participate in terrestrial dynamic routing using a suitable IGP protocol which can use the satellite domain routing information obtained from the satellite route server. A use of multiple ground-based route servers also supports scalability and redundancy where a set of terminals in a VPN can have its own dedicated route server providing dynamic (satellite) routing support to the VPN terminals. So in the aggregate, the SPACEWAY architecture scales to hundreds of thousands of total dynamic routes for hundreds of VPNs. This routing architecture scalability is quite similar to the control plane scalability of large terrestrial backbone routers.

Future transformational satellite networks may have packet routing support quite similar to the SPACEWAY system. However, full routing capability within the satellite can provide better autonomy support (as ground based route servers are not needed for dynamic route calculations). An end-user operational scenario for transformational satellite systems should be very similar to what was tested in SPACEWAY with satellite-based packet switching. Thus full flexibility of packet routed applications, their behavior with respect to satellite hops, and operational considerations for multiple VPNs, and interfacing with external networks can all be further evaluated with SPACEWAY to refine the future satellite system routing requirements, architectural trades and design.

QUALITY OF SERVICE

SPACEWAY maps both Diffserv and Intserv, IETF standards for IP packet networking, capabilities for IP packet quality of service. SPACEWAY implements 4 levels of packet classification (normal volume, high priority volume, normal rate, and high priority rate) to ensure that both best effort and Guaranteed Services (GS) can be supported in a differentiated fashion. The payload packet scheduler uses this priority scheme in policing decisions under loaded conditions. For guaranteed services, resources can be reserved in two ways: one option is to use NOCC based configuration for scheduled connections and the second is to have on-demand connection setup subject to NOCC policy provided to the participating terminals. Figure 5 shows an operation of two flows from the same terminal, one with best effort and the other with guaranteed service QoS.

Under policy control, a traffic packet belonging to the specified flow (governed by packet source and destination addresses, port number, and protocol) can trigger the setup of a connection and the use of guaranteed treatment for the flow packets in all nodes (terminals and satellite) in the data path. It is also possible to configure the connection as a permanent virtual circuit, and as a high volume uplink (dedicated with no need for bandwidth signaling). GS signaling in SPACEWAY is highly scalable, with support for hundreds of such connections processed per second and state for several hundred thousand of such packet flows in the system at any given time. During SPACEWAY OTA, QoS differentiation was demonstrated by making VOIP calls over different types of services and also by measuring associated packet delay and jitter measurements.

The Global Information Grid (GIG) [8] also needs multiple differentiated packet classes and associated transformational satellite extension can consider guaranteed service architecture with standards-based signaling such as RSVP, an IETF standard. SPACEWAY architecture demonstrates that such capabilities are beneficial for the resource constrained environment of satellite networks as well and with the favorable OTA results they can be implemented in a reduced risk fashion for future networks.

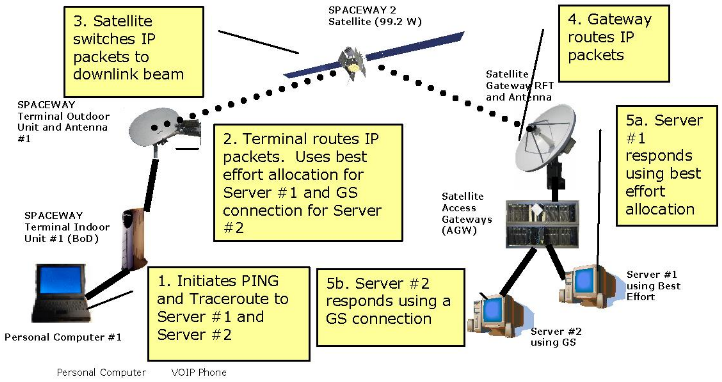

Figure 5. Differentiated and Guaranteed Quality of Service

SECUTITY MANAGEMENT

SPACEWAY has implemented many security facets including authentication, confidentiality, and integrity with over the network re-keying for efficiency and robustness. Data confidentially is maintained with a link level triple DES scheme on the link from terminal to terminal, similar to wireless links in defense applications. Similarly, both the satellite payload management and terminal management and control are also protected. Terminal identification is based on shared keys which are then used in a handshake protocol for unique session level keys. Scalability of SPACEWAY key generation and distribution design assures that more than one million terminals can be accommodated in this protocol for frequent re-keying. This architecture scalability bodes well for the growing use of PKI certificates with digital certificates in large terrestrial networks and their potential application in the defense community for satellite communication.

SPACEWAY multicast data confidentiality is supported with conditional access with keys generated for each multicast group (receive terminals).

Figure 6 shows the operational steps involved in the commissioning of a typical SPACEWAY terminal and the related security implications for various networking functions.

SPACEWAY's layered security design starts with a one-time terminal registration using pre-arranged shared keys. The registration handshake is used to distribute keys for the management session, link-to-link data confidentiality, multicast conditional access, uplink capacity protection keys, and BoD allocation keys.

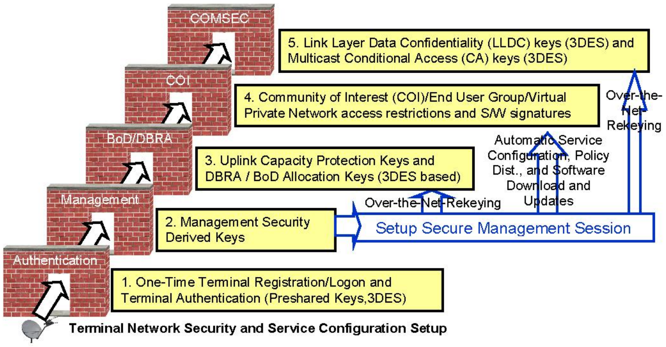

Figure 6. Security Layering in Terminal Commissioning

UPLINK AND DOWNLINK COMPONENTS

Uplink and downlink components play a critical role in satellite network design because of their relative significance in determining the mass, power, and capacity characteristics for the system. Configurable spot beams add the much needed spectral reuse and beam forming capabilities which can better meet dynamic traffic models depicting temporal and spatial variability. For these reasons, SPACEWAY uses spot beams for both uplink and downlink. Frequency reuse algorithms are applied while allocating capacity to specific geographic locations with respect to their coverage by the respective uplink and downlink spot-beams. These configurations reflect the capacity plans [6] generated by the NOCC based on the user service demands and associated service level agreements with respect to the type of service (volume, rate, guaranteed, multicast, best effort, etc.). Supporting a desired capacity plan, the corresponding satellite payload configuration includes allocation of demodulators to beams, configuration of the demodulator channels at the various data rates, and configuration of dynamic resource allocation for various capacity sub-pools for volume and rate services required by customers.

SPACEWAY OTA tested the complete operational concept for this dynamic capacity planning and traffic engineering scenario which included the following: (1) preparing dynamic capacity plans based on user input, (2) checking the plans under hardware, spectral, and power constraints, (3) automatically uploading the associated payload configuration to the payload using inband payload commanding, and (4) using SPACEWAY packet delivery services under the plan as terminals request bandwidth allocations from the satellite payload in control plane. In the data plane, packets are transmitted by a terminal using TDMA bursts in the assigned frequency and time slot. The demodulators and related components in the payload perform decoding, demodulation, security checks and provide packets to the packet switch where they are queued on the correct destination downlink queue. The downlink scheduler prepares downlink bursts so that the packets can be sent to the right terminal in its downlink spot beam. With the use of a phased array antenna, the SPACEWAY beam forming is configurable and it also facilitates the use of dynamic downlink power control based on closed loop control and weather data.

DYNAMIC BANDWIDTH RESOURCE ALLOCATION

Dynamic bandwidth resource allocation is an innovative feature for next generation regenerative mesh satellite networks. Bursty traffic, associated with multimedia and data applications on Internet, requires responsive behavior from the intermediate hops connecting the source and destination hosts. For a satellite network this requires that the TDMA transmission opportunity should be responsively granted to the source terminal. Unlike traditional satellite systems where ground based resource allocation requires additional satellite hops (with additional penalizing Geosynchronous satellite delays), SPACEWAY performs the dynamic bandwidth allocation function on the satellite payload. Figure 7 shows the SPACEWAY operational concept for the dynamic resource allocation scheme where the source terminal requests for bandwidth (for an MP3 file transfer) which is granted by a responsive satellite based implementation.

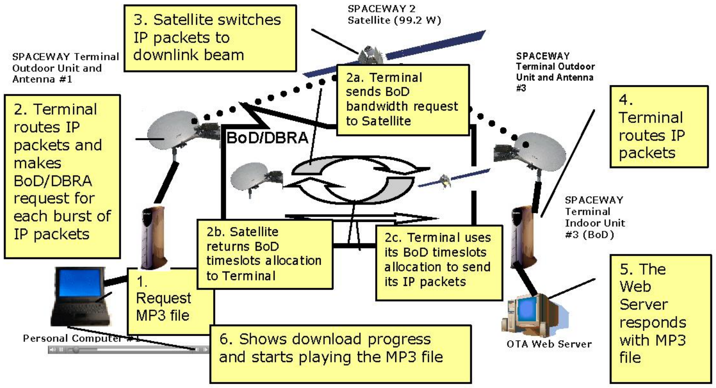

Figure 7. Onboard Dynamic Resource Allocation

Figure 8 describes the various facets of the SPACEWAY resource allocation capability, which because of its similarity with next generation satellite systems, serves as a significant risk reduction step.

Besides better response to varying traffic loads from all source terminals, the resource allocation function also supports multiple coding schemes which can adaptively select the most appropriate coding scheme for a specific environmental condition. For example, during clear weather Ka transmission regular atmospheric attenuation is accounted for in the link margin budget. During rain events, however, the desired signal-to-noise ratio can be compromised because of additional atmospheric energy absorption. Under such conditions, SPACEWAY design can select a more robust coding scheme that provides the extra redundancy to accommodate signal attenuation. In future systems, all three aspects of dynamic radio transmission management-namely, bandwidth, coding, and modulation-can be included in this adaptive satellite payload resource allocation scheme. By demonstrating a multi-dimensional dynamic scheme, SPACEWAY OTA establishes the feasibility of such advanced techniques in transformational communications satellites.

Design Feature	**SPACEWAY Implementation**
Uplink Dynamic Coding and Modulation (DCM)	3 modes; closed loop control each 768ms
Uplink Dynamic Assigned Multiple Access (DAMA)	~10,000 BoD allocations each 96 ms
Uplink RF Channelization	NOCC updates every hour based on capacity plans
Downlink DCM and Downlink Power Control	15dB EIRP range; closed loop control each 768 ms and open loop control
Downlink Statistical Multiplexing	On-the-fly hop mapping; congestion control prevents queue drop in payload
Downlink RF Control	On-the-fly beam-to-carrier mapping

Figure 8. Dynamic Bandwidth Resource Allocation

MULTICAST DESIGN

Multicast applications are well-suited for a satellite network topology where a large number of terminals can be present in the satellite beam footprint. A regenerative satellite such as SPACEWAY allows the use of packets with maximum flexibility for packet routing. For unicast, it means directing the packet to the correct destination downlink beam. For multicast, however, packet processing could require replicating an uplink packet and then sending the copies of the packet to multiple downlink beams. In conjunction with its connection admission capability, SPACEWAY also provides guaranteed service support for multicast traffic.

The SPACEWAY satellite processor has replication capability for multicast packets if such replication is needed for terminals. Spectral and power considerations may require the use of a broadcast to the entire footprint fir a large multicast group. This decision whether to replicate on selected downlink beams or broadcast on a global beam is made in the multicast admission server in the NOCC. Based on the decision, the NOCC commands the satellite payload replication facility with suitable destination downlink beams for specific multicast groups. This payload commanding is dynamic and is driven by dynamic joins and leaves as they are received by terminals and forwarded to the NOCC for a specific multicast group. To the end users, the SPACEWAY system provides IP standards compliant signaling for group management and multicast routing, including support for IETF standards IGMP and PIM-SM. This allows the use of shared multicast trees and rendezvous points, which facilitate communication between a source and multicast recipients. For a more optimal transport, signaling can establish a source-specific multicast tree for PIM-SM standards compliant multicast.

Figure 9 shows SPACEWAY operations for a multicast application which requires replication in two downlink beams. SPACEWAY multicast design uses a common guaranteed service connection admission function for all decision making for joins, leaves, and resource usage leading to high scalability. Packet multicast is likely to be a major service offering for the future defense satellite systems, and the complete standards-based support by SPACEWAY, including guaranteed service, can help further refine requirements and designs in this area.

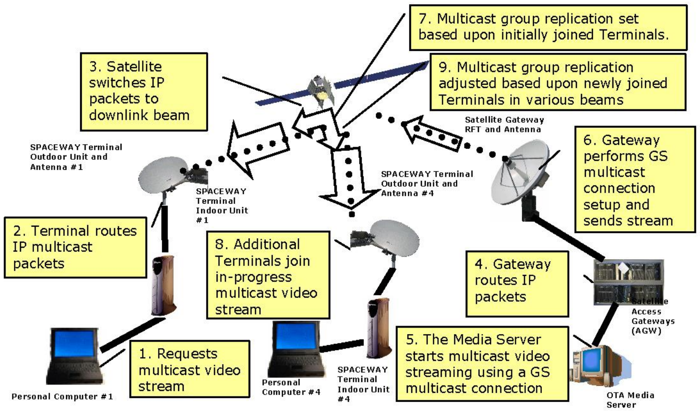

Figure 9. SPACEWAY Multicast Operation

CONCLUSION

SPACEWAY provides an on-demand, high capacity satellite based network to a large number of end user terrestrial networks with full mesh support. As a recent over the air testing demonstrated, it shows high level technological readiness with respect to key satellite radio technologies and its dynamic bandwidth resource allocation implementation. For packet processing, the SPACEWAY system design is similar to the planned transformational satellite architectures that may use Layer 3 IP packet routing within the satellite for higher flexibility and autonomy advantages. SPACEWAY also supports differentiated services for multiple traffic classes for both unicast and multicast using both best effort or guaranteed service modes. One area where SPACEWAY design can be extended is to provide a more direct support for mobile terminals. Facilitated by a flexible architecture, the prototyping of such a feature is being explored so that Communication-On-the-Move (COTM) scenarios can be better understood with an operational in-flight advanced satellite system. Such an operational experience can lead to better requirements for providing a packet service with dynamic resource allocation under varying conditions including channel impairments, intermittent connectivity, and blockage. The associated SPACEWAY mobility design to incorporate these features is presented in [7].

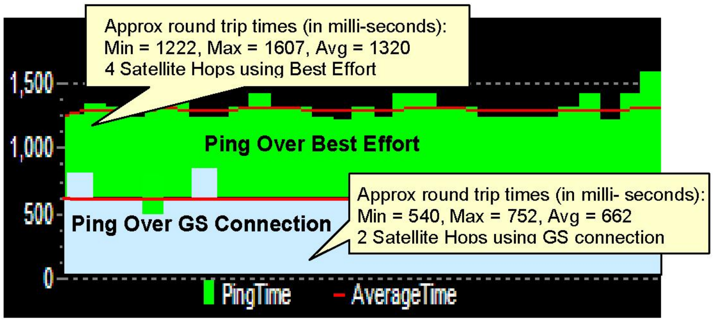

Figure 10: Best Effort and Guaranteed Service Connection QoS (*visual based on representative OTA results*)

The SPACEWAY OTA testing (with a representative test shown in Figure 10), the associated demonstration for the defense department representatives utilized multiple unicast and multicast network applications such as VOIP, web browsing, file transfer, etc. This suite of applications provides an operational model of what the end users of the planned transformational system would experience with respect to meeting their networking needs. Besides its use in technological risk reduction towards the design and development of transformational satellite systems, the SPACEWAY system can also be used for better defining the operational characteristics of future transformational networks. This includes terminal installation, network operations, mission planning, and network management areas including fault management. With wider availability of SPACEWAY services expected in 2007, it can further accelerate and reinforce the system definition and development process for the transformational satellite networks with its ability to reduce networking and operational risks.

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BIOGRAPHIES

Rajeev Gopal received a Ph.D. in Computer Science from Vanderbilt University and a B.E. in Electrical Engineering from BITS, Pilani. He has worked in satellite network development, computing research, biomedical R&D, and large scale information system deployment. Dr. Gopal was one of the SPACEWAY system architects and the chief architect and software manager for the SPACEWAY NOCC development. Currently, he is involved in the Transformational Communications Satellite (TSAT) System project.

David Whitefield graduated from Virginia Polytechnic Institute and State University with a B.S. degree in Computer Science and gained a M.S. degree in Software Engineering from Johns Hopkins University. He joined Hughes Network Systems in 1990 and has worked extensively on satellite communication systems and networking. He has architected, designed, and developed for systems including Transformational Communications Satellite System (TSAT), SPACEWAY broadband satellite system, ICO satellite system, ATM networks, Frame Relay networks, and X.25 networks.

Steven P. Arnold received his M.S. in Electrical Engineering from Purdue University and his B.S in Electrical Engineering from Virginia Polytechnic Institute and State University. At Hughes Network Systems, he has worked on several satellite communication systems, including the SPACEWAY broadband satellite system, ICO satellite system, and Thuraya satellite system. Previous to joining HNS, he worked at IBM Corporation on wireless technologies for Intelligent Transportation Systems.