NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ON-LOCATION PUBLIC AFFAIRS REACH-BACK SYSTEM

by

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March 2017

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2017	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE
ON-LOCATION PUBLIC AFFAIRS REACH-BACK SYSTEM

5. FUNDING NUMBERS

6. AUTHOR(S) Joshua A. Clements

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

Deployed operations necessitate Department of Defense forces to operate in remote and sparsely connected locations that limit their ability to maintain high-quality, high-speed visual communications with the rest of the force. An operational requirement has been established for the provision of video services that can swiftly distribute high-quality video from within the fleet to anywhere in the world with short notice. Such a capability requires rapidly deployable, high-throughput, low-latency satellite communications. Modern satellite constellations can enable this capability acting as a high-speed telecommunications portal.

This research evaluated an integrated, satellite-enabled, high definition portable video processing solution constructed from commercially available components. This solution can be used to deliver ultra high definition (UHD) video from forward-deployed units in a wide variety of use cases and applications. The use case developed in this research utilized commodity digital camera and computing equipment to send a live 4K video stream to the Defense Media Activity's public video media outlet, DVIDS.

This quantitative experimental research found that the O3b Networks Medium Earth Orbit satellite terminal successfully provided sufficient bandwidth and acceptable latency to provide network services for forward-deployed UHD video devices.

14. SUBJECT TERMS
digital video engineering, compression, ultra high definition video, UHD, 4K, MEO satellite, O3b Networks, TFAAS

15. NUMBER OF PAGES
83

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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ON-LOCATION PUBLIC AFFAIRS REACH-BACK SYSTEM

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN NETWORK OPERATIONS AND TECHNOLOGY

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

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TABLE OF CONTENTS

I. INTRODUCTION........1
A. PROBLEM AREA........1
B. SCOPE........1
C. RESEARCH QUESTIONS........1
D. METHODOLOGY........2
E. BENEFITS OF STUDY........2
F. THESIS OUTLINE........2

II. BACKGROUND........3
A. DEFINITION OF ULTRA HIGH DEFINITION VIDEO........3
B. BANDWIDTH REQUIREMENTS FOR 4K VIDEO........3
C. ENCODING DISCUSSION........5
D. NETWORK LATENCY........6
E. SATELLITE COMMUNICATIONS........7
F. NETWORK PERFORMANCE MEASUREMENT........9
G. BACKGROUND SUMMARY........10

III. DESIGN........11
A. REQUIREMENTS........11
B. SATELLITE TERMINAL........12
1. Outdoor Equipment........12
2. Indoor Equipment........13
C. VIDEO SERVERS........16
1. Hardware........16
2. CentOS 6........16
3. viaPlatz 2.0........16
4. FFmpeg........17
5. Panasonic Lumix DMC-GH4 Digital Camera........18
D. USE CASES........18
1. Mobile Server Standalone Mode Using viaPlatz........19
2. Teaming Mode Using viaPlatz........19
3. Mobile Server Standalone Mode Using FFmpeg........20
4. Teaming Mode Using FFmpeg........21
5. Live Streaming to DVIDS using FFmpeg........21
E. TEST PLAN........21
1. System Description........21
2. Objective........22

3. Validation......22
4. Data Collection Plan......23
5. Schedule......24
6. Personnel......24
F. DESIGN SUMMARY......25

IV. RESULTS AND ANALYSIS......27
A. RESULTS......27
B. ANALYSIS......35
C. RESULTS AND ANALYSIS SUMMARY......36

V. SUMMARY AND CONCLUSIONS......37
A. RESEARCH SUMMARY......37
B. RECOMMENDATIONS......38
C. FUTURE RESEARCH......39
1. Hardware Encoding......39
2. Maritime Satellite Terminal......39
3. Large-scale Deployment of MEO SATCOM......40
D. CONCLUSIONS......40

APPENDIX A. GLOSSARY......43

APPENDIX B. DATA......45

LIST OF REFERENCES......55

INITIAL DISTRIBUTION LIST......57

LIST OF FIGURES

Figure 1. Illustrative Bitmap Image 4

Figure 2. I, P, and B-Frames. Source: Amonen (2009). 6

Figure 3. Gravitational and Centrifugal Forces Acting on Satellites Orbiting Earth. Source: Maini & Agrawal (2014). 8

Figure 4. O3b MEO Satellite Handover Process. 9

Figure 5. OnPARS System Diagram 11

Figure 6. TFAAS Antennas 13

Figure 7. Rear View of TFAAS Indoor Equipment 14

Figure 8. 30-amp to 15-amp Adapter 15

Figure 9. FFmpeg Build Options 18

Figure 10. Plural XMS Deployment. Source: NTT IT Corporation (2015). 20

Figure 11. FFmpeg Stream Initiation Command 21

Figure 12. Network Tool Initiation Commands 28

Figure 13. iPerf3 Results – Mobile Server at Camp Roberts to Stationary Server at NPS 29

Figure 14. iPerf3 Results – Stationary Server at NPS to Mobile Server at Camp Roberts 29

Figure 15. iPerf3 Summarized Bandwidth Measurements from Mobile Server to Stationary Server at NPS 30

Figure 16. Ping Results 31

Figure 17. iPerf TCP Results 32

Figure 18. iPerf UDP Results 32

Figure 19. iPerf TCP and UDP Mode Bandwidth Comparison 33

Figure 20. iPerf Jitter Results 33

Figure 21. IPTraf Results 34

Figure 22. FFProbe Results 34

LIST OF TABLES

Table 1. iPerf3 Mobile Server to NPS Server Data 45

Table 2. iPerf3 NPS Server to Mobile Server Data 47

Table 3. Ping Mobile Server to Google's DNS Data 49

Table 4. iPerf Mobile Server to O3b Hub TCP Mode Data....................................51

Table 5. iPerf Mobile Server to O3b Hub UDP Mode Data 52

Table 6. IPTraf Streaming Capture Data 53

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LIST OF ACRONYMS AND ABBREVIATIONS

AVC	advanced video coding
CDN	content delivery network
CentOS	Community Enterprise Operating System
CNAL	Commander, Naval Air Forces Atlantic
DOD	Department of Defense
DISA	Defense Information Systems Agency
DSL	digital subscriber line
DSLR	digital single-lens reflex
FQDN	fully qualified domain name
Gbps or Gb/s	gigabits per second
GEO	geosynchronous Earth orbit
GUI	graphical user interface
HAIPE	high assurance internet protocol encryption
HDMI	high definition multimedia interface
HEVC	high efficiency video coding
IFL	inter-facility link
IP	Internet protocol
JIFX	Joint Interagency Field Exercise
MB	megabytes
Mbps or Mb/s	megabits per second
MEO	medium Earth orbit
NPS	Naval Postgraduate School
OnPARS	On-location Public Affairs Reach-back System
ONR	Office of Naval Research
OOB	out-of-the-box
PAO	Public Affairs Office
RAM	random access memory
RHEL	Red Hat Enterprise Linux
RTMP	real-time messaging protocol
RTT	round-trip time

SATCOM	satellite communications
STIG	security and technical implementation guide
TB	terabyte
TCP	transmission control protocol
TFAAS	tracking fly away antenna system
UDP	user datagram protocol
UHD	ultra high definition
URL	uniform resource locator
VOD	video on demand
VPN	virtual private network
XMS	extreme media server

EXECUTIVE SUMMARY

On-location Public Affairs Reach-back System (OnPARS) provides live ultra high definition video streams from locations with limited data infrastructure via emerging satellite systems that provide “fiber-like” speed.

Introduction

The OnPARS is a portable video server integrated with a high-speed satellite terminal to facilitate the creation, processing, and transmission of high-quality video from a remote location. It is the product of student research efforts at the Naval Postgraduate School (NPS) and sponsored by the Office of Naval Research (ONR) Technology Solutions.

Problem Statement

Deployed operations take Department of Defense (DOD) forces to remote, sparsely connected locations that cut off their ability to maintain high-quality, high-speed visual communications with the rest of the force. An operational need exists to provide ultra high definition (UHD) video from forward-deployed units in remote operating areas using state-of-the-art commercial video capture and encoding technologies. Modern satellite constellations offer a portal back via high-speed telecommunications.

To address the problem, a high-throughput/low-delay, portable, medium Earth orbit (MEO) satellite system was selected to provide network connectivity for a video server. Previous research (Stephens & Adams, 2016) tested a portable video processing system and the performance of an MEO satellite system separately. The previous research concluded that the MEO satellite system that operates on the commercial provider O3b’s satellite constellation provided sufficient bandwidth for transmitting high definition video in real time. It was also concluded that the NPS video cloud server, through its installed viaPlatz software, provided the processing capability required to prepare digital high definition video for transmission over the O3b connection.

This research effort sought to integrate the previously recommended systems to provide the capability to transmit UHD video from a remote location where

telecommunications infrastructure may be limited or damaged. Live UHD video streaming was demonstrated and provides data and a model for further development of the capabilities required by DOD forces.

Methods

viaPlatz provides the ability to ingest and manage a collection of digital video files. It also provides the capability to provide that video to consumers (i.e., higher headquarters, DOD forces, etc.) via a local login system. Consumers of the video must have an account on the local viaPlatz server and login to that specific server. To prevent disruption of service due to movement of the terminal or degradation of the satellite connection, a partner viaPlatz server was installed and configured in the NPS data center (see Figure 1).

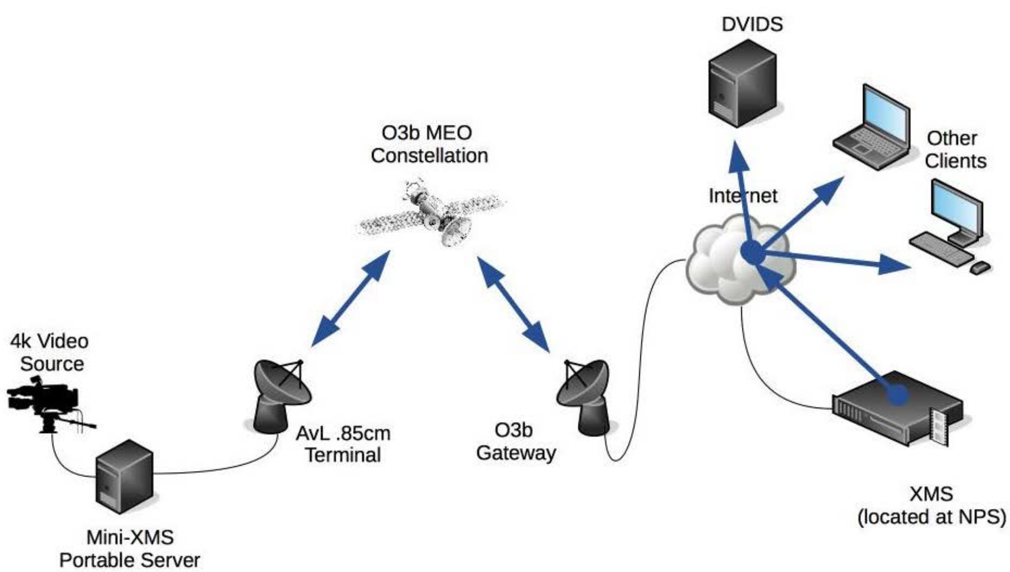


Figure 1. OnPARS System Diagram

Consultation with the producer of viaPlatz, NTT IT Corporation, revealed that the installed version of viaPlatz was not capable of performing in a partnered configuration outside of a local area network (LAN). The theory was to ingest video on a remote viaPlatz server collocated with the satellite terminal. The video would then be transmitted over the satellite link to a stationary server in a data center. The video would then be stored and distributed from the stationary server. NTT IT Corporation suggested that a newer version of the software could provide this capability. The upgrade to viaPlatz version 3.0 is pending.

To test the video streaming capacity of the integrated server and satellite terminal solution, alternative software was selected, installed, and tested. A custom build of FFmpeg was installed on the mobile server to enable the capture of live video. A custom build of NGINX, an open source web server, was installed on the stationary server in the data center to receive and retransmit live video.

O3b Networks operates an MEO satellite constellation with the advertised capacity to provide 800Mbps of bandwidth in each direction, for a total throughput of 1.6Gbps, per beam (O3b Networks, n.d.). The MEO satellite terminal purchased from SES Government Solutions consisted of commercial off-the-shelf (COTS) components, including two 85cm automatically tracking antenna assemblies (satellite dishes). The advertised bandwidth of the system equipped with 85cm antennas is 100Mbps upload and 300Mbps download, with potential upload speeds of 130Mbps in a highly optimized configuration (SES Government Solutions, 2016).

O3b's MEO constellation also provides low-latency speeds that are desirable for use in video applications. Advertised latency of 120ms is achieved through a relatively closer satellite orbit. Where geosynchronous Earth orbit (GEO) satellites occupy a fixed relative location above the Earth at a distance of approximately 22,000 miles, O3b's MEO satellites orbit at a distance of approximately 5,000 miles (SES Government Solution, 2016).

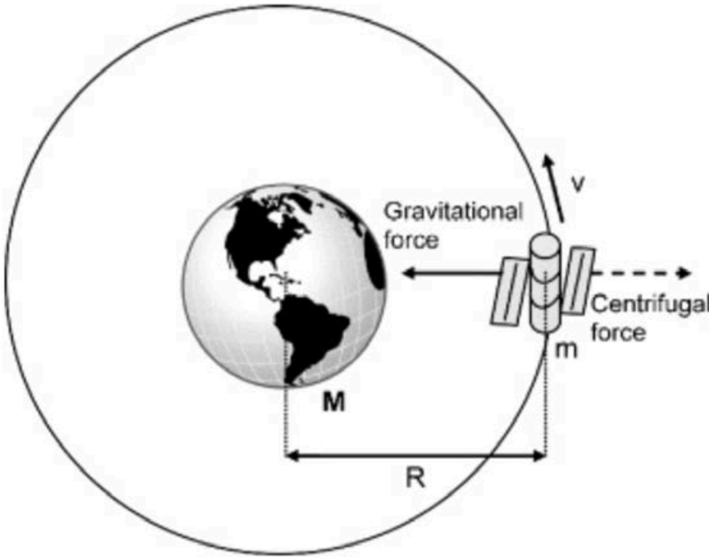
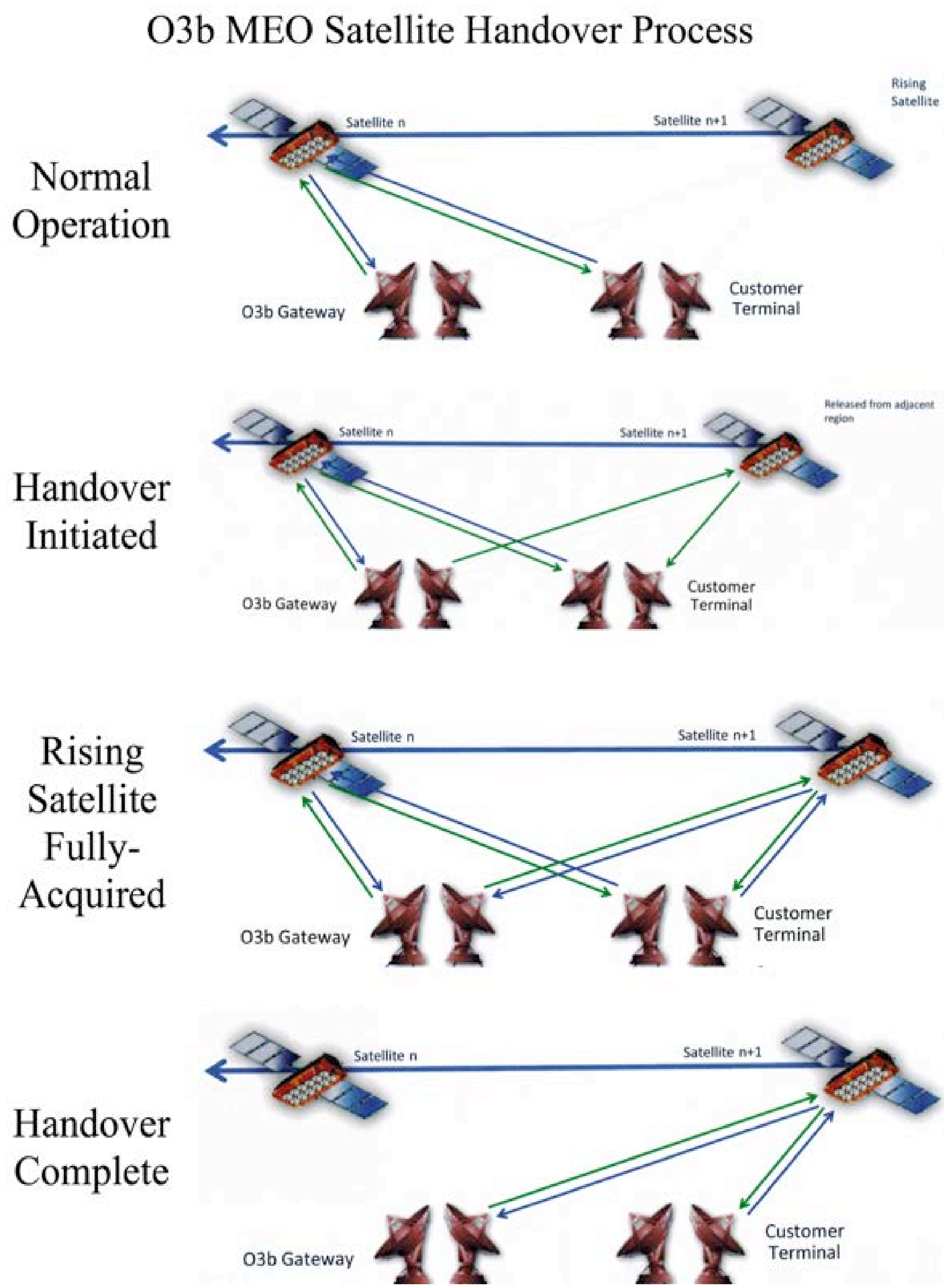


Figure 2. Gravitational and Centrifugal Forces Acting on Satellites Orbiting Earth.
Source: Maini & Agrawal (2014).

Unlike GEO satellite systems, MEO satellite systems require an orbiting constellation of multiple satellites to provide continuous coverage over a given terrestrial location. Kepler's laws of planetary motion as well as Newton's law of gravitation explain how satellites maintain their orbits around the Earth. GEO satellites maintain an orbit speed that is synchronized with the Earth's rotation by maintaining a position further away from the Earth. The satellite's distance (R in Figure 2) from Earth is adjusted so that the resultant velocity (*v*) matches the Earth's rotational speed, allowing the satellite to maintain its relative position over the Earth.

MEO satellite systems reduce the amount of time a signal must travel by decreasing the physical distance between the satellite and Earth. When the distance (R) is reduced, the gravitational force increases, also increasing the centrifugal force on the satellite, which also increases the resultant velocity (*v*). The result is a perceived rising and setting of a given satellite when observed from a fixed spot on the Earth, requiring the ground terminal to track the relative movement of the satellite. Before one satellite orbits below the horizon, the next satellite has risen into view. The dual, automatically tracking antennas provide a seamless transition from the setting satellite to the rising satellite (see Figure 3).



This figure was adapted from O3b Networks training materials (A. Jones, personal communication, 08 September 2016).

Figure 3. O3b MEO Satellite Handover Process

OnPARS was transported from NPS to Camp Roberts, California, to test the integrated solution in a field-representative environment. The entire assembly consisted of eight two-person transportable containers that housed the equipment and protected it during transport. Seven containers made up the satellite terminal, not including spare parts, and one container for the video server. Also required was a compatible camera capable of capturing UHD video.

Several tests were conducted at Camp Roberts to capture data on network and streaming video performance. Standard network performance tools (Ping and iPerf) were used to test latency, jitter, and bandwidth. Another standard network tool, IPTraf, was used to capture the amount of data leaving the video server while it was streaming video. UHD video was streamed to the server in the data center at NPS and to the Defense Video and Image Distribution System (DVIDS) in Georgia.

Finally, the system was demonstrated to an ONR TechSolutions representative at an SES facility in Manassas, Virginia. No testing data was collected during the demonstration, but observed performance was similar to that of the Camp Roberts tests.

Conclusions

viaPlatz 2.0 did not provide the desired functionality and was not tested with the O3b MEO satellite terminal. viaPlatz 2.0 could ingest and manage the media, but would not work with a partner server over the satellite connection. Therefore, viaPlatz was not tested during this research.

FFmpeg was chosen to provide the capability to stream to UHD video from the video server. While functional, this solution was inelegant and ill-suited for routine use. FFmpeg is a command-line program with numerous options that may prove difficult to use for the intended users.

The satellite terminal as configured provided 60–70Mbps of bandwidth in each direction. This throughput was less than advertised, but proved sufficient for UHD streaming. The live UHD stream consumed an average of 0.6 to 1.1 Mbps of bandwidth during transmission as measured by the IPTraf network adapter monitoring tool. An average of 160ms round-trip time (RTT) was observed during network performance testing. O3b technicians explained that the terminal requires optimization upon setup at a new location to achieve the higher advertised performance.

Recommendations

Upgrade the portable and stationary servers to viaPlatz 3.0. NTT IT Corporation suggested that the desired two-server configuration could work with the newer version of their software. Adobe Media Server (AMS), a standard industry media server solution, is an integral component of viaPlatz and could provide the desired streaming functionality independent of the viaPlatz functionality.

Research other COTS video-streaming software solutions. FFmpeg is a versatile open source product that has been integrated into many other projects. A more user-friendly graphical user interface (GUI)-based solution should be sought to provide a reliable and easy to use product for deployed forces. This could have an impact on the annual maintenance costs for the servers.

Collaborate with DVIDS to realize an optimized video-streaming solution. DVIDS currently deploys a video server that provides lower resolution video streams to its content delivery network (CDN). Assistance from DVIDS should be sought to optimize the FFmpeg solution or select more user-friendly software to initiate and manage the video stream.

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ACKNOWLEDGMENTS

None of us is as smart as all of us.

—Management expert Ken Blanchard

It seems you can't get much accomplished today without a little help from your friends. In this case, I made some friends along the way and am most grateful for their contributions, including

- The many helpful people at SES Government Solutions and O3b Networks for their stellar support during testing. Tim Kavanaugh went above and beyond during the deployment of the newly purchased satellite terminal.

- DVIDS, which was crucial in demonstrating the news release use case. Brian Morton and Brian Leighty spent hours on more than one occasion helping to configure and test the stream and were always available when I needed them.

- The research staff at NPS provided great support and intellectual insight into problems that emerged. My gratitude goes to Malcolm Mejia for the muscle (both physical and mental), and my advisors, John Gibson and Doug MacKinnon, for their guidance.

Finally, I thank my wife, Jeanette, for her support, patience, and understanding throughout the production of this research.

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I. INTRODUCTION

A. PROBLEM AREA

An operational need exists to provide high definition video to and from forward-deployed units in remote operating areas. This capability requires the use of state-of-the-art commercial video capture and encoding technologies over emerging extremely high data rate satellite communication links.

This research effort integrated an advanced digital video capability with an emerging commercial broadband satellite capability, as proposed by a previous thesis. Performance and capabilities of the integrated system were validated by a series of field experiments and demonstrations. These demonstrations stressed the portability of the integrated system, to include the time to set-up the system in the field.

B. SCOPE

The scope of this research was limited to the integration and testing of components previously researched by Stephens and Adams (2016) and selected to meet Commander, Naval Air Forces Atlantic (CNAL) capability requirements. This research sought to integrate the chosen solution and validate Stephens and Adams' selection. As the mobile server was previously evaluated extensively, the primary thrust of this research was to assess the performance of the satellite terminal and demonstrate the chosen integrated solution.

C. RESEARCH QUESTIONS

The following research questions were formulated based on the requirements documents provided by the Office of Naval Research (ONR) TechSolutions office.

Primary question:

- How can the video processing system and satellite terminal be integrated?

Secondary questions to answer once the described components are integrated:

- How can the integrated system provide at least 200Mbps uplink and downlink speeds?

- How can the integrated system provide less than 30-millisecond (120-millisecond round-trip) satellite link propagation delays?
- How can the system support the delivery of real-time video?

D. METHODOLOGY

This research builds upon the previous research (Stephens & Adams, 2016), integrating the NPS video cloud server with an O3b Medium Earth Orbit satellite terminal. Data were collected and analyzed using industry-standard processing and network performance measurement tools.

The research consisted of a mix of lab and field work. Software configuration and testing were conducted within the lab. Live operation of the integrated solution, consisting of the satellite terminal, server, and camera, was performed outdoors at the NPS campus and at Camp Roberts, CA.

E. BENEFITS OF STUDY

The primary benefit of this study was to provide a required capability to Commander Naval Air Forces Atlantic (CNAL) Public Affairs Office (PAO). The required capability was to stream live 4K video from remote locations with limited networking infrastructure. Additionally, this study provided data on the use of emerging Medium Earth Orbit satellite systems in tactically-deployed use cases.

F. THESIS OUTLINE

The remainder of this document is organized in the following manner. Chapter II provides background information used to design and conduct this research. This information includes discussions on digital video. Chapter III discusses the design of the research, including the test plan and which data were collected during the research. Chapter IV provides summary results of the research and includes an analysis of the observed results. Chapter V provides a summary of the research, as well as conclusions, recommendations, and suggested future research.

II. BACKGROUND

Ultra high definition (UHD) video is rapidly becoming the standard video resolution class in commercial video applications. As the name implies, 4K images and video offer approximately four times the amount of data as standard HD resolution media; a vast amount of visually rendered digital information.

Increased Internet bandwidth capabilities worldwide enable greater data throughput capability, driving consumer desire for higher resolution video streaming products that provide clear, high-quality imagery on their television at home. Emerging high speed satellite capabilities can enable the satisfaction of end user high bandwidth data requirements where other infrastructure is limited or non-existent.

A. DEFINITION OF ULTRA HIGH DEFINITION VIDEO

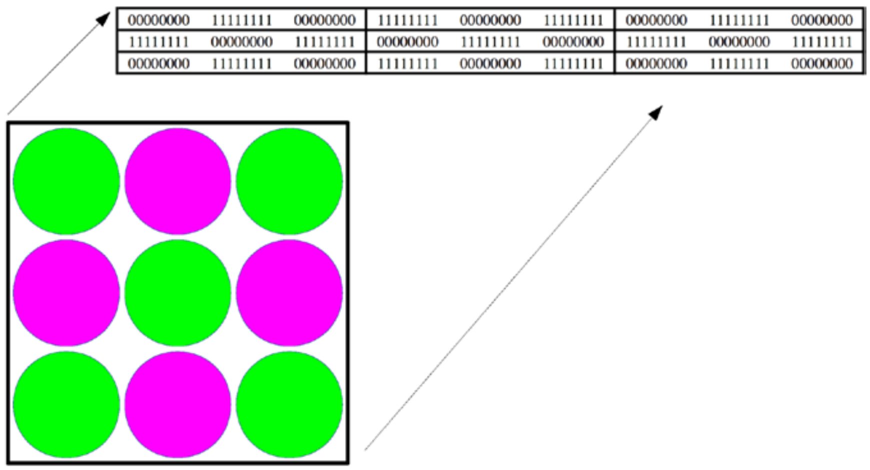
Digital images are displayed as a grid of colored dots called pixels. When viewed together, the pixels represent a view of the light captured by a camera's sensor. Video is essentially still pictures, referred to as frames, shown one after the other to simulate live motion. Changes from one picture to the next give the illusion of movement. The more frequent the pictures are changed per second, the more life-like the video appears.

UHD video is a class of video resolutions that is simply greater than High Definition (HD) video. Within UHD, there are several standardized resolution formats and "the terms are purposefully vague due to the varying international broadcast standards, proliferation of camera types and display options" (Stephens & Adams, 2016, p. 15). For the purposes of this research, UHD 4K was utilized at a resolution of 3,840 pixels in width by 2,160 pixels in height.

B. BANDWIDTH REQUIREMENTS FOR 4K VIDEO

Still and video cameras use a wide array of formats to capture and store pictures and video. These formats are generally described as raw photos or raw video. Raw formats are as numerous as the camera sensor manufacturers and have little impact on the standard outputs from the cameras. Modern cameras offer a wide variety of standard output formats, but almost universally offer JPEG for pictures and MP4 containers for video encoded using the H.264 standard.

One of the more basic digital picture formats that can be used to generally describe raw video bandwidth requirements is the Windows bitmap format. For simplicity's sake, header and various other data within the bitmap format are not considered in this illustration. Figure 1 illustrates how pixels are stored as binary data.



This figure shows a magnified 3- by 3-pixel graphic representing a simplified bitmap image file. Each pixel is defined by 24 bits of data, resulting in a file that is 216 bits, or 24 bytes, in size.

Figure 1. Illustrative Bitmap Image

To calculate the disk space required for this illustrative bitmap image, multiply the height by the width (in pixels) by the color depth (in bits). The space required to store a 4K resolution picture captured in 24-bit color as a bitmap can be calculated as follows:

$$3840 \times 2160 \times 24 = 199{,}065{,}600 \text{ bits}$$

Converted to the more commonly used bytes:

$$199{,}065{,}600 \text{ bits} / 8 = 24{,}883{,}200 \text{ bytes or } 24.9 \text{ megabytes (MB)}$$

Digital video is generally captured at 24 frames per second (fps) up to 60 fps. A theoretical bitmap video at 24 fps would require the following amount of disk space **per second** of video:

24,883,200 bytes x 24 = 597,196,800 bytes or 597 MB

A typical 90-minute motion picture captured in such a format would require 3,223,800 MB or 3.2 terabytes (TB) of storage. This is a rather large amount of data and explains the creation of encoding and compression technologies.

C. ENCODING DISCUSSION

Due to the high resource requirements of raw imagery, encoding technologies were created to increase storage and transmission efficiency. Encoding exchanges disk space for computing time. When applied to network transmission, space is translated to bandwidth.

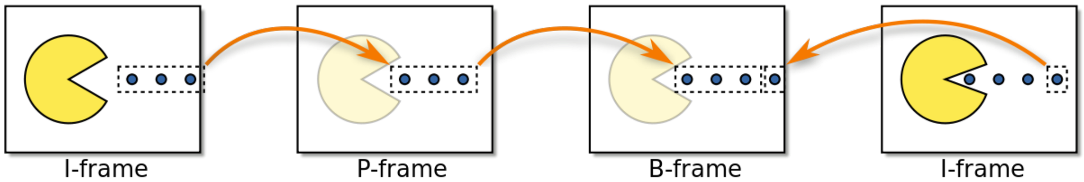
For encoded 4K resolution video, the data volume ranges from 4.2 Gb/s for moderate subsampling, 10-bit color depth and 24 frames per second to over 9.6 Gb/s for RIB (no subsampling), 12-bit color depth and 30 frames per second (Halák, Krsek, Ubik, Žejdl, & Nevřela, 2011). For comparison to the previous discussion on raw imagery, these speeds convert to bytes as follows:

4.2Gb = 4,200,000,000 bits / 8 = 52,500,000 bytes or 525.0 MB

9.6 Gb = 9,600,000,000 bits / 8 = 1,200,000,000 bytes or 1.2 GB

Data volume rates are not only dependent on the method of encoding, but also the amount of motion captured in the video. Video encoders begin with an initial image, called an intra frame (I-frame) (Sethi & Patel, 1995). The I-frame is a complete image that will be the basis for other frame types.

The encoder then calculates the next frame, called a predicted frame (P-frame) (Sethi & Patel, 1995). As seen in Figure 2, the data that is not predicted to change is not encoded into the P-frame. This results in lower data requirements for the P-frame. The more similar the two frames are, the less space each P-frame will consume. Similarly, interpolated bidirectional frames (B-frames) are encoded from previous frames, but also use future frames to make predictions (Sethi & Patel, 1995).



A sequence of intra-coded, predicted and bi-predicted frames in a compressed video sequence.

Figure 2. I, P, and B-Frames. Source: Amonen (2009).

D. NETWORK LATENCY

Assuming an end-to-end connection of the required bandwidth is available for transmission, each component in a system introduces its own latency to the process of transferring captured video from the source to a distribution server. Each component through which video data passes through processes that data, either as a handoff or a transformation of some sort. These delays, though only nano-, micro-, or milliseconds each, compile and can contribute to a diminishing feeling of real time.

The primary factor affecting latency in satellite systems is the distance between the satellite and the Earth. The greater the distance a satellite orbits from the Earth, the longer it will take a satellite signal to travel to and from the satellite. It is for this reason that satellite communication systems employing closer orbiting satellites are being sought.

Streaming video relies not only on low latency in a network, but also on stable network latency to provide quality video that is free of pauses for buffer reset. The evidence can be seen in commercial streaming video solutions where “extensive buffering at the streaming client and conservative rate selection, in order to obtain smooth video rendering with acceptable bandwidth utilization” (Shuai, Gorius, & Herfet, 2014, p. 1) has been implemented. For this reason, it is important for any analysis of satellite network quality to include data regarding network latency variations, referred to as jitter.

E. SATELLITE COMMUNICATIONS

Satellite communications (SATCOM) use directed radio signals from terrestrial sources to satellite vehicles that orbit the Earth. These signals are relayed by the satellite to other terrestrial receivers. The primary benefit of such systems is the ability to conduct reliable and high speed over-the-horizon communications.

Early proliferation of satellite communications utilized geosynchronous Earth orbit (GEO) vehicles that maintained their position over a fixed point on the Earth's surface. While this made for less complicated terrestrial equipment that did not have to track a moving satellite, it required the satellite to orbit at a great distance from Earth, which directly affects the round-trip travel time of the satellite signal.

Kepler's laws of planetary motion, as well as Newton's law of gravitation, explain how satellites maintain their orbits around the Earth. GEO satellites maintain an orbit speed that is synchronized with the Earth's rotation by maintaining a position further away from the Earth. The satellite's distance (R in Figure 3) from Earth is adjusted so that the resultant velocity (v) matches the Earth's rotational speed, allowing the satellite to maintain its relative position over the Earth. A GEO satellite's constant relative position enables the use of single satellite antenna configurations.

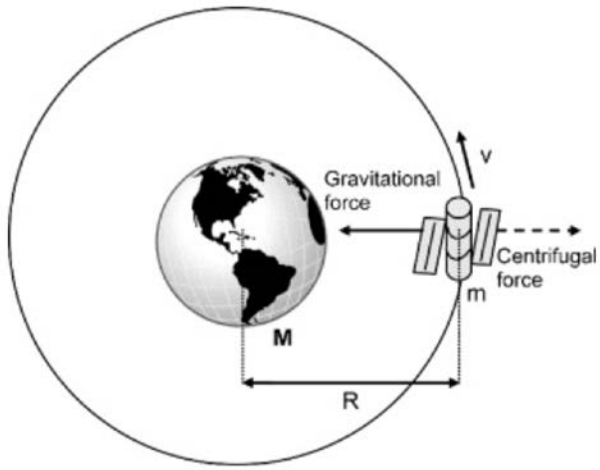
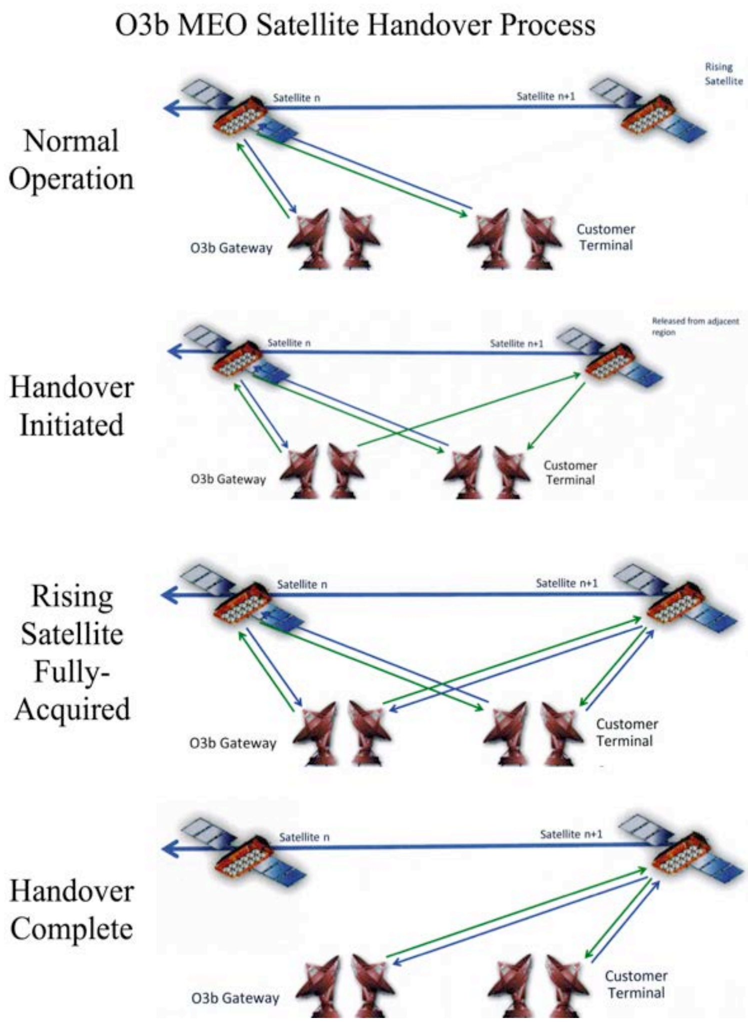


Figure 3. Gravitational and Centrifugal Forces Acting on Satellites Orbiting Earth. Source: Maini & Agrawal (2014).

MEO satellites are relatively closer to the Earth and experience higher gravitational forces. The satellite orbits at a higher velocity (*v*) to generate the appropriate centrifugal force in order to counteract gravitational forces. This velocity is greater than the Earth's rotational speed, resulting in the rising and setting of the satellite when viewed from a fixed position on the Earth.

MEO satellite systems can implement an orbiting constellation of multiple satellites to provide constant coverage. O3b Networks' MEO constellation consisted of 14 satellites, 12 in routine use and two in reserve. These satellite vehicles orbited at 8,062 kilometers, which resulted in a 700-kilometer spot beam at sea level (O3b Networks, n.d.-b). This constellation was of particular interest as this was the system selected as the communications capability for OnPARS.

MEO satellite terminals with one antenna must break connection with a setting satellite in order to connect to the rising satellite. This procedure requires 1–2 minutes where no connection is available. A dual-antenna design as depicted in Figure 4 overcomes this shortcoming.



This figure was adapted from O3b Networks training materials (A. Jones, personal communication, 08 September 2016).

Figure 4. O3b MEO Satellite Handover Process.

F. NETWORK PERFORMANCE MEASUREMENT

Many tools exist to measure network performance. Standard, time-tested command-line utilities like Ping, IPTraf, and iPerf can be used to assess latency, monitor traffic at a network interface, as well as place a simulated load on the connection.

An important measure of network quality is jitter. Jitter represents the variation in packet arrival time. Networking equipment and protocols are designed to account for jitter, but wide variations can have an effect on streaming applications. While lower values of delay are desirable, it is more important that the delay remain consistent so it may be accounted for by the receiving end.

G. BACKGROUND SUMMARY

UHD video is a class of video characterized by its high data requirements. Handling and transport of UHD video requires large amounts of resources, both storage and bandwidth. Transporting UHD video requires quality network conditions characterized by high bandwidth and stable, low-latency connections. This requirement applies to all segments of the network connection between the server and client.

Emerging commercial satellite communications systems are providing lower latency, higher bandwidth capabilities than previously available to consumers. MEO satellite systems in particular offer quality network conditions over the satellite segment that are required to enable quality, high resolution video streaming.

III. DESIGN

In simplest terms, the mobile server, also called the Mini-XMS (eXtreme Media Server), is a typical desktop computer and the satellite terminal acts much like a home Internet router. The link between the satellite terminal and the Internet via the O3b Networks infrastructure can be likened to cable or digital subscriber line (DSL) Internet access service. The 4K video source can be thought of as a webcam.

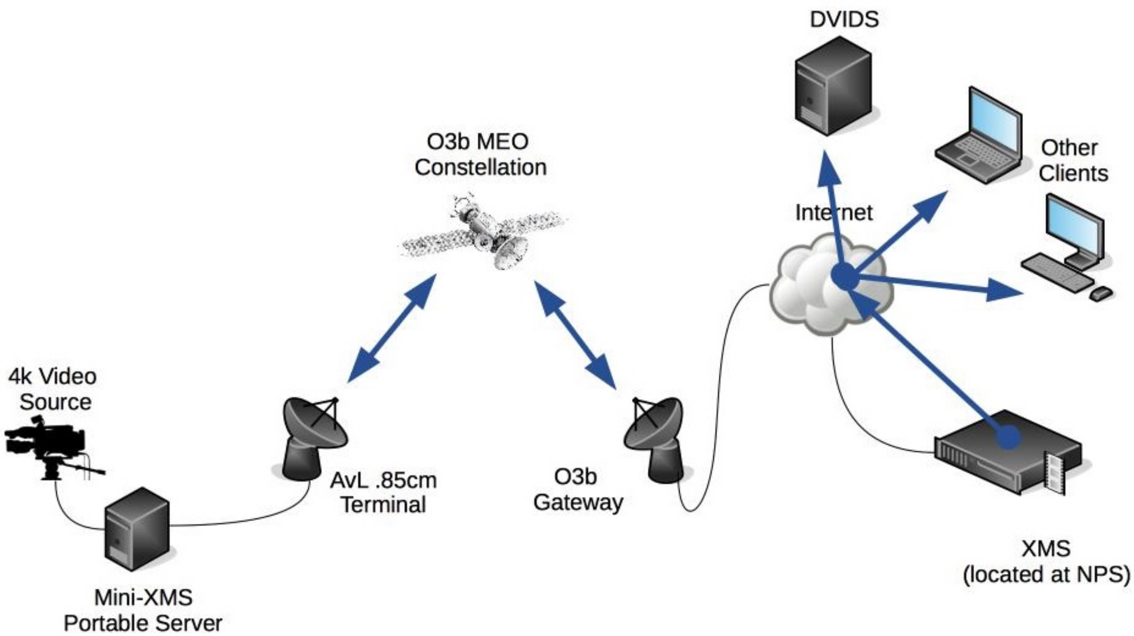


Figure 5. OnPARS System Diagram

A. REQUIREMENTS

The following requirements were extracted from the CNAL PAO Statement of Requirements:

- Must support full-resolution UHD/4K video and multiple compressed video streams at 20Mbps
- Must operate bi-directionally in the range of 200–400 Mbps (200 Mbps minimum)

- Must be less than 30-millisecond link propagation delay (120-millisecond round-trip propagation delay)

B. SATELLITE TERMINAL

The satellite ground terminal was purchased from SES Government Solutions through GSA Advantage. It was assembled from commodity networking equipment and antennas manufactured by AvL Technologies. Together, the outdoor antenna assemblies and indoor networking equipment comprised the Tracking Fly Away Antenna System (TFAAS) (Stephens & Adams, 2016). The TFAAS was configured by SES Government Solutions and O3b Networks to function with the O3b Networks MEO satellite constellation.

1. Outdoor Equipment

The TFAAS outdoor equipment consisted of two .85m AAQ-1 antenna assemblies (Figure 6) and two 100-foot inter-facility link (IFL) cable assemblies. The .85m antenna was rated to receive at up to 300Mbps and transmit at up to 100Mbps. And while "other satellite configurations utilize a 1.0 m or 1.2 m reflector panel for increased performance" (Stephens & Adams, 2016, p. 54), the .85m antenna was selected during Stephens & Adams' research to provide the optimal balance between performance and man-portability. On a highly-tuned .85m system, upload speeds of 130Mbps are possible (T. Kavanaugh, personal communication, 10 August 2016).

The cable assemblies provided power, control, and communication connections between the indoor equipment and the antenna assemblies. Each cable was calibrated to its particular antenna and was labelled appropriately. While the cables are constructed identically, it was recommended that each cable was connected to its respective antenna to prevent performance degradation (T. Kavanaugh, personal communication, 10 August 2016).

OnPARS antennas are set up on the roof of Spanagel Hall at Naval Postgraduate School in Monterey, CA, on 08 August 2016.

Figure 6. TFAAS Antennas

2. Indoor Equipment

The TFAAS’ indoor equipment provided everything required for the operation of the terminal, as well as network connection for external devices, such as a video server or wireless router. This consisted of a network router, patch panel, network switch, and antenna controllers and receivers. The indoor equipment is housed in two transportable rack-mount cases, as shown in Figure 7.

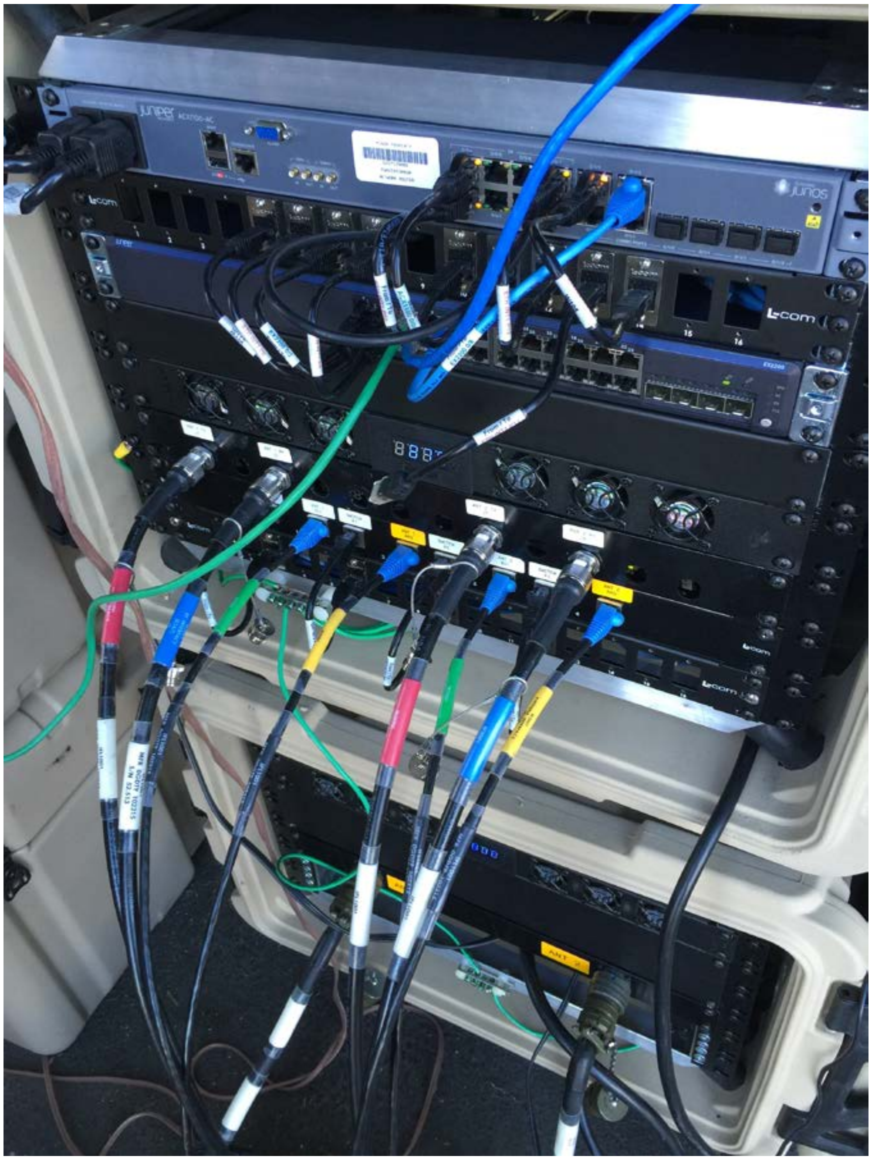


Figure 7. Rear View of TFAAS Indoor Equipment

The indoor equipment also included the power supply for the entire terminal (both indoor and outdoor equipment). The power supply was intended to be connected to a grounded 115-volt AC, 30-amp power source. Normal operation of the terminal does not typically draw more than 15 amps of power (T. Kavanaugh, personal communication, 10 August 2016). The 30-amp design was meant to provide enough extra capacity for windy conditions that require extra work by the antenna motors to keep the antennas stabilized.

Wind conditions during the assessments at Camp Roberts were light enough that the terminal was able to run on standard 15/20A wall outlet using an adapter (Figure 8).

Figure 8. 30-amp to 15-amp Adapter

OnPARS objectives included operation of the system in a forward-deployed location, which might include using a generator as a power source. The power supply installed in OnPARS' TFAAS was not designed to operate with a generator. The specific hazard condition that could have arisen was a ground fault loop. This condition could have caused interference with the signal to and from the satellites, significantly degrading the performance of the system (T. Kavanaugh, personal communication, 10 August 2016). To allow OnPARS to be powered by a generator, a power supply specifically designed to accept power from a generator can also be installed (T. Kavanaugh, personal communication, 2016).

C. VIDEO SERVERS

1. Hardware

The Mini-XMS consisted of typical personal computer hardware, including a fourth-generation Intel i7 quad-core processor, 16GB of random access memory (RAM), and multiple solid-state disk (SSD) drives for storage. The hardware was installed in a four-unit (4U) rack-mount case with drawer slides to facilitate maintenance. The case was then installed in a 4U travel case for protection during transit, which also included handles to facilitate movement by hand.

An atypical, but still COTS, piece of hardware installed in the mobile server was the DeckLink Black Magic 4K Extreme 12G video capture card. This component enabled the system to ingest audio and video from a multitude of source devices, including the Panasonic DMC-GH4 digital camera that was connected via its high-definition multimedia interface (HDMI).

2. CentOS 6

CentOS, pronounced “cent-oss” (Hughesjr, 2005), stands for Community Enterprise Operating System. CentOS is a Linux kernel-based operating system that is derived from Red Hat Enterprise Linux (RHEL) with the aim of being functionally compatible with RHEL (About CentOS, n.d.).

The Defense Information Systems Agency (DISA) Security Technical Implementation Guide (STIG) for Red Hat 6 was applied to both the mobile and stationary servers. This was done to test a real-world representative solution that meets DOD information security requirements. Both servers were also updated to the latest 6 series release available at the time of assessment, CentOS version 6.8.

3. viaPlatz 2.0

viaPlatz is a product of the NTT IT Corporation and version 2.0 was installed on both the mobile and stationary servers. The software was designed to ingest video and provide content delivery and collaboration. viaPlatz’ more granular capabilities included user management, video transcoding, and media management.

Discussions with NTT IT corporation revealed that Teaming Mode functions, as described below, were not available in Internet-connected deployments of viaPlatz 2.0 (Y. Kato, personal communication, 13 June 2016). For viaPlatz to perform the desired functions of ingesting video remotely and transmitting to a dedicated server, an upgrade to viaPlatz 3.0 was required (Y. Kato, personal communication, 13 June 2016). The viaPlatz upgrade would have also required an operating system upgrade to CentOS 7 (Y. Kato, personal communication, 13 June 2016). Funding was not available to secure the support required for such an upgrade, but was requested for eventual execution.

4. FFmpeg

Since the current installation of viaPlatz was not suitable for the application, FFmpeg was selected to test the integrated solution's ability to stream 4K video. FFmpeg is a complete, open source, cross-platform solution to record, convert, and stream audio and video ("About FFmpeg", n.d.). Pre-built binaries are available for most popular Linux distributions, including CentOS.

The most significant drawback to using FFmpeg instead of viaPlatz was the loss of the graphical user interface (GUI). viaPlatz' GUI enabled the automation of many transcoding and media management tasks involved in an efficient video production workflow. While those functions are desirable for routine use by public affairs personnel, FFmpeg provided the necessary functionality to assess OnPARS' video streaming capabilities.

The BlackMagic DeckLink 4K Extreme 12G video capture card installed in the Mini-XMS was not supported by FFmpeg out-of-the-box (OOB). Due to this lack of OOB support, a custom build of FFmpeg was required to enable the BlackMagic DeckLink video capture card. The source code for FFmpeg was freely available for download from multiple sources, including FFmpeg Git repositories and as compressed archives directly from its website.

FFmpeg provides a compilation guide on its website for customization of their software ("Compile FFmpeg on CentOS", n.d.). The required options used for this particular build are illustrated in Figure 9. Key build options that were required for this application were libx264, fdk_aac, and decklink. The libx264 and fdk_aac options were required to enable Flash video streaming via the real-time messaging protocol (RTMP) to the XMS at NPS. The decklink option was required to enable the use of the Mini-XMS' video capture card ("FFmpeg devices documentation", n.d.).

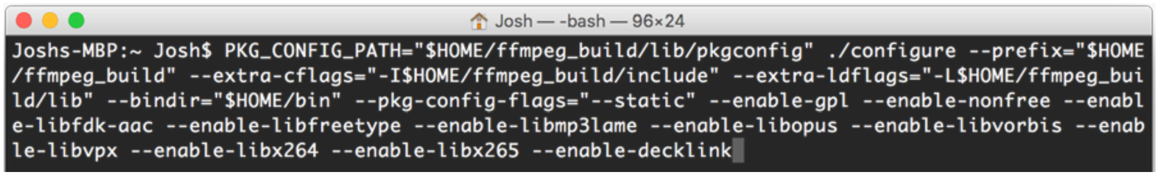


Figure 9. FFmpeg Build Options

To enable support for the video capture card in FFmpeg, BlackMagic's DeckLink Software Development Kit (SDK) was required. This software was freely available for download on BlackMagic's website. The SDK files were extracted to the FFmpeg build directories as described in FFmpeg's compilation guide prior to FFmpeg compilation.

5. Panasonic Lumix DMC-GH4 Digital Camera

A Panasonic Lumix DMC-GH4 digital single-lens reflex (DSLR) camera was used previously to create 4K and HD video files (Stephens & Adams, 2016) to assess the transcoding capabilities of the Mini-XMS. In addition to 4K capture capability, the DMC-GH4 included an HDMI output that could be used to connect it to the Mini-XMS' video capture card. For this reason, the same model camera was chosen to stream live video during OnPARS' assessment at Camp Roberts, CA and demonstration in Virginia.

D. USE CASES

There are multiple ways to employ the equipment included in OnPARS. As with any IT system, how the components are connected and configured can greatly vary the capabilities of the system. This research explored just a few of the ways that OnPARS might meet the research objectives.

The particular use case utilized in assessing OnPARS was teaming mode using FFmpeg. Teaming mode refers to more than one server working in concert to provide a desired outcome. In this case, the mobile server ingested, transcoded, and transmitted 4K video to the stationary server at NPS where it was available for redistribution.

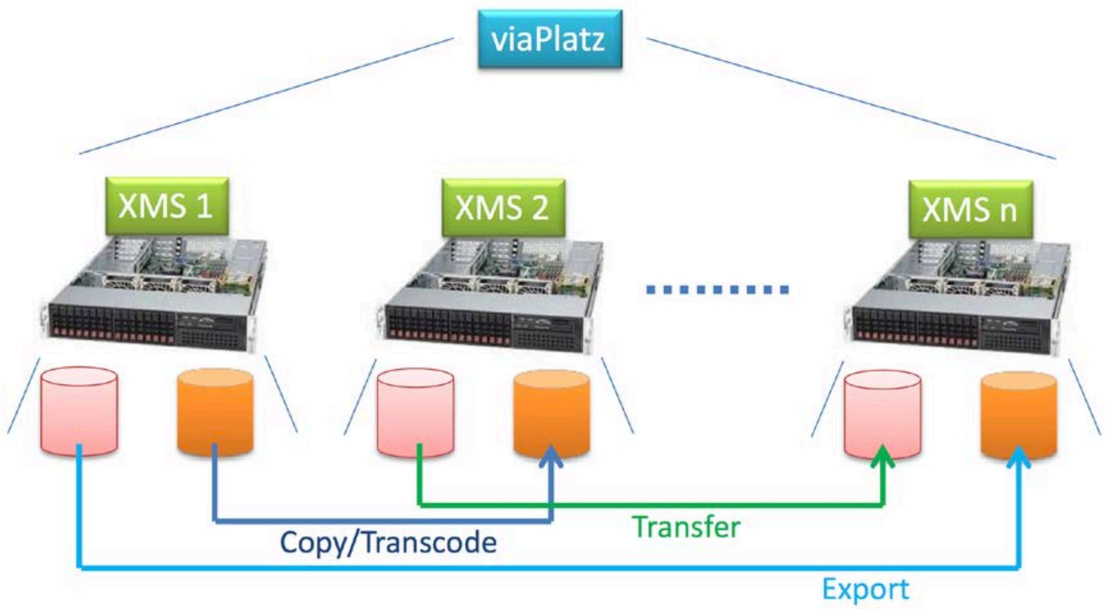
1. Mobile Server Standalone Mode Using viaPlatz

viaPlatz functioned as an all-in-one video processing and distribution solution. It offered capabilities to ingest, transcode, edit, collaborate with external entities, and deliver high quality video to end users. viaPlatz also offered user management functions, including user role and permission functions. In a standalone configuration, users could login directly to the mobile server via its IP address or an assigned fully qualified domain name (FQDN).

Use of the mobile server in standalone mode using viaPlatz over a satellite-enabled Internet connection was not in alignment with research objectives. Use of standalone mode would have involved clients making requests to the mobile server over the satellite link. While the Mini-XMS is frequently referred to as a server, it should be seen more as a data source. In a strict client-server model, the Mini-XMS would be a client to the XMS, which would then serve video to other clients.

2. Teaming Mode Using viaPlatz

viaPlatz documentation provided evidence of multiple servers working together in a myriad of use cases under a local area network (LAN) environment. Any single viaPlatz server could be configured as the "master" server, controlling the work of the other servers (Figure 10). Teaming functionality was not available for Internet-connected applications with viaPlatz 2.0.



This figure illustrates how workload functions can be delegated between multiple machines with viaPlatz software installations.

Figure 10. Plural XMS Deployment. Source: NTT IT Corporation (2015).

It may have been possible to use a virtual private network (VPN) to simulate a LAN environment, thus enabling viaPlatz teaming mode. Use of the NPS VPN to assess this capability was considered, but the network performance would not have met research objectives. According to Stephens and Adams' study (2016), the network speed while utilizing the NPS VPN was limited to 38.87 Mbps upload and 11.72 Mbps. The same study also found that network latency in excess of 200ms was present during NPS VPN use was also excessive.

3. Mobile Server Standalone Mode Using FFmpeg

While FFmpeg lacked the collaboration and user management functions of viaPlatz, it was capable of serving as a video capture and streaming application. FFmpeg was used to capture video directly from the 4K video source, using the installed video capture card. FFmpeg also performed the encoding functions as input by the user. FFmpeg's output could be saved as a file or directed to a network location via the mobile server's network connection.

4. Teaming Mode Using FFmpeg

To use OnPARS in teaming mode with FFmpeg, web server software was installed on the stationary server as a substitute for viaPlatz. Customized NGINX (pronounced “engine x”) web server software was installed on the XMS with support for RTMP streaming. This allowed the XMS to retransmit the live video stream sent from the Mini-XMS. This configuration reduced the load on the satellite link by requiring only a single transmission of the streaming video to the XMS. Distribution of the video was then handled by the XMS over terrestrial links.

```
Josh — -bash — 96×24
Joshs-MBP:~ Josh$ ffmpeg -f decklink -i 'DeckLink 4K Extreme@20' -video_input hdmi -bm_v210 1 -c
:a libfdk_aac -b:a 128k -vcodec libx264 -preset veryfast -tune zerolatency -f flv -flv_metadata
true rtmp://xms.nps.edu/live/test
```

Figure 11. FFmpeg Stream Initiation Command

5. Live Streaming to DVIDS using FFmpeg

DVIDS used the Akamai content delivery network (CDN) to receive and manage streaming video. Streaming from the mobile server required directing the stream to a uniform resource locator (URL) provided by DVIDS. Other than changing the output URL, live streaming to DVIDS was essentially the same as teaming mode using FFmpeg.

E. TEST PLAN

A test plan was developed to guide the research team during assessment of OnPARS. It was based on the background information discussed in Chapter II as well as the experiment design criteria discussed earlier in this chapter. The test plan was used to ensure relevant data was collected and that the assessments were conducted in methodical way in support of answering the research questions.

1. System Description

OnPARS resulted from research efforts at the Naval Postgraduate School (NPS) implementing cloud video processing and storage systems and transmission of Internet

Protocol (IP) transmitted over emerging high speed satellite systems. This research integrated two major subcomponents into the OnPARS system:

- A dual-server subsystem that utilizes video processing and collaboration software from NTT IT Electronics. One server is installed in a portable enclosure and can be equipped with a DC power source for use in remote locations. The second server is housed in a data center and collects transmitted imagery from the portable server.
- A .85m dual-antenna satellite terminal purchased from SES Government Solutions designed to work with the O3b Medium Earth Orbit (MEO) satellite constellation.

2. Objective

The objective of the tests is to determine the suitability of the offered solution to a capability gap identified by the Commander Naval Air Forces, U.S. Atlantic Fleet (COMNAVAIRLANT or CNAL). The requirements to close the identified gap were:

- Transmission of an ultra high definition video stream (also referred to as 4K HD).
- Capability to transmit multiple high definition video streams.
- Bidirectional data transmission rates up to 400Mbps.
- Less than 30-millisecond satellite link propagation delay.
- Less than 120-millisecond round-trip propagation delay.
- Support reach-back from remote locations, such as disaster or humanitarian operations areas.

3. Validation

To validate OnPARS, the following assessments were conducted:

- Connection testing from the portable server to the stationary server, including round-trip delay measurements;
- Live stream of encoded 4K video to the stationary server at NPS;
- Live stream of encoded 4K video to DVIDS.

During the connection tests, bandwidth, latency, and jitter were measured using several common network troubleshooting and measurement tools. The network troubleshooting tool, Ping, was used to measure packet loss and round-trip delay (latency). Another network measurement tool, iPerf (both versions 2 and 3), was used to place a dummy load on the network connection from the mobile server to the stationary server. iPerf has both a TCP and UDP mode and both were used to inject required data types.

4. Data Collection Plan

Each network measurement tool could have its output saved as standard Unix text files. This was done and the files were parsed, allowing the data to be extracted and transferred to spreadsheet programs for analysis. The tools provided some overlapping data types, as well as their own unique data.

Output from Ping:

- Percentage of packet loss.
- Minimum, average, maximum, and standard deviation of latency.

Output from iPerf:

- Amount of data transferred.
- Speed at which the data was transferred (throughput).
- Average variation in delay of data transfer (jitter).

Output from IPTraf:

- Average and peak outgoing data.
- Average and peak incoming data.
- Average and peak total data.

Output from FFProbe:

- Coded picture number;
- Picture type;
- Packet size.

Subjective analysis on the quality of the live video was also conducted. This analysis corroborated the quantified data, ultimately answering the question of whether the system was “usable” for live 4K video transmission.

5. Schedule

Satellite airtime was the major driver of the testing schedule. Airtime was coordinated for the West Coast of the United States from 8 August 2016 to 12 August 2016. For U.S. East Coast testing and demonstration, airtime was coordinated for 30 August 2016 through 31 August 2016, but was later rescheduled to 8 September 2016 through 9 September 2016. Testing of the integrated solution commenced in July 2016 and all testing was complete in September 2016.

Three test events were scheduled:

- Initial integration of the video servers and TFAAS were conducted at the NPS campus.
- OnPARS was transported to Camp Roberts, CA for a performance assessment during the NPS-sponsored Joint Interagency Field Exercise (JIFX) from 10 August 2016 to 12 August 2016.
- The final assessment was conducted in Reston, VA as a demonstration to the research sponsor, the Office of Naval Research (ONR) Technology Solutions on 08 and 09 September 2016.

6. Personnel

Testing was conducted by the Naval Postgraduate School Research Working Group (NRWG) with support from O3b Networks and SES Government Solutions personnel. The NPS research team consisted of:

- primary investigator, John H. Gibson;
- research and thesis advisor, Dr. Douglas J. MacKinnon;
- graduate student from the NPS Graduate School of Information Sciences (GSOIS), LT Joshua A. Clements, United States Navy Reserve (USNR).

F. DESIGN SUMMARY

This research utilized a COTS satellite terminal and commodity computing equipment to stream 4K video from a remote location over a commercial MEO satellite constellation. The satellite terminal utilized for this research was the Tracking Fly Away Antenna System (TFAAS) and was available through GSA Advantage. The TFAAS used for this research was configured to connect to O3b Networks' MEO satellite constellation. Readily available computing equipment was utilized to ingest, encode, and transmit 4K video that was captured from a common DSLR camera. The available media management software, viaPlatz 2.0, that was previously identified did not have the capabilities required for this research. Alternate software solutions, FFmpeg and NGINX, were selected and utilized to assess the system's ability to stream 4K.

The subsystems were integrated at NPS and assessed in a field-representative environment at Camp Roberts, CA. Following the assessments, OnPARS was transported to Manassas, VA where it was demonstrated to ONR TechSolutions personnel. Chapter IV provides the results and analysis of the data collected during those assessments.

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IV. RESULTS AND ANALYSIS

The assessment results provided in this chapter represent a snapshot of the configuration of OnPARS at the time of assessment. Data were collected on 11 August 2016 at Camp Roberts, CA, with the exception of some iPerf3 and Ping data that were automatically collected through the night until the morning of 12 August 2016. The data were collected from the respective tool as redirected standard output to text file. After collection, the data were parsed into comma-separated value files for processing using Microsoft Excel. Figures 13 through 21 are derived from the data tables provided in Appendix B.

A. RESULTS

iPerf3 utilized a client-server model where one node sent data and a second node received data. The iPerf3 commands determine which node acts as the sender and which as the receiver during the specific session. Both the iPerf3 sender and the iPerf3 receiver reported data, providing two data points for each iPerf3 session.

All commands were issued from the Mini-XMS, but alternating commands were issued to capture data where the Mini-XMS and the XMS each alternated roles as the iPerf3 sender and receiver. Figure 12 displays the script used by the Mini-XMS to initiate iPerf and Ping sessions. The commands within the script also redirected the output from those tools to text files.

iPerf and iPerf3 sessions were configured to run for a certain period of time. iPerf sessions were configured to last for 30 seconds. iPerf3 had the capability to push information over the link for a specified amount of time without collecting the data, essentially allowing the session to “warm-up”. This was done to remove some of the fluctuations that can occur early in a connection when TCP parameter negotiations are occurring, commonly referred to as TCP slow start. iPerf3 sessions were configured to use a 10-second “warm-up” followed by 40 seconds of data capture.

networkTests.sh

```
#!/bin/bash

/bin/ping -c 10 8.8.8.8 > \
/home/jclements/Documents/testResults/ping/mobileServer-GoogleDNS_$(date +%Y%m%d_%H%M)

/usr/local/bin/iperf3 -c 205.155.65.150 -p 443 -O 10 -t 40 > \
/home/jclements/Documents/testResults/iperf3/mobileServer-NPS_$(date +%Y%m%d_%H%M)

/usr/local/bin/iperf3 -c 205.155.65.150 -p 443 -O 10 -t 40 -R > \
/home/jclements/Documents/testResults/iperf3/NPS-mobileServer_$(date +%Y%m%d_%H%M)

/usr/local/bin/iperf -c 162.249.178.54 -t 30 -b 100M > \
/home/jclements/Documents/testResults/iperf/tcp_mobileServer_o3bHubVernon_$(date +%Y%m%d_%H%M)

/usr/local/bin/iperf -c 162.249.178.54 -t 30 -b 100M -u -p 5000 > \
/home/jclements/Documents/testResults/iperf/udp_mobileServer_o3bHubVernon_$(date +%Y%m%d_%H%M)
```

Figure 12. Network Tool Initiation Commands

The Mini-XMS was configured to automatically initiate an iPerf3 session every 10 minutes. The automated script was repeatedly executed for almost 18 hours in duration. Figures 13 through 15 show the collected average bandwidth measurement data in graphical form. The figures also depict the differences between what was reported by the iPerf3 sender and by the iPerf3 receiver. The total data presented in Figure 15 represents data from iPerf3 sessions in which the Mini-XMS is the sender. The summarized data shown in Figure 15 indicates that the Mini-XMS was able to transmit at an average of 67.3Mbps and a median of 70.4Mbps.

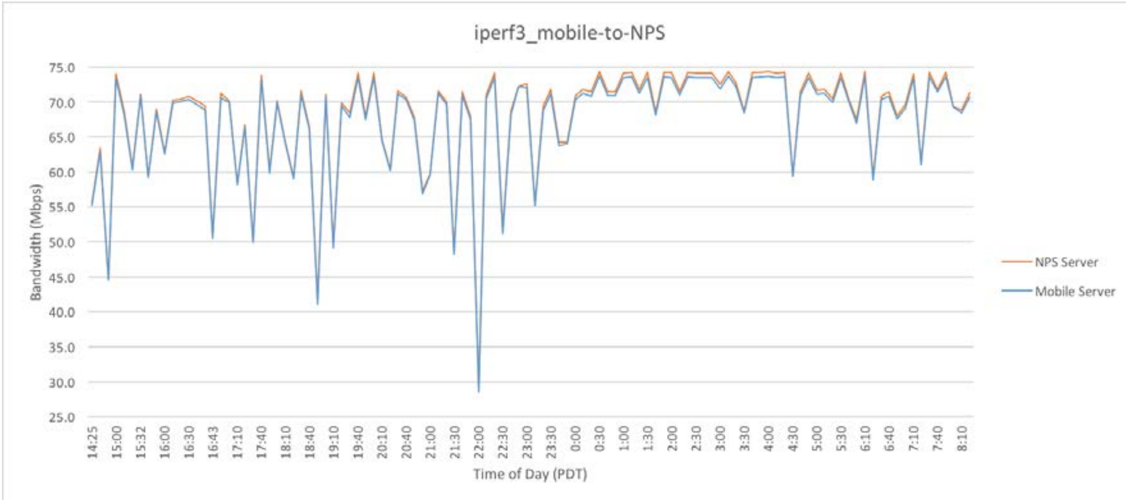

Figure 13. iPerf3 Results – Mobile Server at Camp Roberts to Stationary Server at NPS

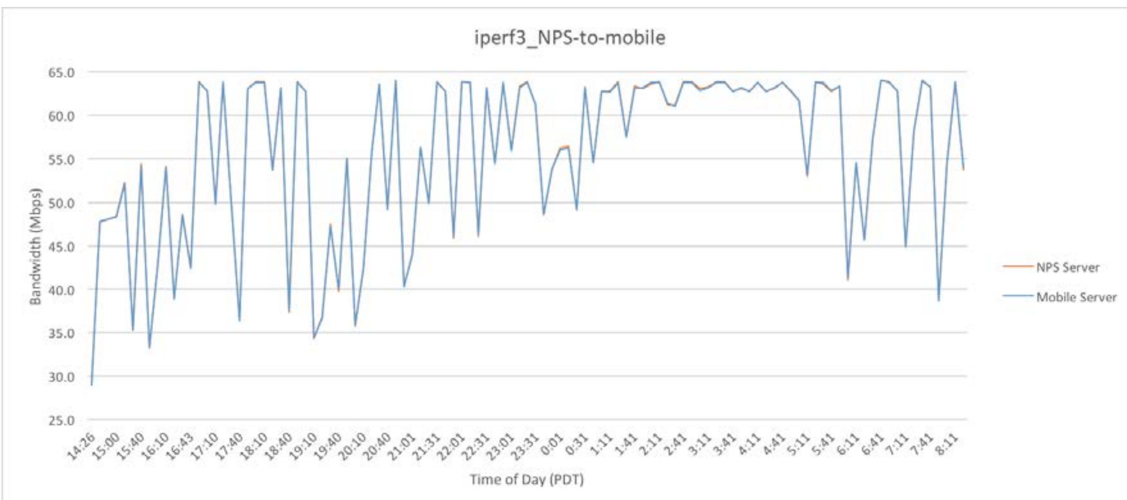

Figure 14. iPerf3 Results – Stationary Server at NPS to Mobile Server at Camp Roberts

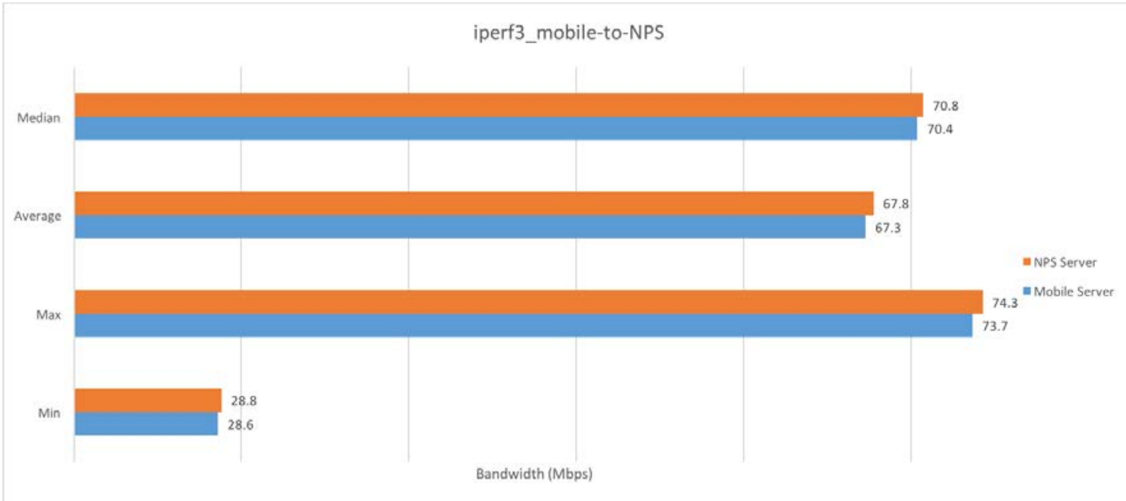

Figure 15. iPerf3 Summarized Bandwidth Measurements from Mobile Server to Stationary Server at NPS

Ping was used to measure packet delay time. The Mini-XMS was configured to automatically send 10 ping requests every 10 minutes. Each data point represents the average round-trip time as calculated by Ping. The NPS network was configured to block Ping requests to the XMS, so a public DNS server owned by Google was used to gather the data depicted in Figure 16. The figure includes a mean line generated by Microsoft Excel based on the data provided in Appendix B, Table 3. The derived line shows that the mean latency was just over 158ms, with point measurements as high as 161ms and as low as 156ms.

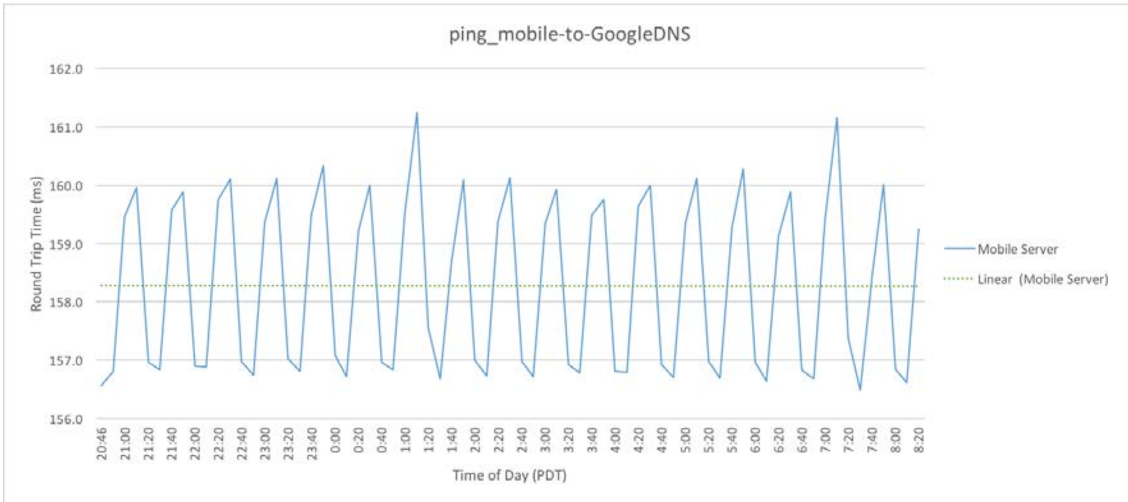

Figure 16. Ping Results

In an effort to capture data that represented the satellite link network performance, iPerf version 2 was used to connect to an iPerf version 2 server at O3b Networks' point of presence (PoP) in Vernon, TX. This server at the PoP was operated and maintained by O3b Networks and was only available for approximately four hours. It would have been optimal to use iPerf3 for a better comparison to data collected during sessions between the XMS and Mini-XMS, but iPerf (version 2) was the only option available on O3b Networks' systems at the PoP. The iPerf UDP tests also collected data on datagram loss. The observed datagram loss rate was a constant 24–25% (see Table 5 in Appendix B). There was no observed reason for this packet loss and the link seemed to function normally.

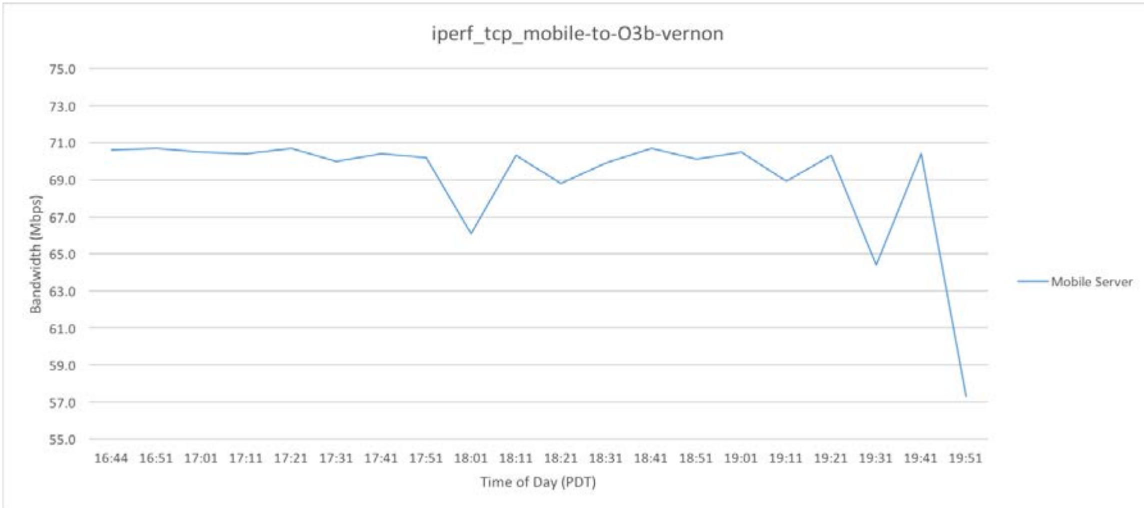

Figure 17. iPerf TCP Results

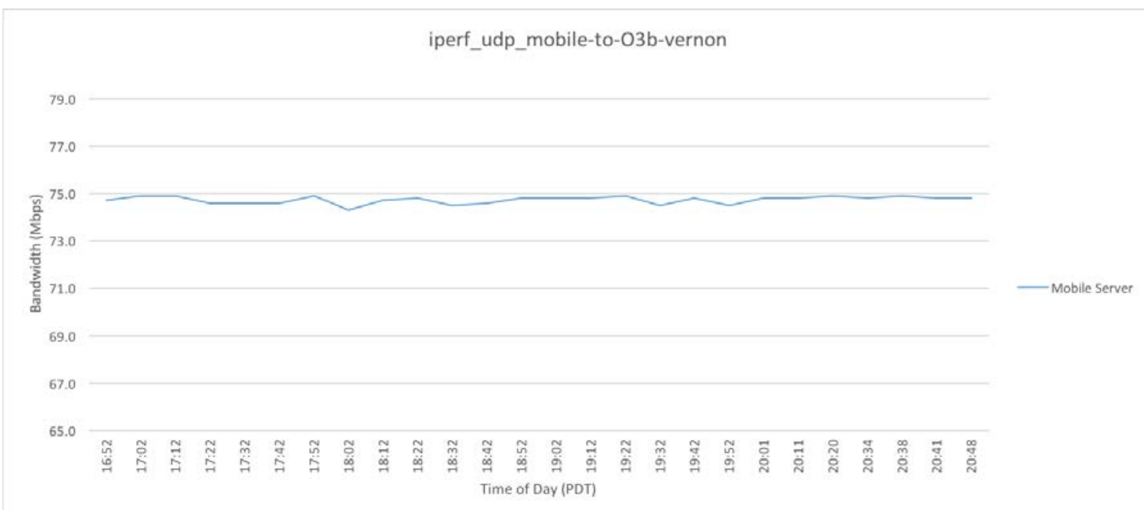

Figure 18. iPerf UDP Results

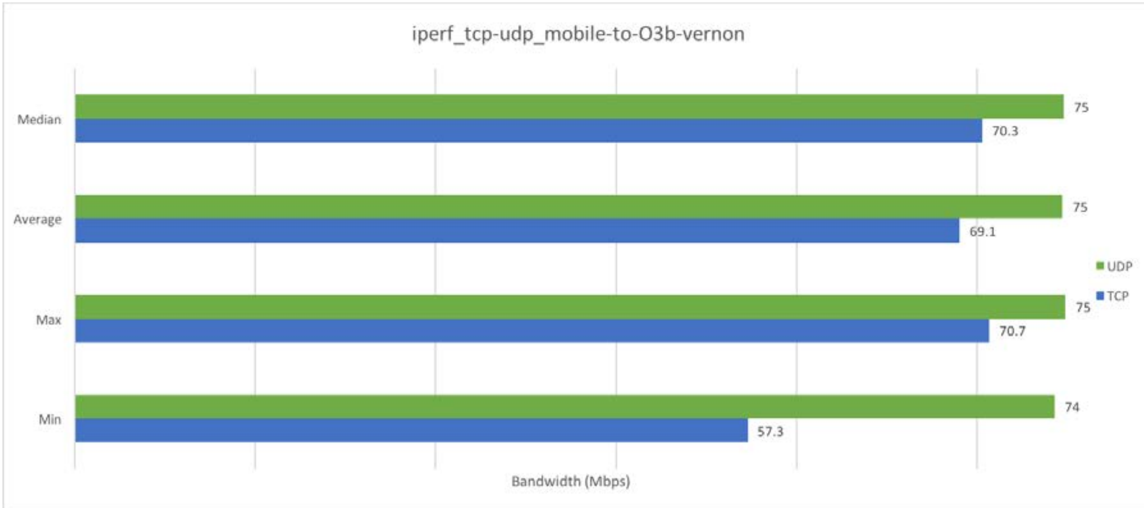

Figure 19. iPerf TCP and UDP Mode Bandwidth Comparison

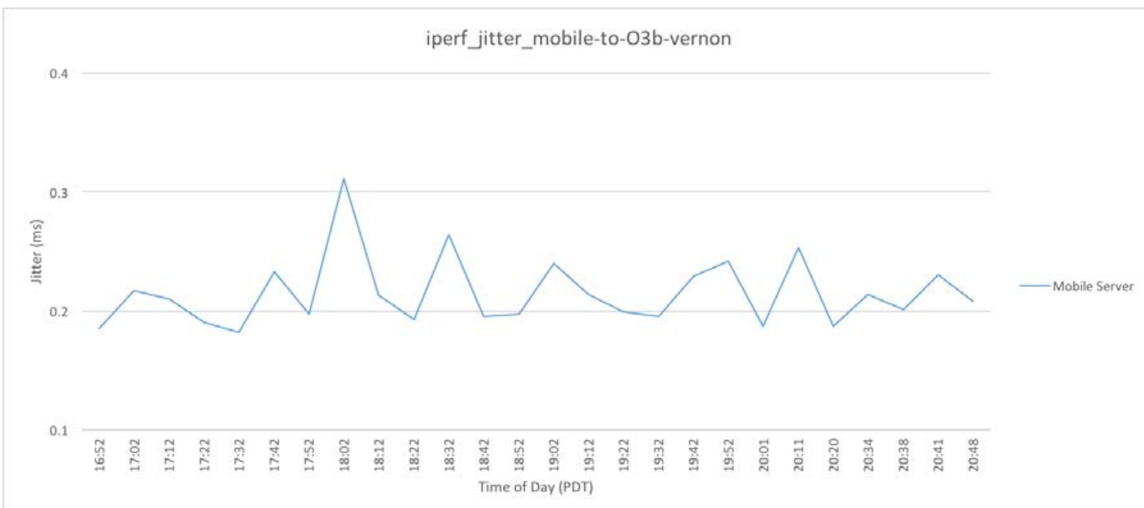

Figure 20. iPerf Jitter Results

In addition to the artificial loading of the network connection with iPerf and Ping, IPTraf was used to capture the amount of data actually leaving the Mini-XMS while streaming live video. The randomly collected data are depicted in Figure 21 and were measured in kilobits per second (kbps). The data showed a peak transmission rate of 3,400kbps, or 3.4Mbps, with average transmission rates below 1,400kbps, or 1.4Mbps.

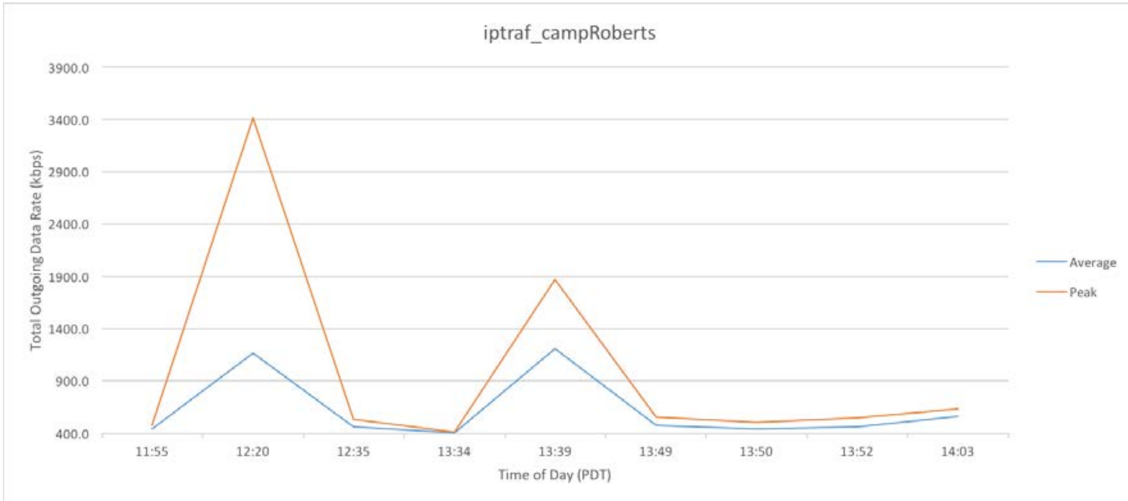

Figure 21. IPTraf Results

FFProbe was a component of FFmpeg used to evaluate the quality of captured media files. DVIDS captured data on the stream transmitted from OnPARS using FFProbe. Figure 22 is a graphical depiction of the FFProbe output DVIDS provided. The spikes represent I-frames and the rest of the data (below the 28,000 bytes line) represent P-frames. No B-frames were captured.

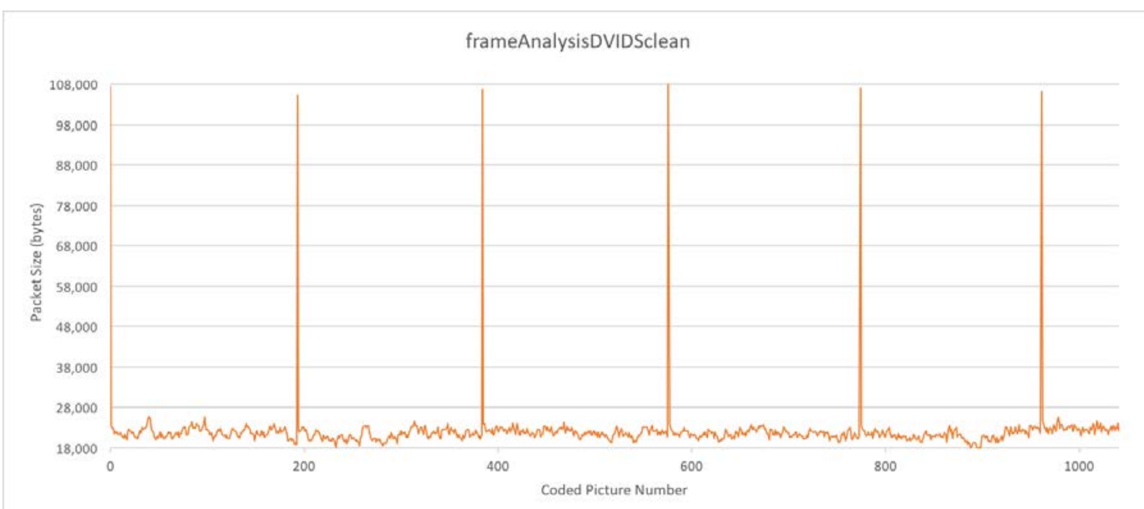

Figure 22. FFProbe Results

B. ANALYSIS

Multiple video streams were not assessed, but the bandwidth measurements suggest that at least three 20Mbps streams could be supported by the satellite link. The peak amount of data observed leaving the Mini-XMS' network interface was approximately 3.4Mbps, as shown in Figure 21. These data suggest that TFAAS could support 19 or more similar streams, based on the average bandwidth measurement of 67.3Mbps, as shown in Figure 15. However, creating more streams would require additional and/or different hardware, such as dedicated video encoding equipment.

The data collected did not suggest that the TFAAS equipped with .85m antennas could support the required 200Mbps minimum total bandwidth. However, O3b Networks personnel stated that the terminal could transmit at up to 130Mbps in an optimized configuration that would be calibrated for its exact location (T. Kavanaugh, personal communication, 10 August 2016). If calibration and optimization of the terminal resulted in the 100Mbps transmission rates for which the .85m antennas are designed, OnPARS could meet the minimum requirement of 200Mbps total bandwidth.

The collected Ping data suggests that OnPARS will likely not meet the requirement for a maximum round-trip latency of 120ms. O3b Networks advertised performance was 130ms for just its MEO satellite system. The public Internet that was used during OnPARS' assessment comes with its own varied and uncontrollable latency conditions. Latency is also introduced by the Mini-XMS and its connection to TFAAS. Despite these conditions, OnPARS experienced an average of 158ms of packet delay and very little jitter, indicating that the evaluated configuration of OnPARS performed well for the desired video streaming application.

The collected jitter data suggest that the TFAAS provided a stable connection over O3b Networks' MEO satellite constellation that is suitable for streaming video transmission. However, the observed 24-26% UDP datagram loss rates were excessive. Murphy, Searles, Rambeau, & Murhpy (2004) observed that "loss rates in excess of 6%... resulted in very poor quality video." OnPARS video transmission was assessed using RTMP, a TCP-based protocol that would compensate for any data loss by retransmitting dropped packets. If the data loss was also present during TCP-based connections, OnPARS would ultimately experience degraded performance at a theoretical rate of 24-26%. Further research into the cause of the data loss and correcting it could yield increased network performance, possibly increasing the bandwidth capacity closer to the 100Mbps for which the antennas are designed.

The iPerf3 data is interesting because it reveals a difference between TCP sessions that are sent from either side of the satellite connection. When the mobile server acted as the receiver in an iPerf3 session, the captured data revealed an average of approximately 12Mbps less bandwidth available (see Appendix B, Tables 1 and 2). This is important because it shows a significantly lower value than when the mobile server acted as the sender during the iPerf3 session. This supports the suggested architecture of a stationary server handling the distribution of the processed video over terrestrial links as TCP sessions initiated to the mobile server across the satellite link may experience degraded performance.

In addition to the quantitative results, the research team was able to view the distributed video stream from both the XMS and from DVIDS as a client on the Mini-XMS' monitor. The tested configuration streamed quality video that arrived back to the portable server in 8–20 seconds. This should be acceptable for a media release scenario.

C. RESULTS AND ANALYSIS SUMMARY

The captured data indicate that OnPARS was not able to quantitatively meet all Commander Naval Air Forces Atlantic (CNAL) requirements as listed in Chapter III. However, OnPARS was able to perform the desired functions that were described in the Statement of Requirements from which the requirements in Chapter III were derived. Ultimately, OnPARS was able to transmit UHD/4K streaming video at 3840 by 2160 resolution over O3b Networks MEO satellite network and it was also able to provide a quality 4K stream to DVIDS.

V. SUMMARY AND CONCLUSIONS

The On-location Public Affairs Reach-back System (OnPARS) provided a rudimentary model for the implementation of satellite-enabled IP-based information system solutions for DOD. The high-bandwidth, low-latency connection provided over the O3b Networks Medium Earth Orbit (MEO) constellation enabled the near real-time streaming of ultra high definition (UHD) video to a well-established Defense public media outlet. The connection is useful to any number of IP applications in the DOD.

A. RESEARCH SUMMARY

This research evaluated an integrated, satellite-enabled, portable UHD video processing solution constructed from commercial off-the-shelf (COTS) components. These components included a typical digital camera capable of UHD resolution captures, general purpose computing equipment for ingestion and processing of video, and a Tracking Fly Away Antenna System (TFAAS) for transmission over a Medium Earth Orbit (MEO) satellite communications system.

Following preliminary integration of the components at the Naval Postgraduate School (NPS) campus, OnPARS was transported to Camp Roberts, CA, for assessment in an operationally representative environment. OnPARS was able to provide an average of 67Mbps of bandwidth and experienced an average of 158ms of latency with very little jitter (less than 1ms). These network connection characteristics suggested that OnPARS would be able to support the transmission of multiple streams of high-quality UHD video.

OnPARS' ability to stream UHD video was also assessed. Live 4K video was streamed from the mobile server at Camp Roberts to the stationary server in the NPS data center where it could be accessed by requesting clients. The mobile server at Camp Roberts was able to access and view its own stream on an attached monitor. The streamed video was viewable on the monitor approximately 8-20 seconds after it was ingested by the camera. Additional 4K streaming was performed to the Defense Video Imagery Distribution System (DVIDS) via the Akamai content delivery network (CDN) with similar round trip viewing time.

OnPARS was then transported to Manassas, VA, for demonstration to Office of Naval Research TechSolutions personnel. Moving the system caused the satellite signal to be routed through different O3b Networks gateways and Internet points of presence (PoP). Though data was not captured during the demonstration, OnPARS displayed similar performance to that of its assessments at Camp Roberts.

B. RECOMMENDATIONS

NTT IT Corporation suggested that the desired dual-server teaming configuration could work with the newer version of their software, viaPlatz 3.0. An upgrade to viaPlatz 3.0 also required an operating system upgrade to CentOS Version 7 or above. The performance of these upgrades is recommended to further enhance OnPARS capabilities.

FFmpeg is a versatile open source product that has been integrated into many other projects but it lacks intuitiveness and is not friendly to the average user. A more user-friendly graphical user interface (GUI)-based solution should be sought to provide a reliable and easy to use product for deployed forces. This could have an impact on the annual maintenance costs for the servers. Additionally, Adobe Media Server (AMS), a standard industry media server solution, was an integral component of viaPlatz 2.0. Should an upgrade to viaPlatz 3.0 not be pursued, alternative solutions using AMS could be explored.

Discussions with DVIDS personnel during the course of the research revealed that DVIDS had a model for deploying a mobile media team. The DVIDS solution also included a Linux-powered mobile video system that was configured to capture and process HD video. Further refinement of OnPARS' capabilities and requirements should involve consultation with DVIDS mobile video team management personnel. Not only could the knowledge provided by DVIDS personnel enable a more efficient workflow for OnPARS but DVIDS could benefit from the experience with higher quality video transmission over high bandwidth connections.

C. FUTURE RESEARCH

This research studied how to integrate a video processing solution and an MEO satellite terminal to deliver UHD video from remote locations. Opportunities for further investigation emerged during the course of this research and are presented below.

1. Hardware Encoding

OnPARS used general purpose computing equipment to encode digital video. During the research, high utilization of system resources was noted. Additionally, the limitations of the fourth-generation quad-core Intel i7 precluded the use of some of FFmpeg’s higher quality presets. These limitations may cause concern over the future viability of the computing equipment assessed in this research.

Use of specialized hardware encoders would be especially useful in implementing potential successors to the H.264/AVC standard that was used during this research. The High Efficiency Video Coding (HEVC) standard, also called x265 or H.265, is one such standard that has displayed significant bitrate savings over H.264. “Compared with the H.264/AVC standard, the computational complexity of HEVC encoding is extremely high, making it hard to implement a real-time, high-quality software HEVC encoder on general purpose processors widely used in cloud-based multimedia encoding/transcoding systems” (Chen, Wen, Wen, Tang, & Tao, 2015, p. 1423). The use of dedicated video encoding hardware is a possible solution to previously mentioned shortcomings, in addition to further optimizing OnPARS’ capabilities.

2. Maritime Satellite Terminal

Given TFAAS’ COTS nature, various components were available that could allow for a wide variety of capability configurations. One such configuration allowed for the integration of the terminal into a maritime platform. Though costlier than the .85m land-based antennas used in OnPARS, stabilized maritime antennas were available to provide service to ships at sea via O3b Networks’ MEO satellite system. O3b Networks was providing MEO satellite connectivity to a number of commercial cruise lines, providing a model suitable for research into the implementation of MEO systems on Naval vessels.

3. Large-scale Deployment of MEO SATCOM

It should be obvious that higher bandwidth, lower latency SATCOM systems could increase the operational capabilities of forces deployed around the world. What may not be so obvious is whether MEO satellite systems could offer an increase in operational capability that would warrant the investment in upgrading the existing DOD SATCOM infrastructure. Perhaps the most interesting opportunity is the possibility of replacing legacy GEO satellite systems with higher performing systems for all Services, thereby offering increased SATCOM capabilities that are normalized within DOD. Several areas of research are possible, including, but not limited to

- Feasibility studies and cost-benefit analyses of upgrading a given ship to MEO from GEO.
- The use of High Assurance Internet Protocol Encryption (HAIPE) devices to provide communication security over MEO SATCOM connections, as identified by Stephens and Adams (2016).
- A cost-benefit analysis of providing MEO SATCOM to a geographical area (e.g., CENTCOM area of responsibility).

D. CONCLUSIONS

A video processing solution was integrated with the TFAAS satellite terminal over the O3b Networks MEO satellite system. TFAAS uses commodity networking equipment, providing an Ethernet port for connection to the customer’s network. This solution can be used to deliver ultra high definition (UHD) video from forward-deployed units in a wide variety of use cases and applications. The use case studied in this research utilized commodity digital camera and computing equipment to send a live 4K video stream to the Defense Media Activity’s public video media outlet, DVIDS.

Commander, Naval Air Forces Atlantic Public Affairs Office identified an operational requirement for the provision of video services that could swiftly distribute high-quality video from within the fleet to anywhere in the world with short notice. The purpose of this research was to integrate previously researched subsystems and to evaluate their ability to work together to meet CNAL’s requirement. The On-location Public Affairs Reach-back System (OnPARS) was the result and it was found to provide the necessary capabilities to satisfy high-quality video requirements of forward-deployed units.

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APPENDIX A. GLOSSARY

byte	eight bits
color depth	refers to the number of bits used to describe colors within an image
gigabit	one billion (1,000,000,000) bits
gigabyte	one billion (1,000,000,000) bytes
megabit	one million (1,000,000) bits
megabyte	one million (1,000,000) bytes
out-of-the-box	configuration of a product when received from the publisher or manufacturer
terabyte	one trillion (1,000,000,000) bytes

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APPENDIX B. DATA

Table 1. iPerf3 Mobile Server to NPS Server Data

iperf3 Tool - Mobile Server to Server at NPS - 40-second Test Interval										
				Sender			Receiver		Sender-Receiver Variation	
Date	**Time (PDT)**	**Time Since Previous Test**	**Elapsed Time**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Retr**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Transfer (MB)**	**Bandwidth (Mbps)**
8/11/16	14:25	0:00	0:00	264	55.3	6	265	55.6	1	0.3
	14:53	0:28	0:28	300	62.9	4	302	63.4	2	0.5
	14:56	0:03	0:31	212	44.5	2	212	44.5	0	0.0
	15:00	0:04	0:35	350	73.4	0	353	74.0	3	0.6
	15:01	0:01	0:36	325	68.1	1	328	68.7	3	0.6
	15:04	0:03	0:39	288	60.3	5	289	60.6	1	0.3
	15:32	0:28	1:07	338	70.9	4	339	71.1	1	0.2
	15:40	0:08	1:15	282	59.2	3	282	59.2	0	0.0
	15:50	0:10	1:25	327	68.6	3	329	69.0	2	0.4
	16:00	0:10	1:35	298	62.6	5	300	62.8	2	0.2
	16:10	0:10	1:45	333	69.8	2	335	70.3	2	0.5
	16:20	0:10	1:55	334	70.0	3	336	70.4	2	0.4
	16:30	0:10	2:05	336	70.4	3	338	70.8	2	0.4
	16:35	0:05	2:10	332	69.6	2	335	70.2	3	0.6
	16:38	0:03	2:13	329	68.9	3	331	69.4	2	0.5
	16:43	0:05	2:18	241	50.5	3	242	50.9	1	0.4
	16:50	0:07	2:25	337	70.6	2	340	71.2	3	0.6
	17:00	0:10	2:35	333	69.9	4	335	70.2	2	0.3
	17:10	0:10	2:45	277	58.1	5	278	58.4	1	0.3
	17:20	0:10	2:55	316	66.4	5	318	66.7	2	0.3
	17:30	0:10	3:05	238	49.9	7	239	50.1	1	0.2
	17:40	0:10	3:15	349	73.2	1	352	73.8	3	0.6
	17:50	0:10	3:25	286	59.9	5	287	60.2	1	0.3
	18:00	0:10	3:35	333	69.8	3	335	70.2	2	0.4
	18:10	0:10	3:45	305	64.0	4	307	64.3	2	0.3
	18:20	0:10	3:55	281	59.0	6	282	59.2	1	0.2
	18:30	0:10	4:05	339	71.0	3	341	71.6	2	0.6
	18:40	0:10	4:15	315	66.1	5	317	66.4	2	0.3
	18:50	0:10	4:25	196	41.1	3	199	41.6	3	0.5
	19:00	0:10	4:35	337	70.7	1	338	71.0	1	0.3
	19:10	0:10	4:45	234	49.1	3	236	49.4	2	0.3
	19:20	0:10	4:55	331	69.4	3	333	69.8	2	0.4
	19:30	0:10	5:05	323	67.8	0	326	68.4	3	0.6
	19:40	0:10	5:15	351	73.5	0	354	74.1	3	0.6
	19:50	0:10	5:25	322	67.5	3	324	67.9	2	0.4
	20:00	0:10	5:35	350	73.5	0	353	74.1	3	0.6
	20:10	0:10	5:45	307	64.4	4	308	64.6	1	0.2
	20:20	0:10	5:55	287	60.2	1	288	60.4	1	0.2
	20:36	0:16	6:11	339	71.1	3	341	71.6	2	0.5
	20:40	0:04	6:15	336	70.4	4	337	70.7	1	0.3
	20:46	0:06	6:21	322	67.4	4	323	67.8	1	0.4
	20:50	0:04	6:25	272	56.9	3	273	57.3	1	0.4
	21:00	0:10	6:35	283	59.5	7	285	59.7	2	0.2
	21:10	0:10	6:45	340	71.2	3	341	71.6	1	0.4
	21:20	0:10	6:55	332	69.6	3	334	70.1	2	0.5
	21:30	0:10	7:05	230	48.2	4	231	48.5	1	0.3
	21:40	0:10	7:15	338	70.9	3	341	71.4	3	0.5
	21:50	0:10	7:25	322	67.5	3	324	67.9	2	0.4
	22:00	0:10	7:35	137	28.6	9	137	28.8	0	0.2
	22:10	0:10	7:45	336	70.5	2	339	71.0	3	0.5
	22:20	0:10	7:55	351	73.5	0	353	74.1	2	0.6
	22:30	0:10	8:05	244	51.2	1	247	51.8	3	0.6
	22:40	0:10	8:15	325	68.2	3	328	68.8	3	0.6
	22:50	0:10	8:25	344	72.2	2	344	72.2	0	0.0
	23:00	0:10	8:35	344	72.1	1	346	72.6	2	0.5
	23:10	0:10	8:45	263	55.1	6	264	55.4	1	0.3
	23:20	0:10	8:55	328	68.8	2	331	69.4	3	0.6

iperf3 Tool - Mobile Server to Server at NPS - 40-second Test Interval											
				Sender			Receiver		Sender-Receiver Variation	
Date	**Time (PDT)**	**Time Since Previous Test**	**Elapsed Time**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Retr**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Transfer (MB)**	**Bandwidth (Mbps)**
	23:30	0:10	9:05	339	71.1	1	342	71.8	3	0.7
	23:40	0:10	9:15	304	63.7	2	307	64.3	3	0.6
	23:50	0:10	9:25	305	64.0	4	307	64.3	2	0.3
8/12/16	0:00	0:10	9:35	336	70.4	2	338	70.9	2	0.5
	0:10	0:10	9:45	340	71.2	2	342	71.8	2	0.6
	0:20	0:10	9:55	338	70.8	1	341	71.5	3	0.7
	0:30	0:10	10:05	351	73.7	0	354	74.3	3	0.6
	0:40	0:10	10:15	338	70.9	1	341	71.5	3	0.6
	0:50	0:10	10:25	338	70.9	2	341	71.5	3	0.6
	1:00	0:10	10:35	351	73.5	0	353	74.1	2	0.6
	1:10	0:10	10:45	351	73.6	0	354	74.2	3	0.6
	1:20	0:10	10:55	339	71.2	1	342	71.8	3	0.6
	1:30	0:10	11:05	351	73.5	0	354	74.2	3	0.7
	1:40	0:10	11:15	325	68.1	3	327	68.6	2	0.5
	1:50	0:10	11:25	351	73.6	0	354	74.2	3	0.6
	2:00	0:10	11:35	351	73.5	0	354	74.2	3	0.7
	2:10	0:10	11:45	338	71.0	1	341	71.6	3	0.6
	2:20	0:10	11:55	351	73.6	0	354	74.2	3	0.6
	2:30	0:10	12:05	350	73.5	0	353	74.1	3	0.6
	2:40	0:10	12:15	351	73.5	0	353	74.1	2	0.6
	2:50	0:10	12:25	351	73.5	0	353	74.1	2	0.6
	3:00	0:10	12:35	343	71.9	1	346	72.5	3	0.6
	3:10	0:10	12:45	352	73.7	0	354	74.3	2	0.6
	3:20	0:10	12:55	344	72.2	1	346	72.7	2	0.5
	3:30	0:10	13:05	326	68.4	3	328	68.7	2	0.3
	3:40	0:10	13:15	351	73.5	0	354	74.2	3	0.7
	3:50	0:10	13:25	351	73.6	0	354	74.2	3	0.6
	4:00	0:10	13:35	351	73.7	0	354	74.3	3	0.6
	4:10	0:10	13:45	351	73.5	0	354	74.1	3	0.6
	4:20	0:10	13:55	351	73.6	0	354	74.2	3	0.6
	4:30	0:10	14:05	283	59.3	1	283	59.4	0	0.1
	4:40	0:10	14:15	338	70.9	1	341	71.5	3	0.6
	4:50	0:10	14:25	351	73.5	0	354	74.1	3	0.6
	5:00	0:10	14:35	339	71.1	1	342	71.7	3	0.6
	5:10	0:10	14:45	339	71.2	1	342	71.8	3	0.6
	5:20	0:10	14:55	333	69.9	3	336	70.5	3	0.6
	5:30	0:10	15:05	351	73.5	0	354	74.1	3	0.6
	5:40	0:10	15:15	333	69.9	2	335	70.3	2	0.4
	6:00	0:20	15:35	319	66.9	3	322	67.5	3	0.6
	6:10	0:10	15:45	351	73.7	0	354	74.3	3	0.6
	6:20	0:10	15:55	280	58.8	4	282	59.2	2	0.4
	6:30	0:10	16:05	335	70.4	2	337	70.8	2	0.4
	6:40	0:10	16:15	337	70.8	1	340	71.4	3	0.6
	6:50	0:10	16:25	323	67.6	4	324	68.0	1	0.4
	7:00	0:10	16:35	329	69.1	3	332	69.6	3	0.5
	7:10	0:10	16:45	350	73.4	0	353	74.0	3	0.6
	7:20	0:10	16:55	291	61.0	4	292	61.3	1	0.3
	7:30	0:10	17:05	351	73.6	0	354	74.2	3	0.6
	7:40	0:10	17:15	340	71.4	2	343	71.8	3	0.4
	7:50	0:10	17:25	351	73.6	0	354	74.2	3	0.6
	8:00	0:10	17:35	330	69.3	2	331	69.3	1	0.0
	8:10	0:10	17:45	326	68.4	2	329	68.9	3	0.5
	8:20	0:10	17:55	337	70.7	1	340	71.3	3	0.6

	Sender			Receiver		Sender-Receiver Variation	
	Transfer (MB)	**Bandwidth (Mbps)**	**Retr**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Transfer (MB)**	**Bandwidth (Mbps)**
Min	137	28.6	0	137	28.8	0	0.0
Max	352	73.7	9	354	74.3	3	0.7
Average	321	67.3	2	323	67.8	2	0.5
Median	335.5	70.4	2	337	70.8	2	0.5

Table 2. iPerf3 NPS Server to Mobile Server Data

iperf3 Tool - Server at NPS to Mobile Server - 40-second Test Interval											
				Sender			Receiver		Sender-Receiver Variation	
Date	**Time (PDT)**	**Time Since Previous Test**	**Elapsed Time**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Retr**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Transfer (MB)**	**Bandwidth (Mbps)**
8/11/16	14:26	0:00	0:00	138	29.0	170	138	29.0	0	0.0
	14:54	0:28	0:28	227	47.7	145	228	47.8	1	0.1
	14:56	0:02	0:30	229	48.1	119	229	48.1	0	0.0
	15:00	0:04	0:34	231	48.4	81	230	48.3	1	0.1
	15:04	0:04	0:38	249	52.3	5	248	52.1	1	0.2
	15:33	0:29	1:07	168	35.3	104	169	35.3	1	0.0
	15:40	0:07	1:14	260	54.4	112	258	54.1	2	0.3
	15:50	0:10	1:24	158	33.2	123	159	33.4	1	0.2
	16:00	0:10	1:34	204	42.8	306	203	42.7	1	0.1
	16:10	0:10	1:44	258	54.1	68	258	54.0	0	0.1
	16:20	0:10	1:54	185	38.9	117	186	38.9	1	0.0
	16:36	0:16	2:10	231	48.5	109	232	48.6	1	0.1
	16:43	0:07	2:17	203	42.5	47	203	42.5	0	0.0
	16:50	0:07	2:24	305	63.9	0	304	63.8	1	0.1
	17:00	0:10	2:34	300	62.8	0	300	62.9	0	0.1
	17:10	0:10	2:44	238	49.9	114	238	49.8	0	0.1
	17:20	0:10	2:54	304	63.8	0	304	63.8	0	0.0
	17:30	0:10	3:04	238	49.9	143	238	49.9	0	0.0
	17:40	0:10	3:14	173	36.4	121	173	36.4	0	0.0
	17:50	0:10	3:24	301	63.1	0	301	63.1	0	0.0
	18:00	0:10	3:34	305	63.9	0	304	63.8	1	0.1
	18:10	0:10	3:44	305	63.9	0	304	63.8	1	0.1
	18:20	0:10	3:54	256	53.7	98	256	53.8	0	0.1
	18:30	0:10	4:04	301	63.1	0	301	63.2	0	0.1
	18:40	0:10	4:14	178	37.4	159	179	37.6	1	0.2
	18:50	0:10	4:24	305	63.9	0	304	63.8	1	0.1
	19:00	0:10	4:34	300	62.8	0	300	62.8	0	0.0
	19:10	0:10	4:44	163	34.3	132	164	34.4	1	0.1
	19:20	0:10	4:54	176	36.8	129	175	36.7	1	0.1
	19:30	0:10	5:04	226	47.5	282	226	47.3	0	0.2
	19:40	0:10	5:14	190	39.8	156	191	40.0	1	0.2
	19:50	0:10	5:24	263	55.1	0	263	55.1	0	0.0
	20:00	0:10	5:34	170	35.7	160	172	36.0	2	0.3
	20:10	0:10	5:44	203	42.5	65	202	42.5	1	0.0
	20:34	0:24	6:08	266	55.7	0	266	55.8	0	0.1
	20:37	0:03	6:11	303	63.6	0	303	63.6	0	0.0
	20:40	0:03	6:14	234	49.2	131	235	49.2	1	0.0
	20:47	0:07	6:21	306	64.1	0	305	64.0	1	0.1
	20:51	0:04	6:25	193	40.4	100	192	40.3	1	0.1
	21:01	0:10	6:35	209	43.9	190	210	44.0	1	0.1
	21:11	0:10	6:45	268	56.3	0	269	56.4	1	0.1
	21:21	0:10	6:55	238	50.0	171	238	49.9	0	0.1
	21:31	0:10	7:05	304	63.9	0	304	63.8	0	0.1
	21:41	0:10	7:15	299	62.8	0	300	62.8	1	0.0
	21:51	0:10	7:25	219	45.9	17	220	46.1	1	0.2
	22:01	0:10	7:35	304	63.9	0	305	63.9	1	0.0
	22:11	0:10	7:45	304	63.8	0	304	63.8	0	0.0
	22:21	0:10	7:55	220	46.1	4	221	46.4	1	0.3
	22:31	0:10	8:05	301	63.1	0	301	63.2	0	0.1
	22:41	0:10	8:15	260	54.5	84	260	54.5	0	0.0
	22:51	0:10	8:25	303	63.6	0	304	63.8	1	0.2
	23:01	0:10	8:35	267	56.0	94	267	55.9	0	0.1
	23:11	0:10	8:45	302	63.4	0	301	63.2	1	0.2
	23:21	0:10	8:55	305	63.9	0	304	63.8	1	0.1
	23:31	0:10	9:05	293	61.3	93	292	61.3	1	0.0
	23:41	0:10	9:15	232	48.6	61	232	48.6	0	0.0
	23:51	0:10	9:25	257	53.8	114	257	53.9	0	0.1
8/12/16	0:01	0:10	9:35	268	56.3	88	267	56.0	1	0.3
	0:11	0:10	9:45	270	56.5	58	268	56.3	2	0.2
	0:21	0:10	9:55	234	49.2	82	234	49.1	0	0.1
	0:31	0:10	10:05	302	63.3	0	301	63.2	1	0.1
	0:41	0:10	10:15	260	54.6	68	260	54.6	0	0.0
	1:01	0:20	10:35	300	62.8	0	300	62.8	0	0.0

iperf3 Tool - Server at NPS to Mobile Server - 40-second Test Interval										
				Sender			Receiver		Sender-Receiver Variation	
Date	**Time (PDT)**	**Time Since Previous Test**	**Elapsed Time**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Retr**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Transfer (MB)**	**Bandwidth (Mbps)**
	1:11	0:10	10:45	299	62.8	0	299	62.7	0	0.1
	1:21	0:10	10:55	304	63.9	0	304	63.7	0	0.2
	1:31	0:10	11:05	275	57.6	0	274	57.5	1	0.1
	1:41	0:10	11:15	302	63.4	0	301	63.1	1	0.3
	1:51	0:10	11:25	301	63.1	0	301	63.2	0	0.1
	2:01	0:10	11:35	303	63.6	0	304	63.8	1	0.2
	2:11	0:10	11:45	305	63.9	0	304	63.8	1	0.1
	2:21	0:10	11:55	292	61.2	2	293	61.4	1	0.2
	2:31	0:10	12:05	292	61.2	26	291	61.0	1	0.2
	2:41	0:10	12:15	304	63.9	0	304	63.8	0	0.1
	2:51	0:10	12:25	304	63.9	0	304	63.8	0	0.1
	3:01	0:10	12:35	301	63.1	0	300	62.9	1	0.2
	3:11	0:10	12:45	302	63.3	0	301	63.2	1	0.1
	3:21	0:10	12:55	304	63.9	0	304	63.8	0	0.1
	3:31	0:10	13:05	305	63.9	0	304	63.8	1	0.1
	3:41	0:10	13:15	300	62.8	0	300	62.8	0	0.0
	3:51	0:10	13:25	301	63.1	0	301	63.2	0	0.1
	4:01	0:10	13:35	299	62.8	3	299	62.8	0	0.0
	4:11	0:10	13:45	304	63.8	0	304	63.8	0	0.0
	4:21	0:10	13:55	300	62.8	0	300	62.8	0	0.0
	4:31	0:10	14:05	301	63.1	0	301	63.2	0	0.1
	4:41	0:10	14:15	304	63.8	0	304	63.8	0	0.0
	4:51	0:10	14:25	299	62.8	6	300	62.9	1	0.1
	5:01	0:10	14:35	294	61.7	7	294	61.7	0	0.0
	5:11	0:10	14:45	252	53.0	62	253	53.1	1	0.1
	5:21	0:10	14:55	305	63.9	0	304	63.8	1	0.1
	5:31	0:10	15:05	303	63.6	0	304	63.8	1	0.2
	5:41	0:10	15:15	300	62.8	0	300	62.9	0	0.1
	5:52	0:11	15:26	302	63.4	0	302	63.4	0	0.0
	6:01	0:09	15:35	196	41.1	58	197	41.3	1	0.2
	6:11	0:10	15:45	260	54.5	75	260	54.6	0	0.1
	6:21	0:10	15:55	218	45.7	96	218	45.7	0	0.0
	6:31	0:10	16:05	273	57.2	99	273	57.2	0	0.0
	6:41	0:10	16:15	306	64.1	0	306	64.1	0	0.0
	6:51	0:10	16:25	305	63.9	0	304	63.8	1	0.1
	7:01	0:10	16:35	300	62.8	0	300	62.9	0	0.1
	7:11	0:10	16:45	214	44.9	29	214	44.9	0	0.0
	7:21	0:10	16:55	277	58.2	0	278	58.3	1	0.1
	7:31	0:10	17:05	306	64.1	0	305	64.0	1	0.1
	7:41	0:10	17:15	302	63.3	0	302	63.3	0	0.0
	7:51	0:10	17:25	185	38.8	203	185	38.7	0	0.1
	8:01	0:10	17:35	260	54.6	84	260	54.5	0	0.1
	8:11	0:10	17:45	305	63.9	0	304	63.8	1	0.1
	8:21	0:10	17:55	256	53.8	107	258	54.0	2	0.2

	Sender			Receiver		Sender-Receiver Variation	
	Transfer (MB)	**Bandwidth (Mbps)**	**Retr**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Transfer (MB)**	**Bandwidth (Mbps)**
Min	138	29.0	0	138	29.0	0	0.0
Max	306	64.1	306	306	64.1	2	0.3
Average	265	55.6	49	265	55.6	1	0.1
Median	292	61.2	0	292	61.3	1	0.1

Table 3. Ping Mobile Server to Google's DNS Data

ping Tool - Mobile Server to Google's DNS (8.8.8.8) - 10-pings Round Trip Time							
Date	**Time (PDT)**	**Time Since Previous Test**	**Elapsed Time**	**Min**	**Avg**	**Max**	**Mdev**
8/11/16	20:46	0:00	0:00	156.529	156.560	156.610	0.178
	20:50	0:04	0:04	156.762	156.813	156.857	0.501
	21:00	0:10	0:14	159.226	159.455	159.533	0.265
	21:10	0:10	0:24	159.915	159.957	160.018	0.537
	21:20	0:10	0:34	156.917	156.965	157.005	0.307
	21:30	0:10	0:44	156.793	156.831	156.886	0.179
	21:40	0:10	0:54	159.521	159.577	159.623	0.400
	21:50	0:10	1:04	159.729	159.883	160.775	0.300
	22:00	0:10	1:14	156.861	156.893	156.936	0.501
	22:10	0:10	1:24	156.836	156.884	156.926	0.355
	22:20	0:10	1:34	159.731	159.755	159.781	0.179
	22:30	0:10	1:44	160.039	160.099	160.150	0.312
	22:40	0:10	1:54	156.951	156.978	157.046	0.251
	22:50	0:10	2:04	156.709	156.747	156.789	0.178
	23:00	0:10	2:14	159.126	159.371	159.448	0.512
	23:10	0:10	2:24	160.057	160.116	160.212	0.507
	23:20	0:10	2:34	156.985	157.027	157.070	0.252
	23:30	0:10	2:44	156.761	156.803	156.836	0.531
	23:40	0:10	2:54	159.420	159.477	159.512	0.358
	23:50	0:10	3:04	160.298	160.334	160.391	0.507
8/12/16	0:00	0:10	3:14	156.716	157.077	157.161	0.216
	0:10	0:10	3:24	156.680	156.716	156.744	0.019
	0:20	0:10	3:34	159.160	159.215	159.261	0.310
	0:30	0:10	3:44	159.935	160.000	160.097	0.475
	0:40	0:10	3:54	156.920	156.966	157.025	0.179
	0:50	0:10	4:04	156.812	156.835	156.887	0.396
	1:00	0:10	4:14	159.473	159.546	159.607	0.474
	1:10	0:10	4:24	161.149	161.243	161.318	0.259
	1:20	0:10	4:34	157.484	157.551	157.608	0.470
	1:30	0:10	4:44	156.629	156.679	156.729	0.252
	1:40	0:10	4:54	158.653	158.688	158.721	0.019
	1:50	0:10	5:04	159.831	160.088	160.164	0.369
	2:00	0:10	5:14	156.978	157.001	157.019	0.307
	2:10	0:10	5:24	156.714	156.733	156.770	0.531
	2:20	0:10	5:34	159.306	159.377	159.460	0.440
	2:30	0:10	5:44	160.062	160.124	160.181	0.401
	2:40	0:10	5:54	156.913	156.975	157.002	0.178
	2:50	0:10	6:04	156.679	156.723	156.770	0.397
	3:00	0:10	6:14	159.304	159.344	159.396	0.310
	3:10	0:10	6:24	159.894	159.939	160.033	0.538
	3:20	0:10	6:34	156.890	156.918	156.947	0.501
	3:30	0:10	6:44	156.737	156.782	156.821	0.434
	3:40	0:10	6:54	159.434	159.487	159.541	0.311
	3:50	0:10	7:04	159.710	159.754	159.861	0.255
	4:00	0:10	7:14	156.782	156.813	156.859	0.355
	4:10	0:10	7:24	156.755	156.793	156.823	0.307
	4:20	0:10	7:34	159.556	159.632	159.682	0.311
	4:30	0:10	7:44	159.619	159.998	160.141	0.463
	4:40	0:10	7:54	156.866	156.920	156.973	0.469

ping Tool - Mobile Server to Google's DNS (8.8.8.8) - 10-pings Round Trip Time							
Date	**Time (PDT)**	**Time Since Previous Test**	**Elapsed Time**	**Min**	**Avg**	**Max**	**Mdev**
	4:50	0:10	8:04	156.655	156.705	156.733	0.178
	5:00	0:10	8:14	159.316	159.358	159.405	0.438
	5:10	0:10	8:24	160.061	160.115	160.158	0.254
	5:20	0:10	8:34	156.946	156.976	157.013	0.396
	5:30	0:10	8:44	156.654	156.698	156.741	0.531
	5:40	0:10	8:54	158.920	159.277	159.349	0.417
	5:50	0:10	9:04	160.197	160.275	160.392	0.054
	6:00	0:10	9:14	156.548	156.960	157.059	0.420
	6:10	0:10	9:24	156.569	156.636	156.801	0.534
	6:20	0:10	9:34	159.046	159.122	159.196	0.439
	6:30	0:10	9:44	159.436	159.880	160.210	0.473
	6:40	0:10	9:54	156.786	156.834	156.869	0.307
	6:50	0:10	10:04	156.648	156.677	156.697	0.016
	7:00	0:10	10:14	159.357	159.400	159.473	0.182
	7:10	0:10	10:24	161.080	161.155	161.265	0.364
	7:20	0:10	10:34	157.323	157.379	157.420	0.397
	7:30	0:10	10:44	156.426	156.481	156.521	0.501
	7:40	0:10	10:54	158.394	158.459	158.526	0.039
	7:50	0:10	11:04	159.968	160.012	160.068	0.474
	8:00	0:10	11:14	156.808	156.844	156.889	0.026
	8:10	0:10	11:24	156.565	156.613	156.679	0.356
	8:20	0:10	11:34	159.199	159.252	159.314	0.505
			Min	156.426	156.481	156.521	0.016
			Max	161.149	161.243	161.318	0.538
			Average	158.193	158.275	158.349	0.343
			Median	157.484	157.551	157.608	0.358

Table 4. iPerf Mobile Server to O3b Hub TCP Mode Data

iperf Tool - TCP Connection from Mobile Server to O3b Hub, Vernon, Tx					
Date	**Time (PDT)**	**Time Since Previous Test**	**Elapsed Time**	**Transfer (MB)**	**Bandwidth (Mbps)**
8/11/16	16:44	0:00	0:00	253	70.6
	16:51	0:07	0:07	254	70.7
	17:01	0:10	0:17	252	70.5
	17:11	0:10	0:27	252	70.4
	17:21	0:10	0:37	253	70.7
	17:31	0:10	0:47	251	70.0
	17:41	0:10	0:57	253	70.4
	17:51	0:10	1:07	251	70.2
	18:01	0:10	1:17	238	66.1
	18:11	0:10	1:27	253	70.3
	18:21	0:10	1:37	246	68.8
	18:31	0:10	1:47	250	69.9
	18:41	0:10	1:57	254	70.7
	18:51	0:10	2:07	251	70.1
	19:01	0:10	2:17	253	70.5
	19:11	0:10	2:27	247	68.9
	19:21	0:10	2:37	252	70.3
	19:31	0:10	2:47	231	64.4
	19:41	0:10	2:57	253	70.4
	19:51	0:10	3:07	206	57.3
			Min	206	57.3
			Max	254	70.7
			Average	248	69.1
			Median	252	70.3

Table 5. iPerf Mobile Server to O3b Hub UDP Mode Data

iperf Tool - UDP Connection from Mobile Server to O3b Hub, Vernon, Tx - Server (O3b Hub) Reported Statistics							
Date	**Time (PDT)**	**Time Since Previous Test**	**Elapsed Time**	**Transfer (MB)**	**Bandwidth (Mbps)**	**Jitter (ms)**	**Datagram Loss**
8/11/16	16:52	0:00	0:00	270	74.7	0.185	24%
	17:02	0:10	0:10	271	74.9	0.217	24%
	17:12	0:10	0:20	271	74.9	0.210	24%
	17:22	0:10	0:30	270	74.6	0.190	24%
	17:32	0:10	0:40	270	74.6	0.182	24%
	17:42	0:10	0:50	270	74.6	0.233	24%
	17:52	0:10	1:00	271	74.9	0.197	24%
	18:02	0:10	1:10	270	74.3	0.311	25%
	18:12	0:10	1:20	270	74.7	0.213	24%
	18:22	0:10	1:30	270	74.8	0.193	24%
	18:32	0:10	1:40	270	74.5	0.264	25%
	18:42	0:10	1:50	270	74.6	0.195	24%
	18:52	0:10	2:00	270	74.8	0.197	24%
	19:02	0:10	2:10	271	74.8	0.240	24%
	19:12	0:10	2:20	271	74.8	0.214	24%
	19:22	0:10	2:30	270	74.9	0.199	24%
	19:32	0:10	2:40	270	74.5	0.195	24%
	19:42	0:10	2:50	270	74.8	0.229	24%
	19:52	0:10	3:00	270	74.5	0.242	24%
	20:01	0:09	3:09	271	74.8	0.187	24%
	20:11	0:10	3:19	271	74.8	0.253	24%
	20:20	0:09	3:28	271	74.9	0.187	24%
	20:34	0:14	3:42	271	74.8	0.214	24%
	20:38	0:04	3:46	272	74.9	0.201	24%
	20:41	0:03	3:49	271	74.8	0.230	24%
	20:48	0:07	3:56	271	74.8	0.208	24%
			Min	270	74	0.182	24%
			Max	272	75	0.311	25%
			Average	271	75	0.215	24%
			Median	270	75	0.209	24%

Table 6. IPTraf Streaming Capture Data

iptraf - 60-second Video Streaming Capture							
		Average (kbps)			Peak (kbps)		
Date	**Time (PDT)**	**Outgoing**	**Incoming**	**Total**	**Outgoing**	**Incoming**	**Total**
8/11/16	11:55	439.92	7.68	447.62	479.38	8.32	487.70
	12:20	1166.47	18.47	1184.95	3414.40	55.62	3463.05
	12:35	462.97	157.52	620.50	534.34	416.92	923.88
	13:34	404.98	9.10	414.08	408.44	9.37	417.56
	13:39	1205.52	17.53	1223.05	1869.64	29.78	1894.07
	13:49	477.00	49.45	526.45	552.16	377.49	849.45
	13:50	442.83	7.45	450.30	503.00	8.70	511.69
	13:52	459.22	58.37	517.58	549.73	220.35	646.32
	14:03	562.38	64.83	627.22	635.41	435.45	1021.20
Min		404.98	7.45	414.08	408.44	8.32	417.56
Max		1205.52	157.52	1223.05	3414.40	435.45	3463.05
Average		624.59	43.38	667.97	994.06	173.56	1134.99
Median		462.97	18.47	526.45	549.73	55.62	849.45

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