SOAR

STATE-OF-THE-ART REPORT (SOAR)
FEBRUARY 2022

CSIAC-BCO-2021-189

DIGITAL TRANSFORMATION OF SATELLITE COMMUNICATION NETWORKS

By Juan Deaton, Phil Payne, and Ryan Fowler
Contract Number: FA8075-14-D-0001
Published By: CSIAC

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JUAN DEATON, PHIL PAYNE,
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE
February 2022

2. REPORT TYPE
State-of-the-Art Report

3. DATES COVERED

4. TITLE AND SUBTITLE
Digital Transformation of Satellite Communication Networks

5a. CONTRACT NUMBER
FA8075-14-D-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Juan Deaton, Phil Payne, and Ryan Fowler

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADRESS(ES)
Cybersecurity & Information Systems Information Analysis Center (CSIAC)
SURVICE Engineering Company
4695 Millennium Drive
Belcamp, MD 21017-1505

8. PERFORMING ORGANIZATION REPORT NUMBER
CSIAC-BCO-2021-189

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Technical Information Center (DTIC)
8725 John J. Kingman Road
Fort Belvoir, VA 22060

10. SPONSOR/MONITOR'S ACRONYM(S)
DTIC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/ AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. ABSTRACT

Driven by the rapidly changing space segment, satellite ground networks are in the midst of evolutionary change called the digital transformation. This transformation will enable the satellite communications (SATCOM) to realize benefits in speed of innovation, scale, and cost. More importantly, it will help fulfill the key demands of next-generation SATCOM networks. The digital transformation comprises two components widely accepted and adopted in the larger telecommunications industry—digitization and virtualization. Digitization modularizes and commoditizes SATCOM modem architectures to use common hardware and introduces a new digital intermediate frequency (IF) interface. Additionally, standardization of digital IF is paving the way for these next-evolution architectures. The move to common hardware through digitization forms the basis for virtualization, which creates agile terminals that can deploy a variety of waveforms and applications. Leveraging virtualization, network function virtualization provides a new paradigm to support virtualized service chains and management of virtual network functions. Through these architectures, SATCOM-as-a-Service networks can be easily managed and deployed with custom configurations. Other critical components of the digital transformation are advanced antenna systems that support multi-band, multi-orbit, and multi-beam. Through a digitally transformed ground network, SATCOM systems can leverage new operational use cases that improve network and terminal agility and resilience. This state-of-the-art report describes the SATCOM network's key demands, technological components, and future operations.

14. SUBJECT TERMS
electromagnetic interference, shielding effectiveness, spectrum, radiation, electromagnetic pulse, defense infrastructure, civilian infrastructure

15. SECURITY CLASSIFICATION OF:			**16. LIMITATION OF ABSTRACT**	**17. NUMBER OF PAGES**	**18a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	58	Vincent "Ted" Welsh
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED			**18b. TELEPHONE NUMBER** *(include area code)* 443-360-4600

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

ON THE COVER:
(Source: 123rf.com)

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ABSTRACT

Driven by the rapidly changing space segment, satellite ground networks are in the midst of evolutionary change called the digital transformation. This transformation will enable the satellite communications (SATCOM) to realize benefits in speed of innovation, scale, and cost. More importantly, it will help fulfill the key demands of next-generation SATCOM networks. The digital transformation comprises two components widely accepted and adopted in the larger telecommunications industry —digitization and virtualization. Digitization modularizes and commoditizes SATCOM modem architectures to use common hardware and introduces a new digital intermediate frequency (IF) interface. Additionally, standardization of digital IF is paving the way for these next-evolution architectures. The move to common hardware through digitization forms the basis for virtualization, which creates agile terminals that can deploy a variety of waveforms and applications. Leveraging virtualization, network function virtualization provides a new paradigm to support virtualized service chains and management of virtual network functions. Through these architectures, SATCOM-as-a-Service networks can be easily managed and deployed with custom configurations. Other critical components of the digital transformation are advanced antenna systems that support multi-band, multi-orbit, and multi-beam. Through a digitally transformed ground network, SATCOM systems can leverage new operational use cases that improve network and terminal agility and resilience. This state-of-the-art report describes the SATCOM network's key demands, technological components, and future operations.

EXECUTIVE SUMMARY

The rapidly evolving space segment is driving the digital transformation of satellite communications (SATCOM), which is the next evolutional transformation of satellite ground and terminal segments. Given the rapidly changing environment and variegated space and terminal segments, the following are the key demands of next-generation SATCOM networks:

- Key Demand-1: Freedom From Vendor Lock-In
- Key Demand-2: Reduction in Total Cost of Ownership (TCO)
- Key Demand-3: Ground Segment Sustainability
- Key Demand-4: Terminal/Modem Agility
- Key Demand-5: System Agility/Resiliency
- Key Demand-6: High Computational Density/ Efficiency

As both the U.S. Department of Defense and commercial SATCOM networks migrate toward next-generation architectures to satisfy these key demands, these networks will undergo a digital transformation. The digital transformation of SATCOM will enable the enterprise networks to realize benefits in speed of innovation, scale, and cost of these systems. This transformation is based on two principles widely accepted and adopted in the larger telecommunications industry—digitization and virtualization.

Digitization of the ground segment satisfies many of the key demands through rearchitecting SATCOM modem architectures. L-band intermediate frequency transmission systems are replaced with internet protocol-based interfaces, creating digital intermediate frequency (IF). Replacing L-band transmission systems with digital IF can possibly increase system radio frequency (RF) performance, network agility, and resilience. More importantly, digitized SATCOM modems and network architectures can take advantage of common hardware, which provides the foundation for virtualization. With these many benefits, the movement into digital IF is fast underway as an interoperable standard lead by the digital IF interoperability consortium.

The virtualization component of the digital transformation has several dependencies. The first dependency was the reliance upon common hardware, which was provided through digitization of the ground segment. Virtualization, generally, meets several key demands. However, a fully virtualized SATCOM network requires network function virtualization, operations and business support systems, and management/orchestration system frameworks. These dependencies allow service orders and translation of those orders into virtualized service chains. Those service chains comprise virtual SATCOM functions, which can be deployed on demand. Virtualization will allow rapid scalability, reduced maturation cycles, and reduced barriers to prototyping, testing, and deployment new capabilities. Additionally, virtualization accelerates the speed of innovation by fostering a larger pool of competitors where superior functions can be selected and deployed independent of vendors.

New Low Earth Orbit constellations are moving toward V-band frequencies to obtain more bandwidth. Additionally, multi-band, multi-orbit, and multi-beam antenna technologies are required for complete interoperability between satellite networks. Multi-band technologies have been deployed with Geosynchronous Earth Orbit (GEO)

EXECUTIVE SUMMARY, *continued*

satellites using fixed antennas, where the GEO satellite operates on multiple frequencies. Multi-band systems also require multiple RF transmission systems, which increase size, weight, and power (SWaP). With maritime applications, mechanical steering is required with multi-band solutions, and these have been adapted to create multi-orbit solutions. Mechanical steering, multi-orbit solutions do not meet SWaP requirements for many applications. Thus, electronically steerable array (ESA) antennas have been making a push into the market to address that gap. Although ESAs have the most potential for creating a multi-beam solution, they are still limited to single-band applications since their multi-element design depends on frequency.

A digitally transformed SATCOM environment allows several new operational use cases that will increase terminal/modem agility. These new use cases include dynamic applications/waveforms, waveform diversity, and satellite link diversity. Additionally, new operational use cases for the system agility/resiliency include gateway resource sharing and gateway routing. Gateway resource sharing supports hybrid Cloud capabilities, which is one of the final characteristics of the digital transformation.

ACKNOWLEDGMENTS

The authors would like to acknowledge the following individuals who helped review content or who contributed to the intellectual exchange of ideas with the authors.

- A. J. Vigil, Ph.D., P.E., Senior Scientist, Systek
- Mike Dean, SATCOM Chief, DoD, CIO, C3IO
- Brian Beauchamp, Senior Systems Engineer, Envistacom
- Scott Grose, Senior Principal Engineer, Envistacom
- Ben Hilburn, Head of Strategic Initiatives, Microsoft
- Mahmud Harun, Senior Engineer, Ground System Architecture, SES

You input was valuable to help shape the outcome of this effort. Thank you for your time and talent.

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SECTION 01

INTRODUCTION

Over the last decade, record capital investments, lower launch costs, lower development costs, emergence of new applications, and increased capability of satellites have driven significant changes into the rapidly evolving space segment. These changes subsequently are paving the way for digital transformation of satellite communication (SATCOM) [1], which will enable SATCOM enterprises the needed capabilities required from the rapidly changing space segment. The purpose of this state-of-the-art report (SOAR) is to educate the reader on the importance of the digital transformation of SATCOM ground systems and the associated technological issues. In this section, we review the challenges and motivations for the digital transformation, introduce the concepts of digitization and virtualization, and motivate the reader to seek more detail from the subsequent sections. This section concludes with a summary of the remaining sections of the SOAR.

1.1 CHALLENGES AND MOTIVATION

Capable of delivering global high-throughput data, SATCOM is the primary beyond line-of-site communications used by the U.S. Department of Defense (DoD). Due to SATCOM's importance, the DoD demand for data compound annual growth rate is 21% [2]. While there is an ever-increasing need to fulfill the growing demand for data throughput, there are evolutionary challenges facing SATCOM systems. In 2020, the U.S. Space Force released their vision for SATCOM [3], which outlined some of the challenges with existing SATCOM services used by (within) the DoD. The major challenge is stovepiped systems operated and controlled by multiple service organizations. Additionally, further complexity challenges are brought through the many additional levels of variegation—the SATCOM type (wideband, narrowband, etc.,) to space segment, terminal segment, ground segment, and operational domain. These many aspects of variegation are shown in Figure 1-1 [4]. At the Satellite 2021 Conference, Mike Dean, SATCOM Chief of the DoD Chief Information Officer, pointed out that the DoD currently manages over 17,000 total terminals, with 135 different types of terminals. As a result, the DoD has engaged in multiple, different request for information (RFI) efforts to address examining commercial SATCOM-as-a-Service (SATCOMaaS) business model [5], virtualization of satellite modems and waveforms [6, 7], specifications for next-generation architectures [8], and next-generation tactical terminals [9].

The complexity that comes from the rapidly evolving space segment brings a variegated set of constellations, orbits, frequencies, and waveforms. With up to 50,000 active satellites predicted to be in orbit over the next 10 years [10], these new satellites include the novel Low Earth Orbit (LEO) constellations, such as Starlink (among many others [11]), new Medium Earth Orbit (MEO) [12], and new Geosynchronous Earth Orbit (GEO) satellites [13]. The evolving space segment drives the need for SATCOM ground and terminal segments to create flexible and adaptable networks capable of operating on a myriad of different waveforms, orbits, and constellations while simultaneously maintaining service quality and operational sustainability. In the

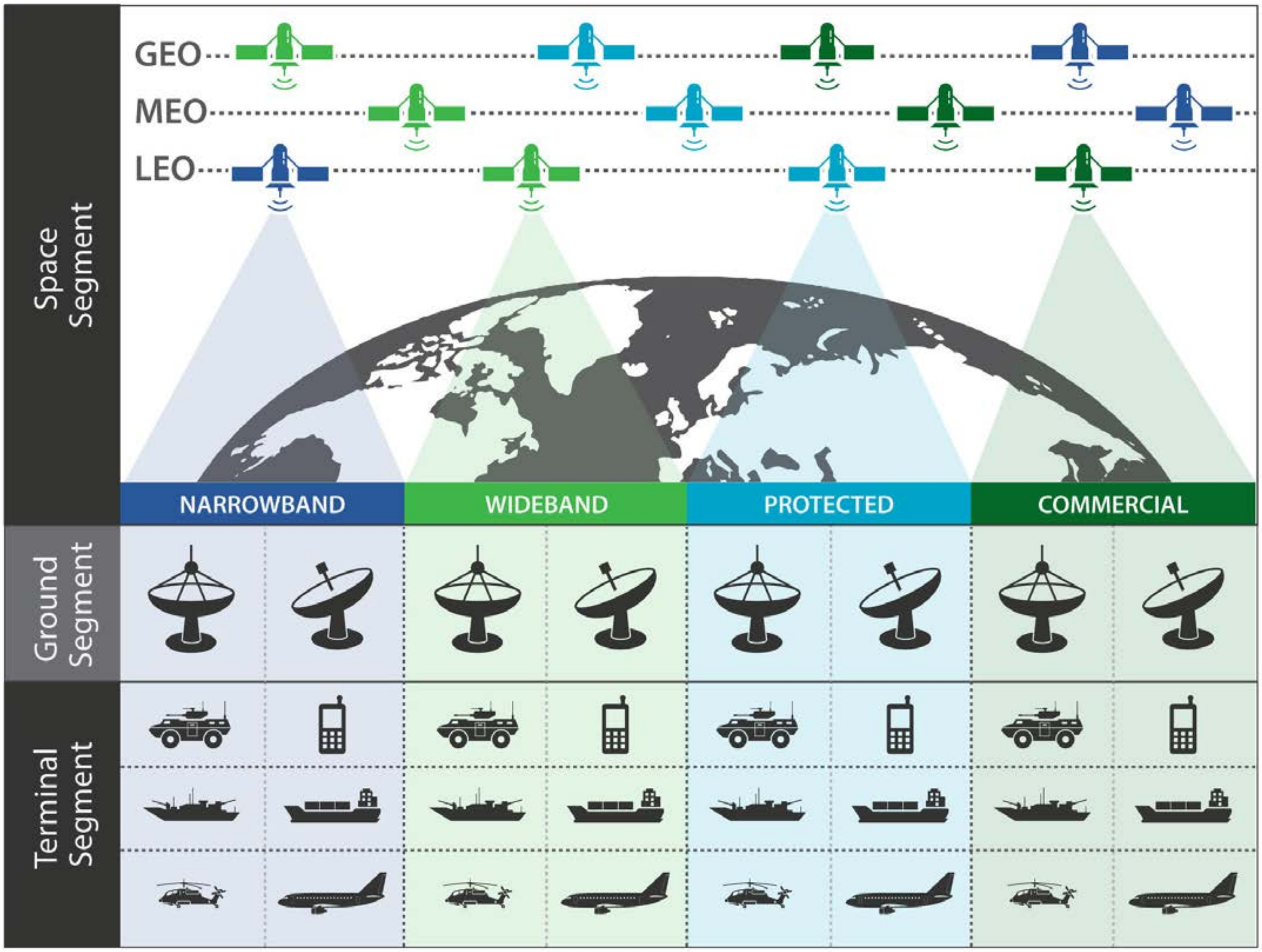

Figure 1-1: SATCOM Complexity Is Brought Through Many Levels of Variegation: the SATCOM Type (Wideband, Narrowband, Etc.) to Space, Terminal, Services, Operation Domain, and Ground Segments.

past, access to space resources was expensive. As a result, a limited number of purpose-built proprietary vendors thrived. These rigid solutions, which dominated SATCOM networks for decades, are now unfit to meet the needs of current networks. As leading global satellite and space market research firm Northern Sky Research (NSR) recently reported, legacy "satellite ground networks … lack the scale and agility necessary to avoid the palpable risk of becoming bottlenecks" [14]. Terminal and ground segments are creating bottlenecks in both DoD and commercial systems. Given the rapidly changing environment and challenges addressed by the surveyed literature, we have articulated (in no specific order) the following key demands of next-generation SATCOM networks.

Key Demand-1: Freedom From Vendor Lock-In
Proprietary-based modems complicate networks, logistics, migration, increase costs, and contribute to stove-piped systems. Vendor lock-in business models are an antiquated way of doing business that form rigid oligopolies that limit innovation and technology progression.

Key Demand-2: Reduction in Total Cost of Ownership (TCO)
Operating and capital expenses are key drivers in network sustainability. In commercial networks, managing SATCOM networks' costs is important in maintaining profitability. In DoD networks, managing SATCOM networks' costs is important in maintaining network longevity.

Key Demand-3: Ground Segment Sustainability
Operational complexity and large logistical footprint create upgrade stagnation. Sustainable networks require migration paths with minimal network impacts.

Key Demand-4: Terminal/Modem Agility
Terminal segments, along with their antennas, need to operate on multiple waveforms, bands, and orbits. Modems should also operate on a variety of waveforms.

Key Demand-5: System Agility/Resiliency
SATCOM ground and terminal segments should deploy automated configurations based on mission needs, maintained connectivity through contested environments, and changing network demand.

Key Demand-6: High Computational Density/Efficiency
The demand for reduced size, weight, and power (SWaP) is ever present. Rack space in many networks is reaching capacity, creating additional operational costs to meet the increasing demand for throughput.

As both DoD and commercial SATCOM networks migrate toward next-generation architectures to satisfy these key demands, these networks will undergo a digital transformation. The digital transformation of SATCOM will enable these networks to realize benefits in speed of innovation, scale, and cost of these systems. Figure 1-2 illustrates the different components and dependencies of the digital transformation. For example, digitization is complete when the concepts of digital intermediate frequency (IF), edge device, and digital IF modem are completed.

1.2 THE DIGITAL TRANSFORMATION OF SATCOM

The digital transformation of SATCOM is based on two principles that are widely accepted and adopted in the larger telecommunications industry: ***Digitization*** and ***Virtualization***.

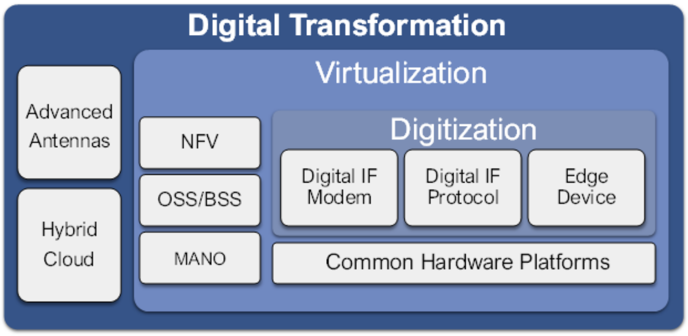

Figure 1-2: Two Major Components of This Digital Transformation Are Digitization and Virtualization.

- ***Digitization*** refers to replacing the L-band IF interfaces with Internet Protocol (IP)-based interface, i.e., digital IF. Simply put, the evolution to digital IF is analogous to transitioning from broadcast TV to Netflix.
- ***Virtualization*** refers to the abstraction of computing resources from the specific hardware to create a virtual computing environment. With virtualization, multiple, independent virtual computing systems are instantiated to behave like independent computers or servers. These virtual computing environments can share the same physical hardware resources. With virtualization, a panoply of applications and functions is consolidated onto common hardware. Most importantly, virtualization separates application and hardware vendors, which eliminates the need for purpose-built hardware.

Mobile network operators (MNOs; e.g., Verizon and AT&T) have adopted and developed standard approaches using these principles. Mobile network digitization standards started in 2011 with the Common Public Radio Interface (CPRI) and was superseded in 2019 by enhanced CPRI (eCPRI). In essence, the eCPRI standard provides transport of digital samples over IP networks [15]. Similarly, virtualization was adopted by MNOs through the Network Function Virtualization standard [16] in 2013, which specified a common architecture and approach to virtualize network functions onto common hardware. While these principles are now common for MNOs, they are starting to show promise in SATCOM networks as well.

1.2.1 Digitization of SATCOM

At the most basic level, digitization of modems means separating the digital IF modem processing from the radio frequency (RF) front end and introducing a digital IF interface between these two components. In a purpose-built modem, as shown in Figure 1-3, these functions are combined into a single device. The digital IF modem transmutes the signals between data bits and digital samples, and the RF front end then transmutes signals between digital samples and L-band IF. As shown in Figure 1-4, these two functions are separated in a digitized modem architecture, where we call the RF front end an "edge device." The digital IF modem and the edge device are connected using the digital IF interface, which is IP-based transport protocol used to communicate digital samples and their contexts across a data network.

While the differences between Figures 1-3 and 1-4 may seem subtle, there are significant implications for SATCOM networks, which is discussed in detail in Section 3 (Digitization of SATCOM Networks). Digitized SATCOM modem architectures meet the following identified key demands of next-generation SATCOM networks [17].

Key Demand-1: Freedom From Vendor Lock-In
In a digitized architecture, digital IF modems can be moved onto common and commodity hardware since specialized modem components are separated. Additionally, edge devices become more commodity components since integration with the vendor intellectual property is no longer a dependency. This primarily depends on an interoperable digital IF standard.

Key Demand-2: Reduction in TCO
When comparing capital expenditures, instead of analog transmission lines and distribution equipment, digital IF transmissions are based on commercial-off-the-shelf (COTS) IP routers and switches, which, generally, have lower capital and operation costs. Additionally, network reconfiguration or migration does not require operators to disconnect transmission cabling for equipment replacement. These network operations can be entirely managed by reassigning digital IF IP addresses or simply plugging in a new digital modem into a router.

Key Demand-3: Ground Segment Sustainability
While only a terminal architecture is shown in Figures 1-3 and 1-4, analog transmission lines' and distribution equipments' monolithic nature can cause bottlenecks in system migration paths. In a digital IF architecture, transmission equipment is based on COTS IP routers and switches, which, generally, have lower operation costs and are easier to expand capacity.

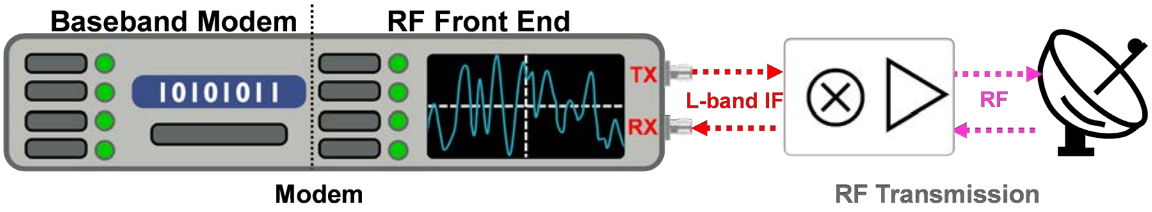

Figure 1-3: Traditional, Purpose-Built SATCOM Terminal Architecture.

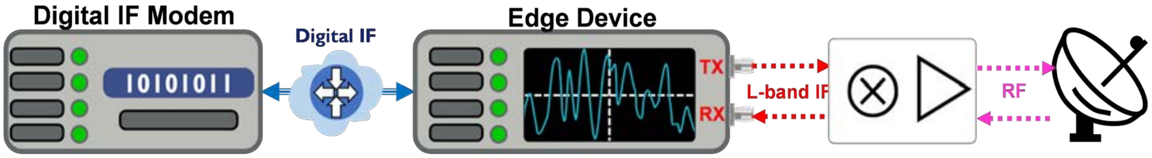

Figure 1-4: Digitized SATCOM Terminal Architecture.

Key Demand-4: Terminal/Modem Agility
In a digitized architecture, digital IF modems are decoupled from edge devices, supporting easy reconfiguration of the network. With a standardized digital IF interface, digital IF modems could replace and back up one another for redundancy through simple IP network configurations. Digital IF streams could also be duplicated, combined, and separated digitally to provide new capabilities like diversity gain, beam forming, and amplifier distortion correction.

Key Demand-5: System Agility/Resiliency
Since digital IF modems use IP-routed traffic, networks for modems in ground segments could be rerouted to different antennas, which do not need to be connected to the local teleport. This allows access and resiliency through antenna and teleport system diversity. When digital IF modems and edge devices use IP-routed networks, they are fully connected to one another. This enables rapid transition between edge devices for coordinating handoffs between networks or operation on multiple simultaneous networks. Additionally, with a reliable digital IF transport, digital IF modems can communicate to distant edge devices, adding additional network resilience, and even leverage Cloud computing.

Key Demand 6: High Computational Density/ Efficiency
In the ground segment, moving from analog IF transport to digital IF transport system will significantly reduce the need for analog IF systems and replace them with COTS IP routers and switches.

1.2.2 Virtualization of SATCOM

Virtualization will enable many different types of waveforms and modem features to be consolidated onto common hardware, thereby eliminating the need to manage purpose-built hardware and many different modem types. A digital IF architecture provides a smooth transition to virtualization since digital IF modem processes can now run on COTS servers. As digitization enables network agility, virtualization enables modem and terminal agility by more effectively providing dynamic reprogrammable functionality onto the digital IF modem. A diagram showing logical abstraction of a virtualized computing environment using a digital IF modem as the virtualization host is shown in Figure 1-5.

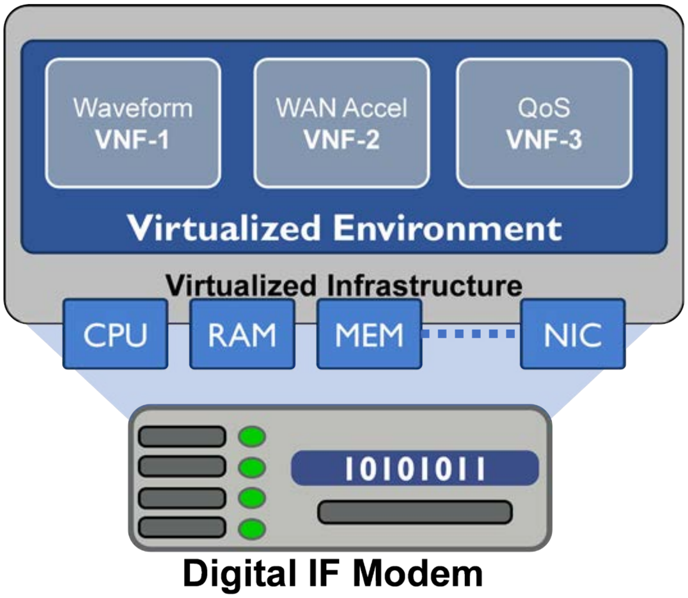

Figure 1-5: Virtualized Network Functions (VNFs) Provide Modem Agility Since VNF Functions Are Not Conjoined to Specific Hardware and Software.

In purpose-built modems, several different SATCOM functions are provided. These SATCOM functions include, but are not limited to, waveforms, wide area network (WAN) acceleration, quality of service (QoS) management, and more. In purpose-built modems, these functions are almost always conjoined to each other and the underlying hardware. Generally, these conjoined functions are not capable of operating independently or separated easily. In a virtualized architecture, these SATCOM functions are "softwarized" into their own virtual machine/ computing environment called VNFs. These VNFs operate independently from other VNFs and the underlying hardware. Leveraging virtualized SATCOM modem architectures will meet the following key demands.

Key Demand-1: Freedom From Vendor Lock-In
Since virtualization untethers hardware from SATCOM functions, best-in-class SATCOM functions can be selected independently from distinct application vendors. In this new paradigm, application vendors could offer VNFs like the apps offered in smartphone ecosystems. Additionally, pure software entrants are encouraged to compete since there is no need to develop hardware to enter the market. Virtualized architectures accelerate speed of innovation by fostering a larger pool of competitors, where superior functions can be selected and deployed together.

Key Demand-2: Reduction in TCO
When VNFs are deployed, hardware migrations generally are turned into software migrations. Rather than replacing racks of purpose-built modems, migrations with virtualized architectures require only deploying new VNFs. Because common hardware can be used for multiple architectures, new purpose-built hardware does not need to be purchased or managed. Additionally, consolidation allows more efficient use of existing hardware resources, which can support a multiplicity of functions and simultaneously take advantage of hardware and software economies of scale enabled by larger telecom and information technology sectors.

Key Demand-3: Ground Segment Sustainability
When VNFs are deployed, hardware migrations generally are turned into software migrations. Rather than replacing racks of purpose-built modems, migrations with virtualized architectures require only deploying new VNFs. Because common hardware can be used for multiple architectures, the logistical footprint of multiple purpose-built hardware systems is no longer required. Additionally, with purpose-built modems, the design-integrate-deploy lifecycle is costly and time consuming. These lifecycles will stifle the deployment of new technologies. With rapidly changing and diverse space layer shortening lifecycles, purpose-built systems will create evolutionary bottlenecks.

Key Demand-4: Terminal/Modem Agility and System Agility/Resiliency
The rapidly changing space layer requires the SATCOM network to quickly reconfigure itself to deploy new waveforms or capabilities and connect with multiple, different orbits. With VNFs, these functions can easily be prototyped, tested, and deployed, with minimal impacts to network hardware.

Key Demand-5: System Agility/Resiliency
With consolidation of hardware, data handoffs could occur between orbits, waveforms, and constellations. Leveraging existing infrastructure, on-demand services with VNFs can deploy flexibility. Additionally, with digital IF and virtualization, other different mission needs, such as information operations and electronic warfare (EW), could be served with the same equipment [18].

Key Demand-6: High Computational Density/Efficiency
Virtualization allows consolidation of hardware, which leads to more efficient hardware utilization means reduction in SWaP. Purpose-built appliances, by nature of development, have only the computing capability required for their application. Purpose-built modems have compounded the complexities and costs of managing SATCOM networks. In an exponentially growing SATCOM market, managing purpose-built modems has scalability constraints due to rack space, power, and operation knowledge necessary for managing many different models and vendors. A network with N different modems means a network with N times more rack space, switching equipment, network cost, and complexity.

1.3 SUMMARY AND CONCLUSION

We highlighted the importance of the digital transformation of SATCOM, introduced the concepts of digitization and virtualization, and further motivated the reader to seek more detail from the subsequent sections.

In Section 2 (Background), we provide more background on a variety of subjects that build a foundation for understanding the technical importance of digitization and virtualization. With this background information, we continue with Section 3 (Digitization of SATCOM Networks), which includes discussion in digital IF standardization, the introduction of digital IF modems and edge devices, impacts to the ground segment, and new considerations regarding issues with networking and resilience. With digitization supporting the transition to virtualization, Section 4 (Virtualization of SATCOM Networks) discusses how network function virtualization (NFV) concepts lay the foundation for SATCOM applications. This section also discusses current applications that use virtualization to support functions in related applications to SATCOM. In Section 5 (Advanced Antennas), we include a brief summary, trends, and survey of terminal antenna technologies supporting multi-band, multi-orbit, and multi-beam antenna. Our report concludes in Section 6 (Use Cases) with examples of operational use cases for a digitally transformed SATCOM network.

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SECTION 02 BACKGROUND

2.1 INTRODUCTION

This section will provide the reader with background concepts that will be elaborated in later subsections. The first subsection, "The Ground Segment," discusses how ground segments' gateways are configured and managed. This generalized architecture represents both DoD and commercial SATCOM networks. "Traditional Modem Design" describes how modems are designed and how these designs drove modems into vertically integrated proprietary systems. In "Software-Defined Radio Architectures," we describe how software-defined designs changed the perspective of modem design. VME bus "International Trade Association (VITA) 49" discusses how VITA 49 is used as a data representation language for digital sample transport. The final subsection, "Telecommunications Industry Association (TIA) 5041," concludes with a summary of TIA-5041 and its attempt to first digitize DoD SATCOM networks.

2.2 THE GROUND SEGMENT

The ground segment primarily comprises the set of gateways that support the terminal segment. Gateways contain components of consolidated ground facilities, including modems, IF transport equipment, frequency mixers, amplifiers, and antennas. A diagram of a simplified gateway architecture is shown in Figure 2-1. In this simplified gateway architecture, there are three main components that comprise the system: (1) the Proprietary Modem Bank (PMB), (2) the L-band Switching System (LSS), and (3) the RF transmission system. The PMB, left in Figure 2-1, comprises a variegated

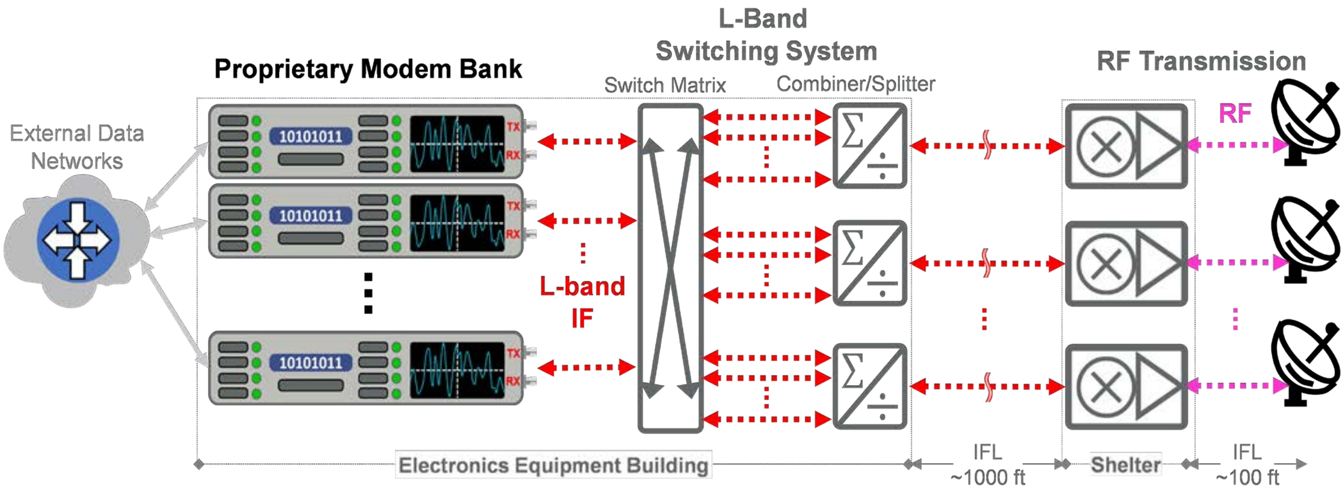

Figure 2-1: Ground Segment Simplified Gateway Architecture Comprises a Proprietary Modem Bank (PMB), L-band Switching System (LSS), and an RF Transmission System.

set of modem models from different vendors. In some gateway sites, there may be up to eight different modem models to manage. Such a large number of different modem models quickly consumes rack space and creates a large logistical footprint. We assume data interfaces into each of the PMB modems. These data interfaces connect user terminals to external networks through modems in the PMB.

The LSS switching system in Figure 2-1, middle, comprises a switch matrix and combiners and splitters. Switch matrix systems are fan-in or fan-out configurations, i.e., signals are usually routed in one direction from a single device. For example, the single switch in Figure 2-1 represents two switch matrixes—one for transmitting and one for receiving. Following each switch matrix is an analog combiner and splitter paired to each RF transmission system. RF transmission systems include a frequency converter, power amplifier, antenna, polarization of antenna, frequency band, and target satellite (not shown). In the transmit direction, the role of the switch matrix is to route IF signals from modems to appropriate combiners, which route IF signals to the targeted RF transmission system (i.e., frequency mixer, amplifier, and antenna). In the receive direction, the role of the switch matrix is to route signals from the signal splitters to the appropriate destination modem.

The PMB and LSS are contained in the Electronics and Equipment Building (EEB). Signals are transported between the EEB and shelters near the antennas through an interfacility link (IFL). In some configurations, the IFL link can be between 1,000 and 3,000 ft. These links can use L-band analog transmission cabling, which transports the IF signals to the frequency translation and amplification systems of the RF transmission system for the appropriate antennas. Long, analog cable lengths create power loss and slope distortion, which impact system performance.

The PMB and the LSS are where drivers of the key demands originate. Key demands and their drivers from the PMB and the LSS are shown in Table 2-1. PMB causes the "multi-model modem" problem, which increases the logistical and operations complexity by a factor equal to the number of modem models supported. Logistical footprints include spare part management, equipment upgrade paths, and operational knowledge required to operate each of the different modem models.

Table 2-1: PMB and LSS Drivers of the Key Demands in SATCOM Systems

Key Demands	PMB	LSS
1: Freedom From Vendor Lock-in	Causes multi-model modem problem; root to many demands.	NA
2: Reduction in TCO	Multiple modem models increase: (1) logistical costs (2) operational costs (3) capital costs	L-band IF increases: (1) logistical costs: from growing amount of equipment (2) operational costs: reconfiguration of LSS equipment with network change
3: Ground Segment Sustainability	Multiple modems exhaust of rack space limits upgrades to new equipment.	Capacity cannot keep up with bandwidth demand.
4: Terminal/Modem Agility	Proprietary modems are constrained to proprietary vendor waveforms.	NA
5: System Agility/ Resiliency	Modems are interfaced directly to LSS.	Limited distance signal routing. Larger distances possible with specialized equipment.
6: High Computational Density/Efficiency	Multiple modem vendors multiply the need for rack space.	LSS systems require excessive amounts of rack space to future capacity needs.

Modem vendors have recognized this need and branded "software-defined" modems which have multi-waveform operation. However, these software-defined modems still rely primarily on proprietary waveforms, which still require their own set of unique hardware. Additionally, the multi-model modem problem is driving EEBs to reach their rack space capacity and LSS capacity. This problem also increases complexity in field terminals, which may require multiple modem models at each terminal. As a result of reaching the rack capacity limit, migration costs increase, and network sustainability is constrained. These cost increases and sustainability constraints are driving the key demand for more computationally dense and efficiency modem computing.

LSSs also create drivers for some of the key demands. LSS are inherently monolithic architectures that increase operational complexity and costs. First, LSS increases operational complexity/costs when increasing capacity. Capacity can be increased either through adding parallel IF system cabling and routing systems or through replacing entire LSS systems to a higher capacity system. Removal, replacement, and reconfiguration of LSS disrupt network availability and require a significant amount of cable installation/rerouting. Second, with additional steps for IF transmission, certification is required for DoD systems. Large LSSs degrade RF transmission performance by introducing signal distortion and degradation when moving through LSS equipment. Additionally, long IFLs create signal distortion transmission and additional signal power loss. Usually, these problems can be compensated by advanced features, i.e., line equalization, inside the LSS equipment or line amplifiers. In any case, the use of IF for long-range signal transport, by nature, is inefficient. This inefficiency requires extra equipment features, equipment, and additional analysis to ensure signal loss from the LSS does not impact signal performance. As a result, LSS may occupy multiple racks of equipment, which are again reaching capacity in the EEBs.

2.3 TRADITIONAL MODEM DESIGN

The multi-model modem problem is deeply rooted in proprietary hardware, which has been created by vendors to create a barrier of integrated wares. This barrier means simply that siloed hardware, software, and firmware have continued to perpetuate a market of proprietary SATCOM modems. Modems have one primary purpose: to transmute packet data, primarily IP data, into RF signals and vice versa. A diagram of a typical modem architecture is shown in Figure 2-2. Starting from the left, modems traditionally have two IP interfaces—one for data and the other for management and configuration. A central processing unit (CPU), like the ones found in modern-day personal computers, serves as the brain of the modem by managing traffic and presenting a webpage for users for management and configuration.

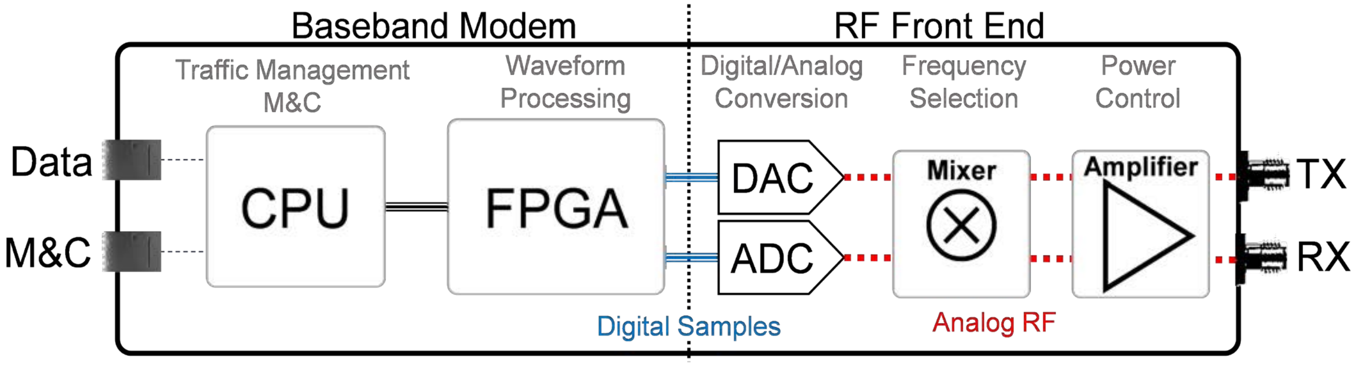

Figure 2-2: Baseband Modem and Analog Front-End Architectures.

The FPGAs are used to implement waveform processing by transmuting data bits to/from digital samples, which are eventually turned into RF signals. FPGAs are programed with *firmware*, which inherently is more rigid and computationally efficient than CPUs, which are programed with more flexible *software*. In the computing toolbox, FPGAs excel at performing a limited number of tasks very fast, while CPUs excel at performing a wide variety of tasks much less efficiently. Using an analogy, an FPGA is like a screwdriver, and a CPU is like a Swiss army knife. A screwdriver and a Swiss army knife can both be used to tighten a screw, but the screwdriver is more efficient to its one purpose.

FPGAs also provide digital interfaces that accept and receive digital samples. These digital samples are translated to/from the analog domain through digital-to-analog converters (DACs) and analog-to-digital converters (ADCs), respectively. The remaining "analog front end" comprises mixing (i.e., frequency band selection), amplification (power control), and RF connections for transmit (TX) and receive (RX) cables that will go to the antenna's subsystems. In general, two major functions comprise a SATCOM modem: (1) the baseband modem, which processes signals between packet data and digital samples, and (2) the analog front end, which processes signals between digital samples and RF.

While powerful for use in communications applications, FPGAs have contributed to shaping the SATCOM industry into a siloed market of proprietary appliances for two main reasons. First, FPGAs are more difficult to work with since they require specialized training and knowledge to program firmware. Second, FPGAs require developers to build proprietary hardware and firmware to support interfaces to other hardware components (i.e., CPU, DAC, ADC, etc.). Consequently, each modem vendor's design surrounded the FPGA, creating a barrier of entry of integrated proprietary wares (i.e., a silo of software, firmware, and hardware).

2.4 SOFTWARE-DEFINED RADIO (SDR) ARCHITECTURES

In 2001, software developers were observing the exponential rise of CPU processing power and betting on Moore's law to take them past the need for FPGAs. In this expectation to overcome the FPGA development barriers, experiments migrating FPGA functions to the CPU were explored. Since these architectures moved all waveform processing out of *firmware* into *software*, the term SDR was coined. Figure 2-3 shows an illustration of a generic SDR architecture. SDR architectures introduced a digital sample interface for the transport of the digital samples between the software waveform and the SDR front end to translate the signals between digital samples and analog RF domains. In this architecture, software developers now had control over waveforms and the flexibility of development. In SDR architectures, FPGAs had a single simple function—to unpack/pack digital samples. This introduced a new modem component called an

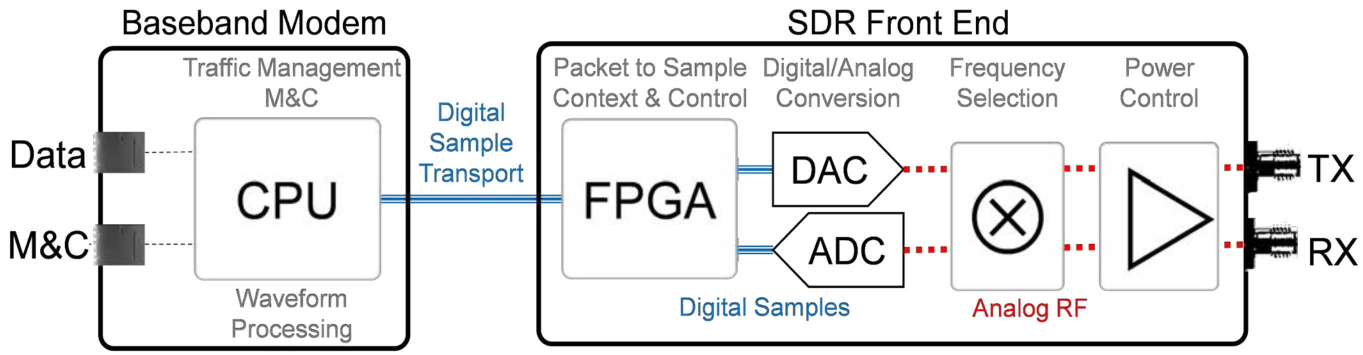

Figure 2-3: SDR Architectures Reduced the FPGA's Role to Collect and Package Digital Samples.

SDR front end (sometimes called an SDR radio). Like the analog front end, the purpose of the SDR front end is to transmute signals between digital samples and analog domain.

The advancement of SDR was further accelerated by the open-source tool GNU Radio, which provided software radio libraries that further lowered barrier to entry. However, research truly began to accelerate around 2003, when Ettus Research developed the Universal Software Radio Peripheral (USRP), which was the first commercially available SDR front end. With this new SDR front end, any PC with USB 2.0 and used as the digital sample interface could receive or transmit a radio waveform. USRP and GNU Radio provided a low-cost entry that allowed researchers to explore new avenues of experimentation. Leveraging the same plan as Ettus and due to the low entry barrier, a large number SDR front ends, some based on GNU Radio (and other government and commercial variants), were developed. This created niche markets.

While SDR front ends were finding a wide range of uses in niche markets and useful for experiments with researchers, engineers in multiple industries quickly realized that modularization of modem architectures offered additional flexibility, capability, and cost savings. For flexibility and capability, baseband modem functions could be deployed in commodity computing systems and leverage any SDR front end. For cost, in many applications, this architecture created significant RF performance benefits, CAPEX, and OPEX savings over nonmodularized architectures. However, to fully leverage the benefits of this new architecture, the digital sample interface required standardization, where digital sample standard defines the format and messages for packetized digital samples and context information of the digital samples. Over the last decade, there have been two different efforts to define these digital sample transport protocols—we will refer to them as digital IF.

2.5 VITA 49

In May 2009, VITA published the 49 standard effort to support the development of COTS equipment for the SIGnal INTelligence community [19]. The primary task of VITA 49.0 was to provide a message protocol for spectrum monitoring by transporting digitized RF samples and context associated with those samples (i.e., sample rate, frequency, antenna parameters, etc.). Figure 2-4 shows how an SDR architecture could implement VITA 49.0. The VITA 49.0 protocol defines data packets, where the digital samples are collected from the ADC, and context packets, which define the frequency, sample rate, and other important information relevant to the data packets. Additionally, it is important to note that VITA 49 only specifies the data representation layer framework for received digitized samples. The

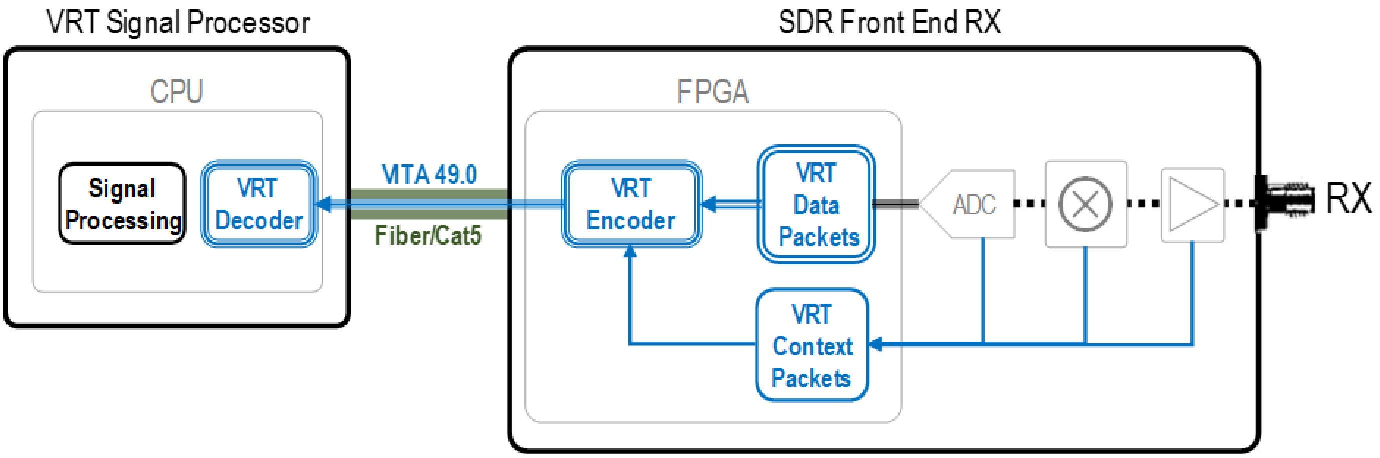

Figure 2-4: VITA 49.0 Implementation in the SDR Architecture.

physical and transport layers used to transport the data between endpoints is left to implementations.

Because of the receive-only limitation, VITA 49.2 was released in 2017 to support communications, EW, and radar applications [20]. Like Figure 2-4, Figure 2-5 shows the VITA 49.2 implementation in the SDR architecture. The standard also added support for precision, time-stamped data and command packets to support communications applications. As a result of VITA 49.2 standardization and modularization, there have been more 49.2-based SDR front ends coming to the market for a variety of applications.

2.6 TIA 5041

In 2016, the U.S. Army Communications-Electronics Research, Development and Engineering Center, now known as DEVCOM C5ISR Center, Space and Terrestrial Communications Directorate, SATCOM Systems Division standardized TIA 5041 as part of the Open Standards Digital Interface (OSDI) effort in the Future Advanced SATCOM Technology (FAST) program [21]. Figure 2-6 shows an illustration of the TIA standard. The main objective of the OSDI effort was to consolidate baseband processing onto common hardware and use edge devices to dynamically meet mission requirements and eliminate the need for analog IF transmission cabling and switching systems by replacing them with a digital IF interface. TIA 5041 specified the following network elements for satellite ground networks:

- **Digital Modem (DM)**
  Modem designed to receive/transmit using digital sample IP protocol.
- **Wideband Signal Processor (WSP)**
  Network element for multiplexing/demultiplexing, multiple, digital sample streams into a single digital sample stream.
- **Conversion Subsystem (DCS)**
  Network element used for translating between digital and RF signals to receive digital sample IP protocol.

TIA provided unprotected and protected digital IF for transport. The protocol stacks for the unprotected and protected digital IF are shown in Figure 2-6, bottom right. In unprotected digital IF, packet ordering and reliability are provided by the Reliable Transport Protocol. In local, tightly controlled networks, unprotected transport is adequate. However, when dealing with packet loss, common with the internet, there is a requirement for more protection. Using the protect digital IF, DMs can communicate to any WSP in any gateway over the internet. In this way, DMs are not required to be colocated with the WSPs. Unfortunately, TIA 5041 was not adopted

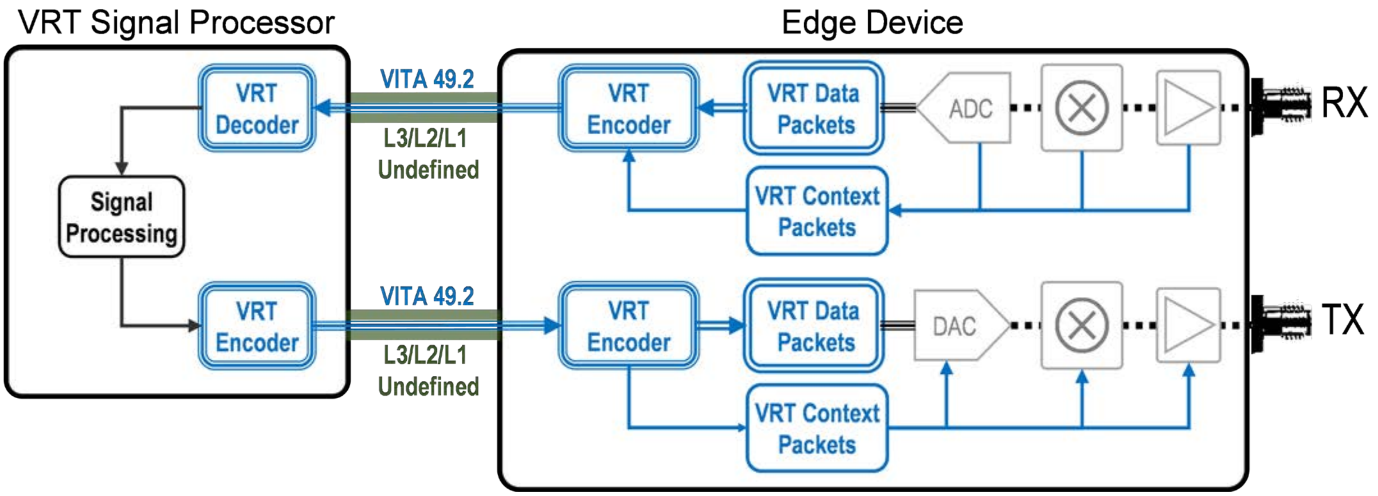

Figure 2-5: VITA 49.2 Implementation in the SDR Architecture.

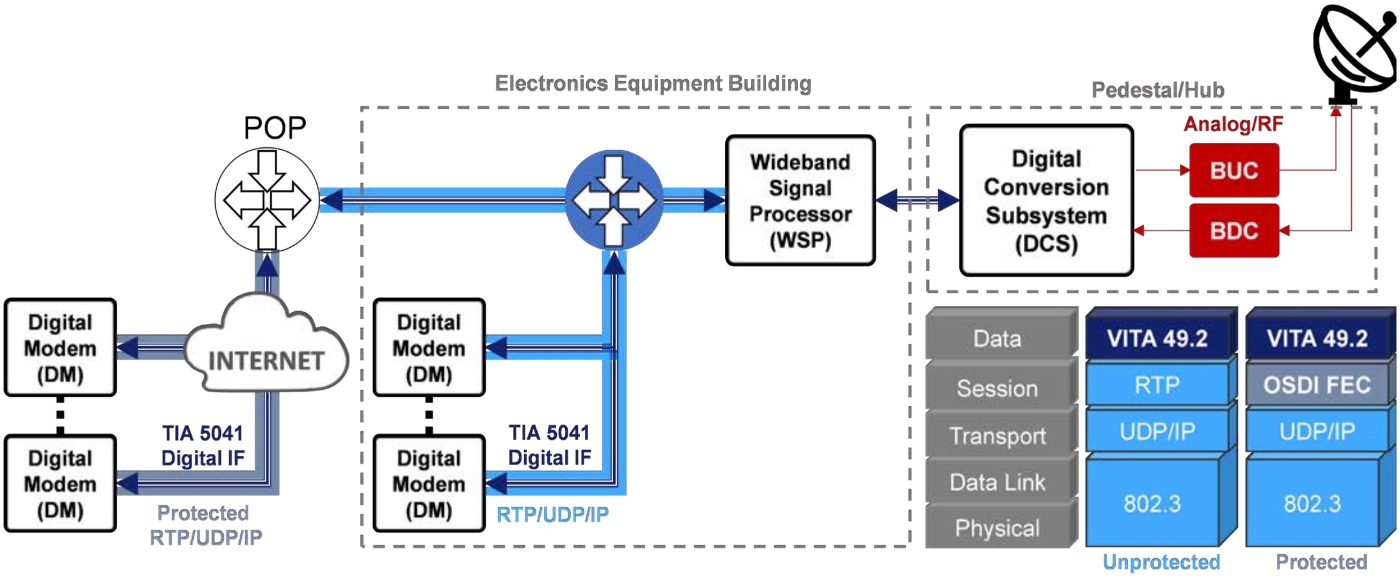

Figure 2-6: TIA 5041 Architecture [22] Centers Around the DMs, WSPs, and the DCSs.

due to technical issues, limited industry ownership, and industry timing. However, TIA 5041 was not a loss and is used to influence the Army in the process of developing its Enterprise Digital IF Multicarrier (EDIM) Modem program [23].

2.7 SUMMARY AND CONCLUSION

We summarized how the ground segment drives several key demands—specifically, drivers created from the PMB and LSS. Traditional modem designs gave rise to the barrier of integrated wares because access to FPGA was necessary for waveform digital processing. SDR architectures have split modem design into two functional components for RF front ends and waveform processing. With the adoption of SDR architectures, VITA 49.2 was created as a framework for how to represent digital samples within data packets. TIA 5041 was the DoD’s first attempt to standardize digital IF base SATCOM networks. In the next section, we discuss how digitization satisfies the key drivers.

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SECTION 03

DIGITIZATION OF SATCOM NETWORKS

3.1 INTRODUCTION

Section 1 defined digitization as the replacing of the analog L-band IF interfaces with a digitized version called digital IF. The background sections showed how SDR architectures influenced modems to be divided into three new components—digital IF modem, digital IF protocol, and the edge device. Figure 3-1 shows these components that form digitization in the larger scope of the digital transformation. We begin by describing how the digitization of SATCOM networks will meet the key demands of the ground segment. Next, we discuss the current applications using digitization and EDIM specification's call for a digitized SATCOM network. We close with a discussion on the current challenges to digitization, specifically with the Digital IF Interoperability (DIFI) standard.

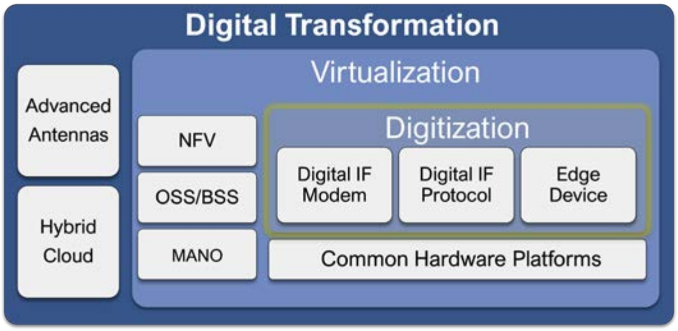

Figure 3-1: Transforming Into Digitized Architectures Requires Digital IF Standards, Edge Devices, and Digital IF Modems.

3.2 DIGITIZING THE GROUND SEGMENT

When the three components of digitization are applied to the ground segment, it separates the ground segment into three layers: (1) the digital IF modem bank (DMB), which is a bank of digital IF modems that transmute data signals between IP data bits and digital IF streams; (2) the digital IF local area network (LAN)/wide area network (WAN), which transports packets of digital samples using an IP network and interoperability/connectivity between all digital IF modems and edge devices using a standard digital IF protocol over the digital IF IFL (DIFL); and (3) the edge devices, which transmute signals between digital IF and RF transmission system. These layers are shown in a digitized ground segment in Figure 3-2. The digitization of the ground segment meets many of the key demands through the DMB, digital IF LAN/WAN, and edge devices. Table 3-1 presents a summary of how digitization meets the key demands.

3.2.1 Digital Modem Bank

In the DMB, no specialized RF front end is required in the digital IF modem. Additionally, the digital IF protocol provides interoperability between the digital IF modem and edge device. With these features, digital IF modems can be deployed using commodity rackmount servers that enable common hardware. Through common hardware, waveforms are not dependent on specific hardware and, thus, hardware/waveforms may be separated. In this separation paradigm, vendor lock is more difficult to accomplish since modems are not vertically integrated as before. Additionally, after common hardware is deployed, adding, removing, and changing or updating waveforms does not necessarily require a hardware replacement. Consequently, freedom from vertically integrated hardware/waveforms

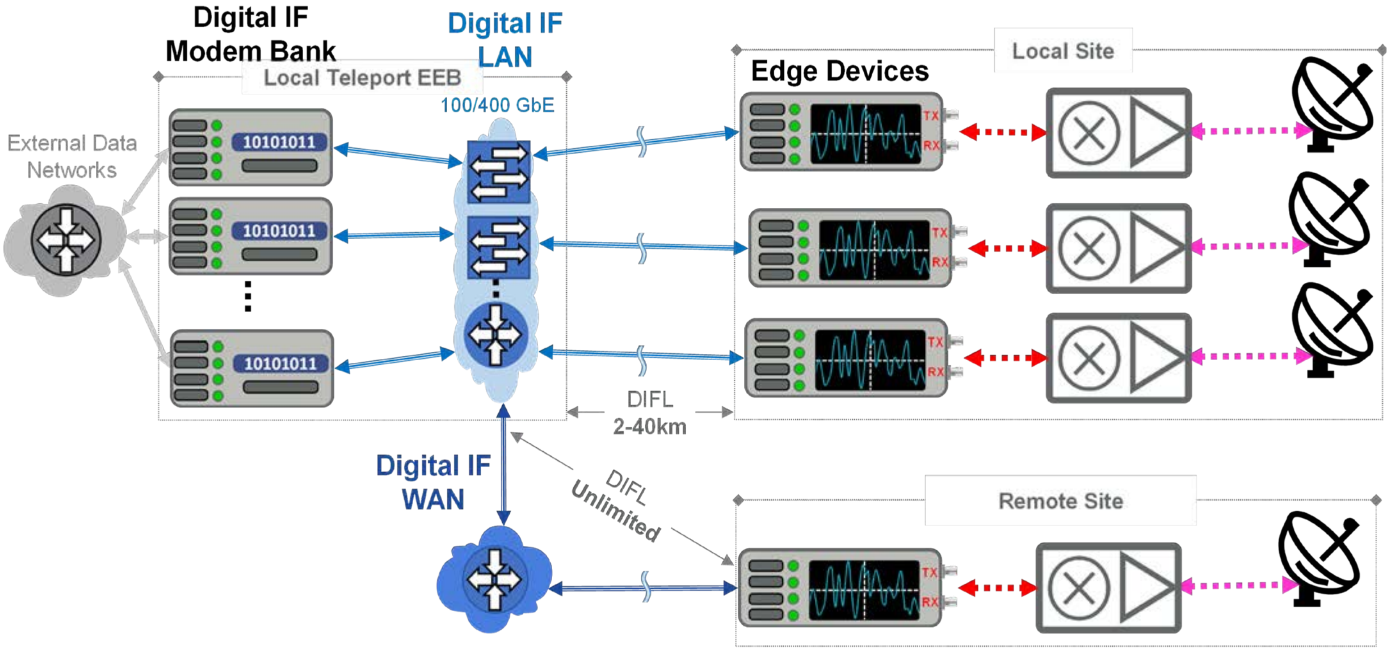

Figure 3-2: The Digitized Ground Segment Replaces the Proprietary Modem Bank With the DMB and the LSS With IP Networking Equipment and Edge Devices.

increases network sustainability. Since any digital IF modem hardware can replace any other digital IF modem hardware, there is no longer a need to make unique hardware redundancy and, thus, resilience increases. Under common hardware, waveform flexibility intrinsically increases modem/terminal agility and computational density/efficiency of the DMB since hardware can be consolidated.

3.2.2 Digital IF LAN/WAN

In the digitized ground segment, the LSS is replaced with the digital IF LAN/WAN and edge devices, which use IP networks based on COTS routers and switches. While digital IF does require a significant amount of bandwidth to represent data bits as samples, COTS IP network current capital costs are roughly equivalent to that of the LSS. Additionally, IP network costs are continually declining with capacity continually increasing, while LSS systems are reaching capacity limits [24]. In an IP network, port/capacity increases can be as easy as connecting additional switches/routers while modems and edge devices remain fully connected. For routing, digital IF modems and edge device digital IF streams only require IP addresses for their destinations. Furthermore, standard IP network equipment is already available for 100 GbE, and quad small form pluggable 28 transceiver transmit ranges are between 2 and 40 km. Using these larger transmission distances, digitized ground segments significantly increase geographic diversity of available teleport resources through the LAN. Also, the distance between the DMB and edge devices is unlimited when using DIFL WAN transport. Finally, while movement to 400 GbE does require different equipment, migration and transmission ranges all support sustainable IP networks for many decades to come.

3.2.3 Edge Devices

Edge devices meet many of the key demands of SATCOM networks. An interoperable digital IF protocol enables lower barrier to entry and a competitive market, which will drop costs and prevent vendor lock-in. While there will be a basis of must-have functionality, there will be little to differentiate competing vendors other than price. Thus, edge devices are likely to become more commodity

Table 3-1: Key Drivers Meet Through SATCOM Digitization

Key Demands	Digital IF Modem Bank	Digital IF LAN	Edge Devices
1: Freedom From Vendor Lock-in	No RF front-end processing required, and digital IF interoperability allows use of common hardware, which separates hardware and waveform vendors.	Enables digital IF modems, edge devices, and switching from LSS to COTS IP networking hardware.	Interoperability requirement and waveform removal lowers barrier to entry, creates competitive market, and enables drop-in replacements.
2: Reduction in TCO	Move to common hardware reduces number platforms to manage.	IP-based capital cost is equivalent and dropping, with operations simplified.	Low development entry barrier price for edge devices will drop rapidly.
3: Ground Segment Sustainability	Hardware/waveform separation allows migrations to different waveforms without hardware replacement.	IP-switched networks' capacity growth is modular; newer equipment has long range and high bandwidth. Logistics are made simple through COTS hardware.	Edge devices are flexible for any waveform.
4: Terminal/Modem Agility	Waveform flexibility increases agility.	Increases band/constellation flexibility as well as diversity gain options.	
5: System Agility/ Resiliency	Common hardware allows flexible redundancy to large pool of hardware.	Scalable geographic diversity using WAN capacity and equipment consolidation flexibility.	
6: High Computational Density/Efficiency	Common hardware moves the need to maintain unique sets of equipment, increasing density/efficiency.	N/A	N/A

components since there is lower barrier to entry to develop these devices. Additionally, with an interoperable protocol, vendors' hardware could act as drop-in replacements for each other, preventing any vendor lock-in. Together with digital IF LAN/WAN, edge devices provide band/constellation/antenna site flexibility, which increases modem agility and resiliency.

3.3 CURRENT AND FUTURE APPLICATIONS

3.3.1 Digitization and Software Receivers

While digitization has still not been widely adopted by the SATCOM industry, there have been some niche applications for software receive waveforms. The first applications for digitization in the satellite industry have been sold to small satellite operators for Earth Observation (EO) applications. Around 2014, many small satellite startups were formed due to removal of entry barriers, such as lower component and launch costs for creating small satellites [25]. However, costs constrained the ability for these small satellite operators to build their own ground stations. Consequently, many of waveforms for command and control were common in software form. Additionally, some customized ground stations have been built using USRPs and GNU Radio for collecting weather data. Similarly, the processing bandwidth of these systems is small (50–100 MHz), and the computational resources used for modulation and decoding have low complexity. Thus, a software-based waveform, leveraging digitizers, was an ideal solution to support these applications [26]. Furthermore, when Cloud computing companies built out their global networks, they continued to extend connectivity through satellite.

Leveraging their existing and available infrastructure, software waveform processing, and newly available digitizers, network operators (Cloud computing and satellite network operators) began offering ground station-as-a-service (GSaaS) for satellite operators. Figure 3-3 shows an illustration of a GSaaS architecture. GSaaS enables satellite operators access to their satellite data without the need for building out their own ground station infrastructure. Using an edge device (in this case, used in a receive-only configuration), network operators collect digital sample data based on the satellite ephemeris, ground station location, and frequency for the satellite operator. The edge device collects digital samples and transports them using a proprietary digital IF protocol to the network operator's storage and processing systems. The digital samples are stored, sorted, prepared, and stored by the network operator for delivery to the satellite operator. Satellite operators are then able to retrieve their data or process it in the Cloud using their software waveform or download the data for their own local processing. In EO, final processing creates data products for the satellite operators' customers.

3.3.2 Enterprise Digital IF Multicarrier Modem

While commercial industry has deployed edge devices for primarily receive applications, there is yet to be a full duplex SATCOM digitized ground segment. The U.S. Army, through Product Manager, Wideband Enterprise Satellite Systems, has released two RFIs for their EDIM modem specification [27], which has a specification of a digital IF hybrid modem. An illustration of an architecture supported with an EDIM modem in the DMB is shown in Figure 3-4. It is most likely that the Army, through the EDIM program, could deploy the first digital IF modem. The EDIM modem specifies many electrical, RF, and waveform requirements for the appropriate components but also digitized modem components.

In terms of digitized ground segment components, the specification suggests edge devices and a novel network element called the digital IF aggregator/de-aggregator (DAD), which combines/divides digital IF signals in the transmit/receive direction, respectively. In other words, the DAD is the digital equivalent of analog combiners/splitters. Through the DAD, sets of digital IF streams can be rerouted to a remote site using the digital IF WAN. This contrasts with Figure 3-2, which routes individual digital IF from modems rather than a combined digital IF stream from a DAD. Additionally, in any digitized ground segment, there are new requirements for routing digital IF streams for satellite handoff, transponder load balancing, resilience, and diversity. Finally, the EDIM specification also called for the DIFI protocol for all digital IF transport.

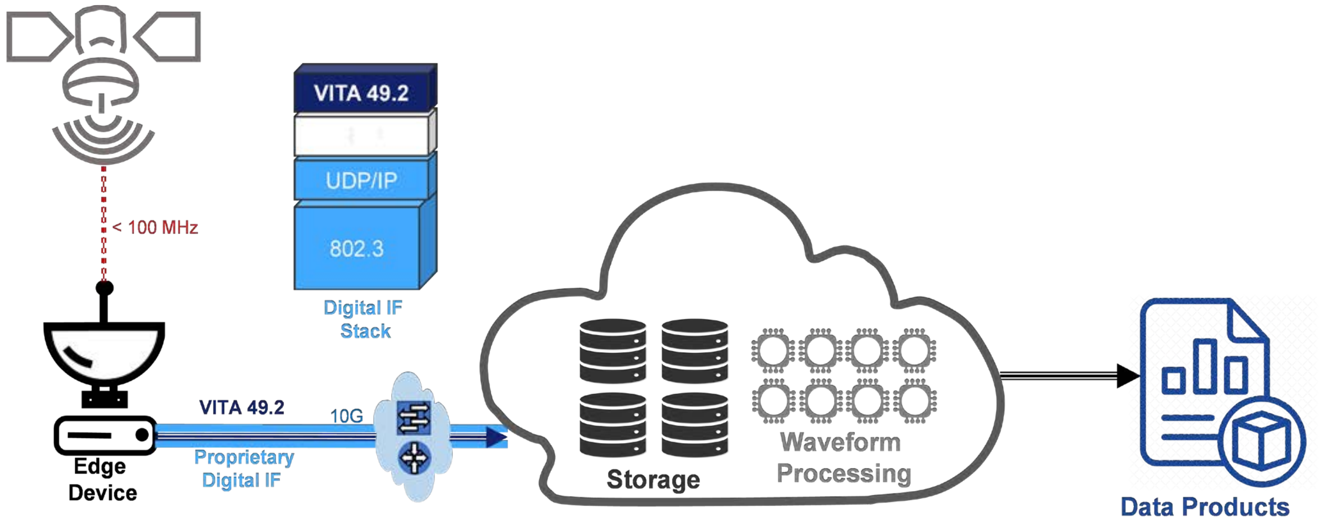

Figure 3-3: Current Digitization Solutions Are Primarily Oriented Around a Waveform Receiver to Create a Ground Station as a Service Application.

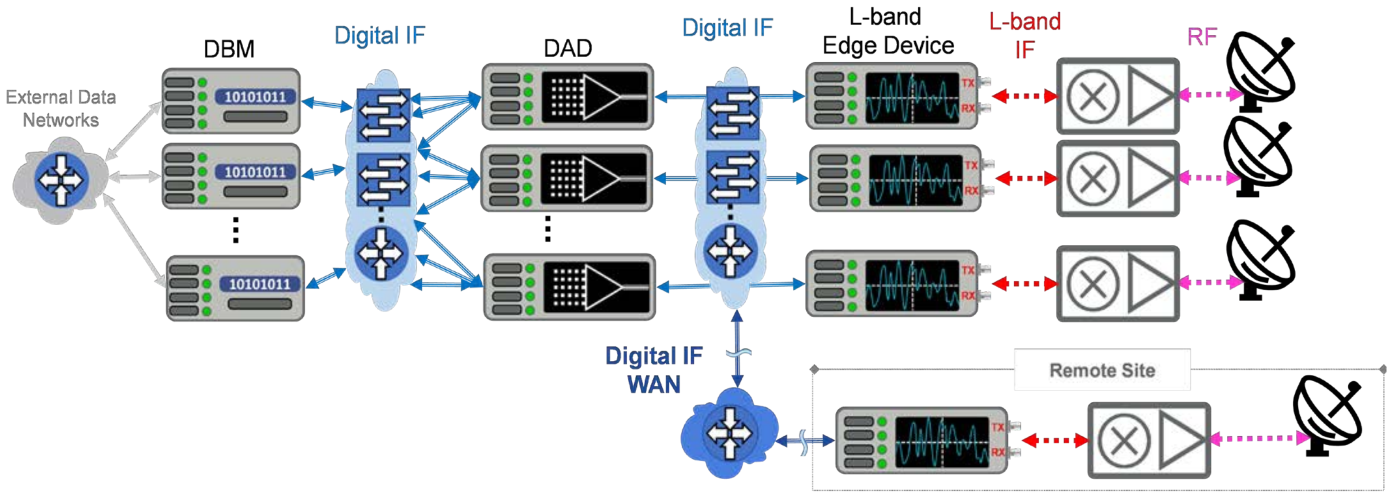

Figure 3-4: EDIM Specification Architecture Adds the DMB, DAD, and Edge Devices Into the SATCOM Architecture.

3.4 DIGITIZATION CHALLENGES

Digital IF protocol is at the root of meeting many key demands since it enables creation of and interoperability among digital IF modems and edge devices. The recently formed DIFI consortium [28] released an initial standard in August 2021. Figure 3-5 illustrates the protocol stack of DIFI and the associate protocol relative to the Open Standards Interface (OSI) protocol stack. Currently, the DIFI v1.0 standard is little more than a skeleton, specifying a few VITA 49.2 packets over user datagram protocol (UDP) and 802.3 standards. In future versions, DIFI will specify important transport features needed for reliable packet delivery. Specifically, the session layer will need to address reliable transport of UDP packets.

To address the needs for reliable transport protocol, there are two challenges that DIFI will be required to solve:

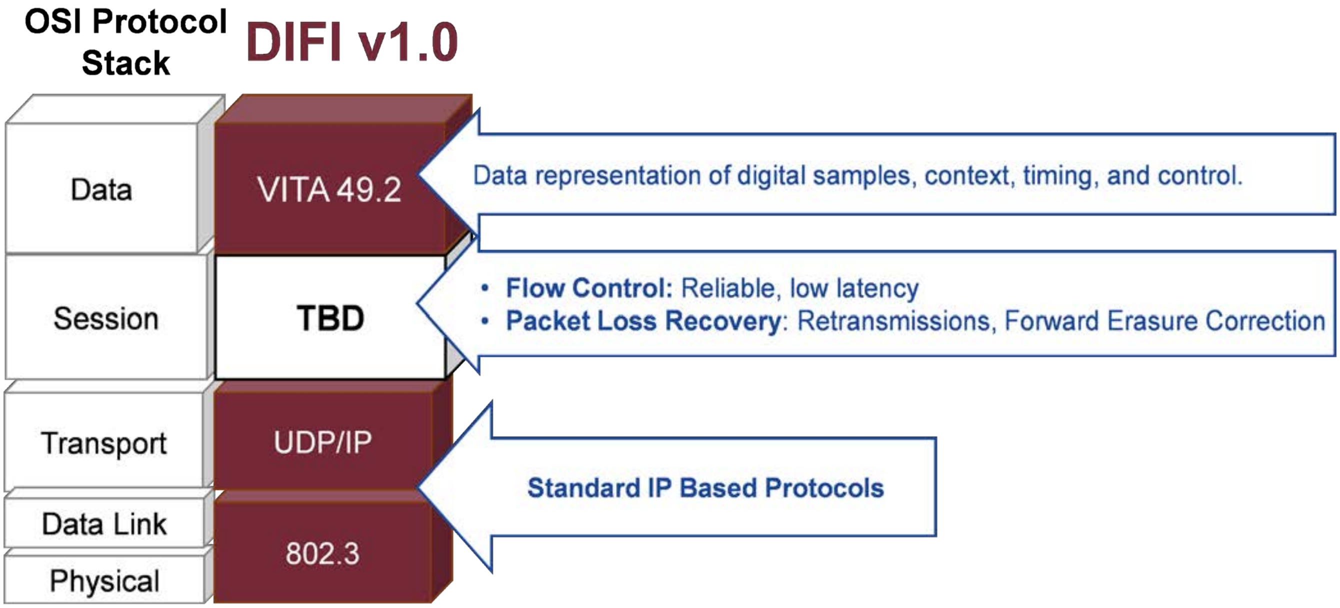

Figure 3-5: DIFI v1.0 Uses Two Context and One Signal Data Packet Type Over UDP.

- **Flow Control** – Without flow control, overflow and underflow of buffers will cause loss of modem lock. Digital IF senders and receivers require packet rate metering and management of recovery buffers to cope with network jitter.
- **Packet Loss** – Packet loss across WANs or even LANs can be caused by router/switch congestion. Additionally, if there is link degradation, packets can also be dropped by routers/switches.

3.4.1 Flow Control

In digital IF streams, flow control is important to prevent underflow and overflow of receive packet buffers. Buffer-flow problems cause waveform discontinuities, which will unlock SATCOM links and potentially cause adjacent channel interference.

An illustration of the buffer-flow problem is shown in Figure 3-6. In an ideal flow case and assuming no packet loss, the depth of the RX packet buffer is large enough to handle any packet jitter (i.e., variation in packet delay caused by switch/router congestion). Overflow events (Figure 3-6, middle) are caused when the digital IF TX packet production rate is faster rate than the RX packet consumption rate. When the RX packet buffer is full and packets are still being sent by the digital IF TX, those packets will be dropped. In the underflow case (Figure 3-6, bottom), the digital IF TX does not send packets or there is a significant network delay. In this case, the digital IF RX processes all the packets in the RX buffer until there are no more packets to process. Buffer-flow events are analogous to live-streaming video, where the overflow case is analogous to frame skipping and underflow case is analogous to locked or stopped video. All buffer-flow events can cause the far side modem to become unlocked and will require a waveform reacquisition.

To overcome the buffer-flow problem, DIFI should provide accurate timing of packet delivery through timestamps and clock drift correction. When using timestamps, the sender and receiver time stamp each packet according to its required processing time. However, since the sender and receiver may have unsynchronized clocks, a time drift of a few microseconds occurs every minute. Drifting over many days can cause buffer-flow problems, which cause buffers to slowly underflow or overflow. In the case where both the digital IF modem and edge device receive clock information from the same source, this not such an issue. However, if the digital IF WAN network is used for long-range transport drift, correction will be required.

Without adequate drift correction, buffer-flow problems will degrade SATCOM networks' perfor-

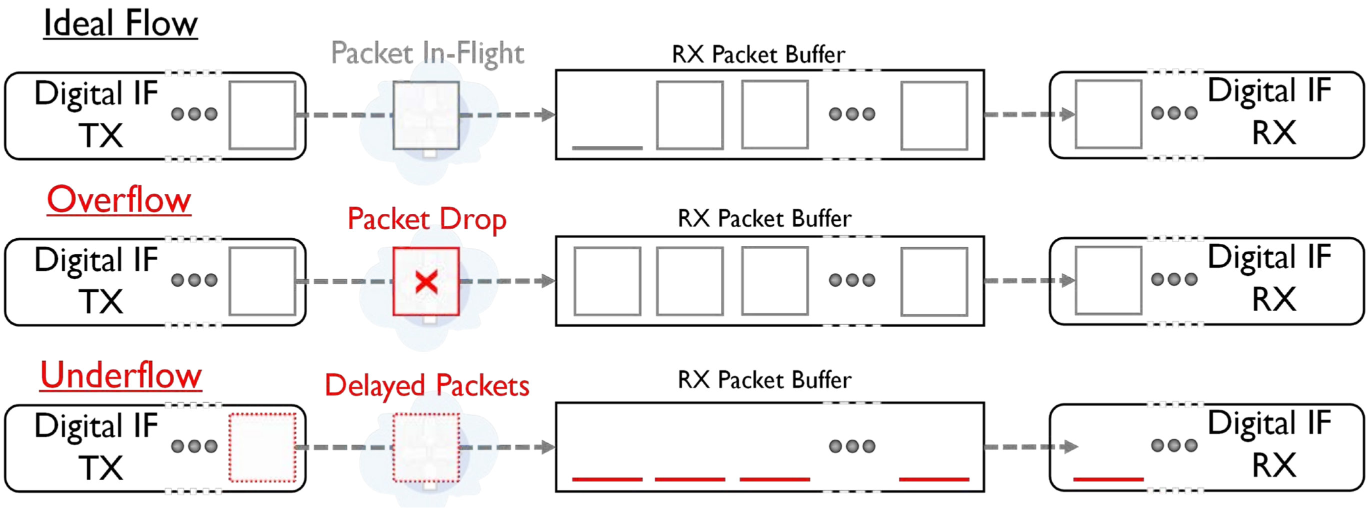

Figure 3-6: The Buffer-Flow Problem Occurs When Digital IF RX Buffers Are Overflowed or Underflowed, Which Can Cause Modems to Become Unlocked.

mance and reliability. Through drift correction, every packet delivery time can account for these fluctuations in timing. To calculate the drift, DIFI could compute the time difference between when the packet was expected, relative to an established base time, and the average round trip time (RTT). If the receiver continually monitors RTT and using periodic ACK (Acknowledge) and ACKACK responses from the sender to make this measurement, the RTT can then be used to correct the clock drift. Figure 3-7 shows an example of the ACK and ACKACK messages.

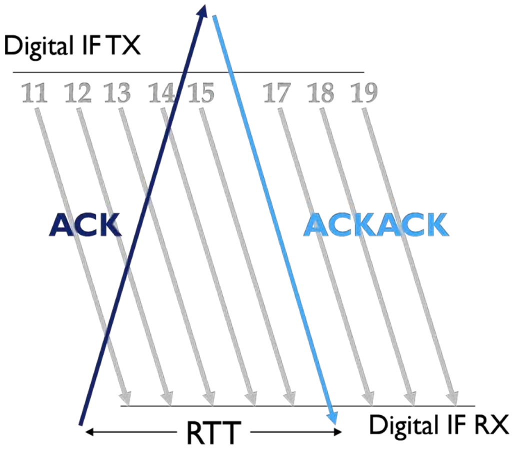

Figure 3-7: RTT Measurement Using ACK and ACKACK Messages Provides a Constant Periodic Measurement of RTT to Correct Clock Drift.

3.4.2 Packet Loss

Automatic repeat requests (ARQs) and retransmissions are a common approach to combat packet loss. With ARQs, packets are numbered and sent in order. That way, if a numbered packet is missing, the RX notifies the TX to resend the missing packet. However, this approach requires packets to be held in the receive buffer (i.e., delayed) so that if packets have been lost, they can be retransmitted before the RX processes them. Retransmission for live-streaming video recommends that these buffers be on the order of 3× the RTT [29]. Assuming an average RTT of 100 ms, receive buffers could add 300 ms of additional latency. For comparison, a LEO/GEO satellite would have ~40/600 ms of delay, respectively.

Longer latency can impact time-sensitive data, which impacts user quality of experience. Thus, an approach would be to minimize the need for retransmissions, which would minimize latency. To this end, a superior approach would be to use packet forward erasure correction (FEC) with hybrid automatic repeat request (HARQ) to minimize latency. Unlike traditional FEC for bit error rate control, erasure codes reconstruct data blocks when enough of the encoded data is received. Figure 3-8 shows an example where *k* source data packets (i.e., equivalent rows of data or parity blocks) are encoded into *n-k* parity packets by applying FEC algorithm to each column. When ***ANY*** *k* packets, data, or parity are received, the original data block can be reconstructed. Therefore, in the event of packet loss, any parity packet can be sent until *k* total packets (data + parity) are received. Furthermore, in the event of no packet loss, no additional parity will need to be sent. Three of the data packets were lost due to packet loss and required three additional parity packets to completely reconstruct the data block.

Unlike standard ARQ methods which resend specific missing packets, HARQ only requests more packets when they are needed for reconstructing the data block (i.e., until *k* packets are received). This technique optimizes latency in networks with variable packet loss and is useful for broadcast transmissions. The signal flow for a HARQ protocol is shown in Figure 3-9. In this example, the transmission is initiated by only sending data packets for the first block. In this transmission of the data packets, there is some loss. This packet loss is calculated by the digital IF RX, which sends an ACK message to communicate the loss to the digital IF TX. The digital IF TX calculates additional parity packets required to overcome measured packet loss and sends the required parity packets. After receiving this set of parity packets, *k* packets are received to decode the block, and the ACK for the block is sent. The next block is sent with data and parity and overcomes the current packet loss.

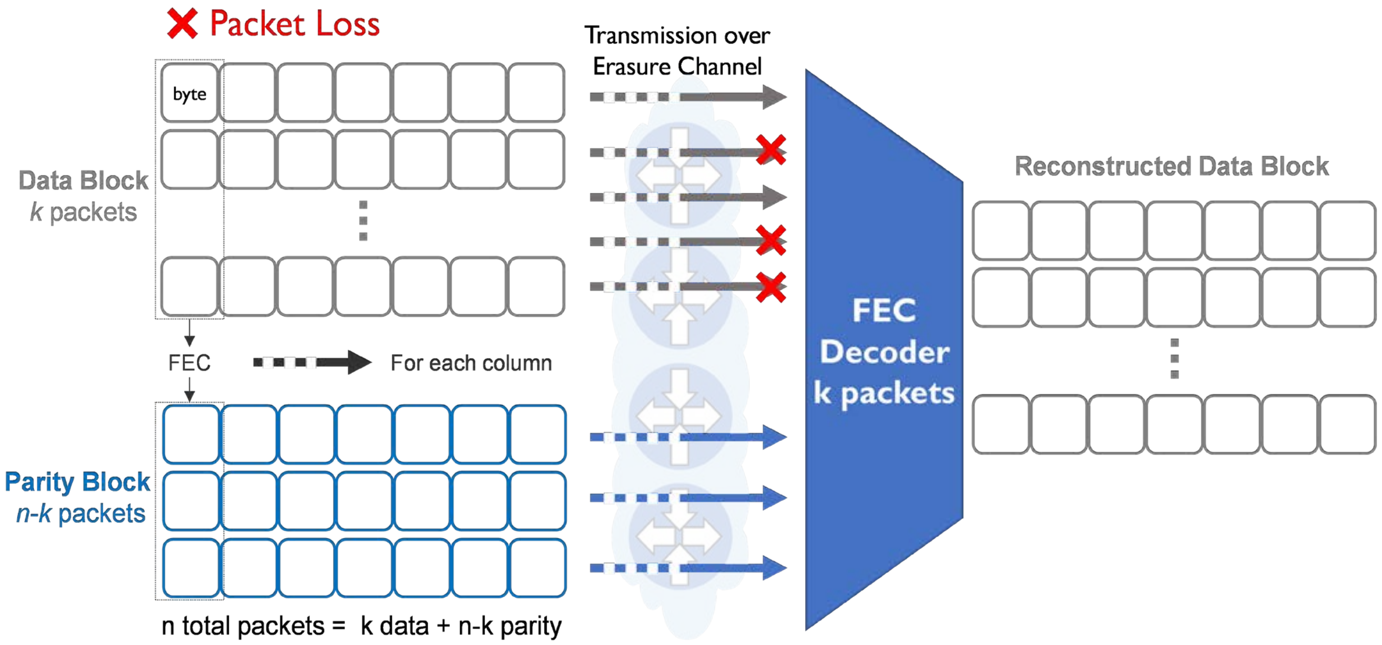

Figure 3-8: Packet Erasure Codes Allow Source Data Reconstruction When *k* of *n* Encoded Data Blocks Are Received [30]. Each Column Is Encoded With an Erasure Code, and Rows Are Sent as Individual Packets.

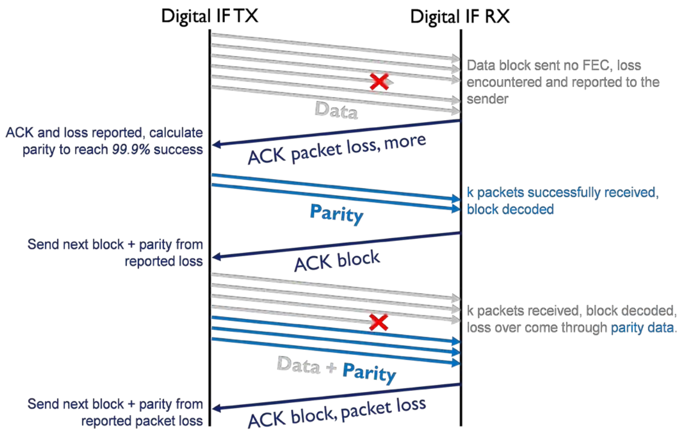

Figure 3-9: HARQ Mechanism ACKs Are Sent to Indicate the Need for Additional Parity to Report Loss Rates for Parity Calculation.

3.5 SUMMARY AND CONCLUSION

Digitization of the ground segment satisfies many of the key demands. The introduction of the digital IF interface created digital IF modems and edge devices, which consolidated functionality to enable common hardware and reduce vertical integration. This architecture reduces vendor lock and simultaneously reduces hardware costs. Additionally, network agility and resilience are increased by allowing any digital IF modem to dynamically access any edge device. Current applications for digitization have focused on software-based receivers for LEO EO applications. These applications have been useful for on-demand receivers to support GSaaS. The EDIM program is poised to create the first SATCOM digitized ground segment. While DIFI is poised to become the digital IF standard protocol, there remain challenges of addressing the need for flow control and packet loss.

SECTION 04

VIRTUALIZATION OF SATCOM NETWORKS

4.1 INTRODUCTION

In this section, we introduce and discuss virtualization from two different perspectives. First, we introduce the basic concept of virtualization and how it is used to abstract functionality away from purpose-built hardware. Second, we refer to virtualization as the second major component of the digital transformation. From this second perspective, shown in Figure 4-1, virtualization as a component has its own dependencies. We introduce the dependencies of the virtualization component, which include network function virtualization, operational support systems business support systems (OSS/BSS), and management and network orchestration (MANO). Additionally, migration to common hardware platforms is also the literal basis for virtualization. We close with a short summary of emerging technologies that seek to fill the gaps of these dependencies.

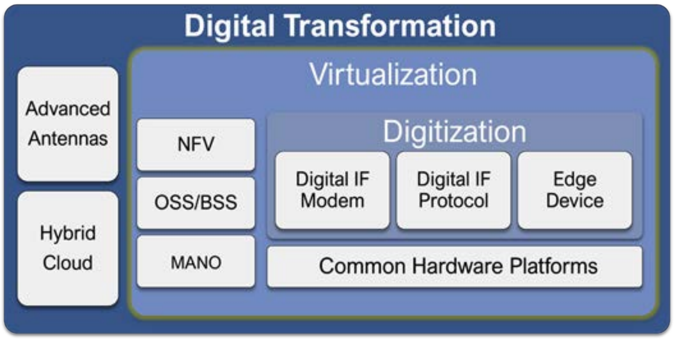

Figure 4-1: Transforming Into Digitized Architectures Requires Digital IF standards, Edge Devices, and Digital IF Modems.

The need to promptly evolve the SATCOM network architecture depends on virtualization. Virtualization, in our first perspective, refers to the abstraction of computing resources from the specific hardware to create a virtual computing environment. Similar to virtual reality, multiple, independent, virtual computing systems are instantiated to behave like independent computers or servers, which operate on common hardware. Virtual computing environments can share the same physical hardware resources, allowing more efficient and flexible use of computing resources. Figure 4-2 shows an illustration comparing traditional computing (shown left) with a virtualized computing infrastructure using a hypervisor (shown right) [31]. With virtualization, a panoply of applications and functions is consolidated onto common hardware through a hypervisor. In Section 3 (Digitization of SATCOM Networks), we explained how the digitization component migrated proprietary-based systems to common hardware platforms. More precisely, common hardware is the idea of commodity hardware platforms approved/validated for virtualized operations. This includes platforms that conform to standards, such as DIFI for digital IF, and provides adequate computing resources for the required functions like hypervisors.

Most importantly, virtualization separates application and hardware vendors, which helps eliminate the need for proprietary, purpose-built hardware. Leveraging virtualization, SATCOM network operators can reduce TCO, increase terminal/network

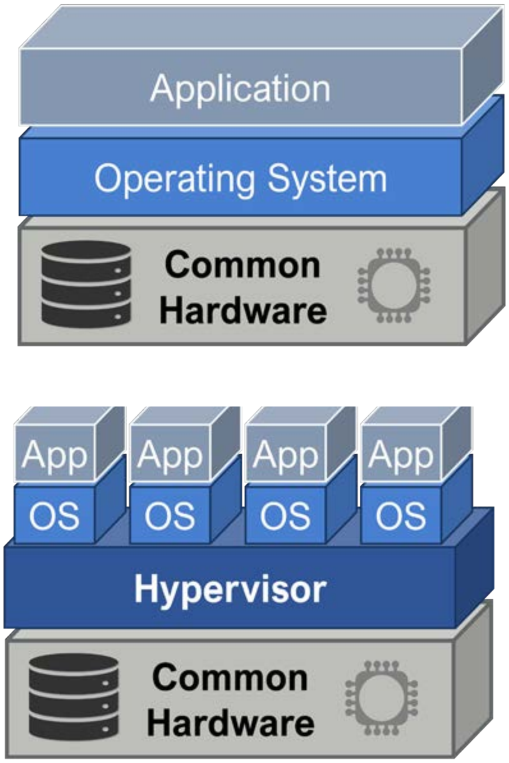

Figure 4-2: Traditional Computing System (Top) and Virtualized Computing System Using Hypervisors (Bottom).

agility, and, most importantly, accelerate the speed of innovation by separating applications from hardware. Virtualization has made revolutionary changes to the way business is done in computing. X-as-a-Service (XaaS) business models have created new opportunities and fostered innovation by eliminating the integrated ware barriers and allowing third-party software entrants.

4.2 NFV

MNO networks (e.g., Verizon and AT&T) have been populated with a large and increasing variety of proprietary hardware appliances to perform the functions required for operating cellular radio access networks. Migrating to next-generation standards for MNOs became more difficult due to space and power availability for the many proprietary-based appliances. As cellular technology rapidly progressed with every generational upgrade, MNOs were required to replace all network elements in their radio access networks since each network element was contained in one box. This monolithic architecture created upgrade cycles that were rigid, expensive, slow, and complicated [32]. Additionally, replacing end-of-life appliances required complicated migration plans, increasing additional costs with managing networks.

To overcome these many problems, MNOs embraced virtualization of these network functions to create a concept called NFV. NFV is the approach of stringing together several virtual machines together to form a service chain, where each virtual machine performs a specific network function. Virtualization is not the same as NFV, but the first step of NFV is to virtualize the infrastructure. The second step is to wrap the infrastructure with a layer that provides service-driven virtualized infrastructure. In pursuit of NFV, the mobile network developed standards to create an ecosystem where pure software entrants can deploy their own virtual network functions on common hardware [33]. In this new architecture, MNOs used commodity hardware and deployed network elements as virtual machines, abandoning the one-element-per-box paradigm. Figure 4-3 shows a simplified NFV reference architecture.

In this NFV reference architecture, there are four main logical components:

1. **Network Function Virtualization Infrastructure (NFVI)**
   The NFVI component represents all hardware and software components that support the deployment of virtualized network functions (VNFs). This layer includes processing, storage, and networking that form the basis for the VNFs.
2. **Virtualized Network Function (VNF)**
   The virtualization component is used to abstract the underlying infrastructure layer into VNFs, which can be deployed as software modules. Generally, this abstraction is provided using hypervisors and virtual machines (e.g., VMWare, OpenStack, etc.). However, containerized software solutions (e.g., Docker and Kubernetes)

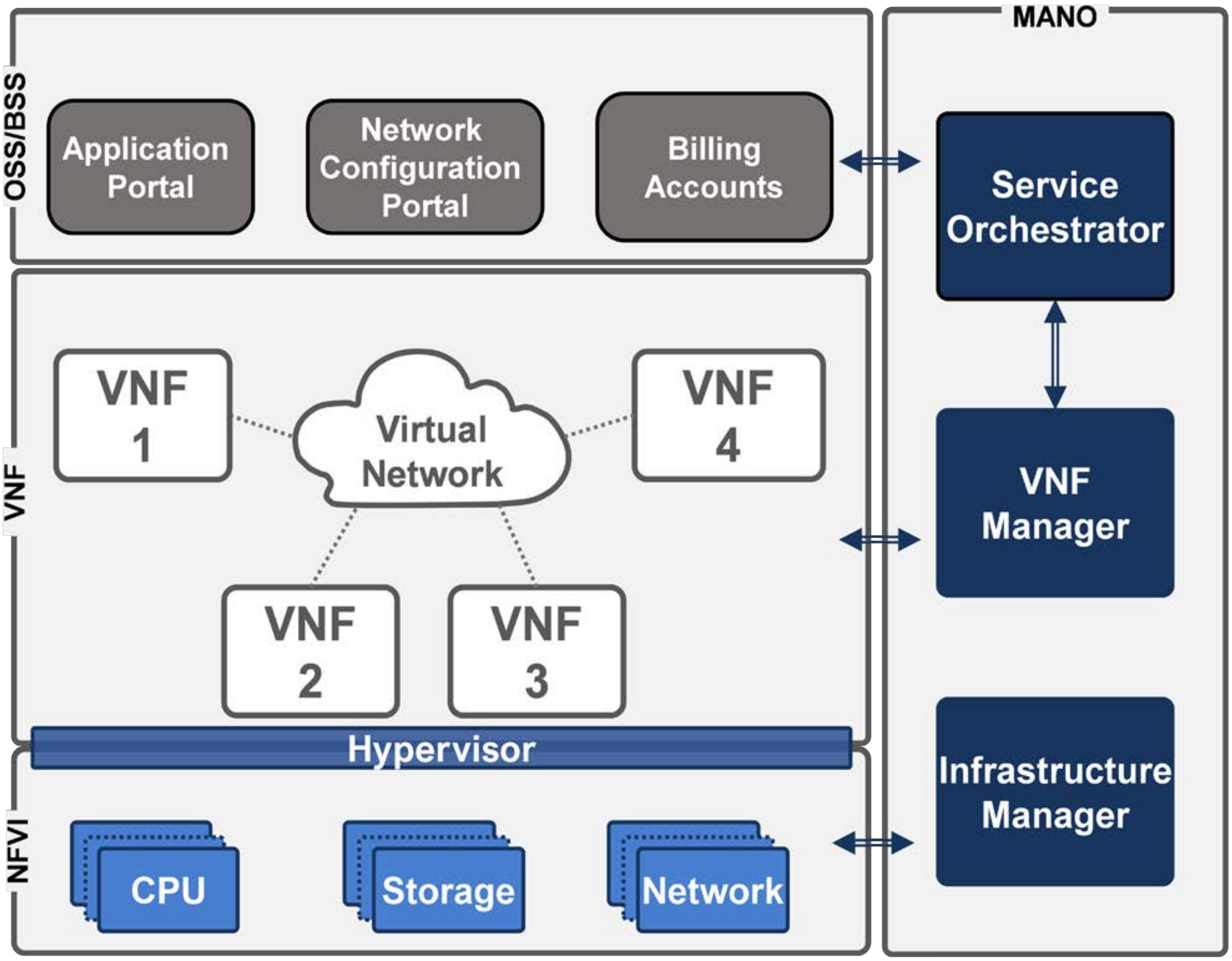

Figure 4-3: Network Function Virtualization Reference Architecture Adopted by the MNOs.

have found applications in this area as well. Virtualization in the network domain works similarly by virtual networks (e.g., virtual LANs and software-defined networking [SDN]).

3. **Operations and Business Support Systems (OSSs/BSSs)**
   The business service component refers to the representative functions that allow the network operator supporting their business functions. The OSS/BSS orders services from the management and orchestration functions. This system is used to order, deploy, and monitor network services.
4. **NFV Management and Orchestration (MANO)**
   The NFV MANO component has the tasks of managing and deploying networks, VNF deployment and termination, and infrastructure resource assignment and optimization through the service orchestration, VNF manager, and infrastructure manager.

With the move to the NFV, the MNO equipment vendors market has changed dramatically from a handful of proprietary systems vendors to an ecosystem of hardware vendors and VNF developers [34]. Additionally, there are significant development efforts in developing open-source projects for different VNF functions within the MANO. While these principles are now common for MNOs, they are starting to show promise in SATCOM networks as well.

4.2.1 SATCOMaaS Architecture

XaaS architectures provide users with flexible, customizable, on-demand resources for performing services. As such, we propose that a SATCOMaaS architecture needs to leverage an NFV architecture, which would provide flexible, customizable, and on-demand SATCOM services. Figure 4-4 shows how the NFV architecture could support a SATCOMaaS. The NFVI uses a digitized SATCOM network architecture, which creates common hardware platforms. The DMB and edge devices then serve as computing resources that can be used to enable VNFs or, in the case of SATCOM, VNFs.

The VNFs, which would be deployed logically in the VNF layer, could include virtualized waveforms, QoS, antenna control units, WAN acceleration, encryption, and data compression applications. DMBs could host a variety of additional functions, such as spectrum monitoring and test signal generation. Network management systems and enterprise management systems could also be deployed on unused resources, from the DMB or other resources, to help manage network configurations. Virtual hosts on edge device platforms would be used primarily for coordinating the management of spectrum and digital IF network resources. Additionally, these virtual hosts could digitally combine/split carriers and route to antenna ports.

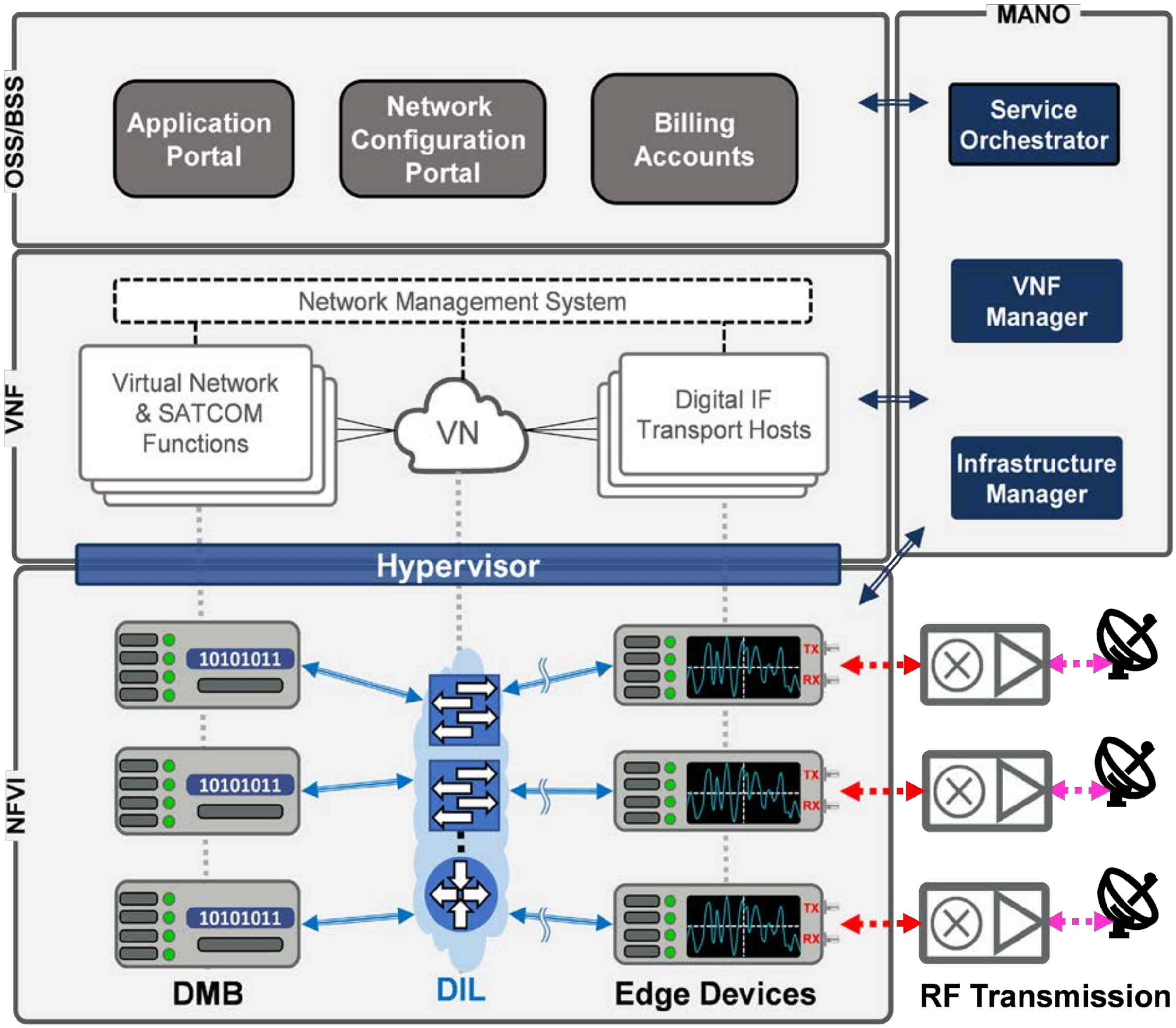

Figure 4-4: SATCOMaaS Provides Network and Enterprise Agility.

4.2.2 OSS/BSS and MANO Operations

While the introduction of a SATCOMaaS architecture creates additional flexibility and capability, it also introduces a new dimension of network management. In this new paradigm, SATCOM services are ephemeral and dynamic, i.e., their resources are assigned to services and reassigned as needed. To support this dynamic reassignment, the OSS/BSS and MANO system process user service orders to deploy these dynamic services. Figure 4-5 illustrates how the OSS/BSS initiates the order of a service chain. In the first step, the operator processes a service order of a specific type of SATCOM services that needs to be deployed. The OSS/BSS processes this interaction and then forwards this request to the MANO system, which allocates/configures the hardware resources and virtual functions required to deploy the service chain. While not shown, this could also initially include a network management system for more complicated deployments. After the service chain is deployed, the confirmation to the user operator is passed through the OSS/BSS. At the conclusion of the service order, the MANO system will terminate the VNFs and free resources for new services.

4.3 SATCOM VIRTUALIZATION AND MEETING KEY DEMANDS

For the reader's convenience, the following key demands from Section 1.2.2 are repeated here. With better context from this section, we encourage the reader to review these again, with a new understanding of scope of virtualization.

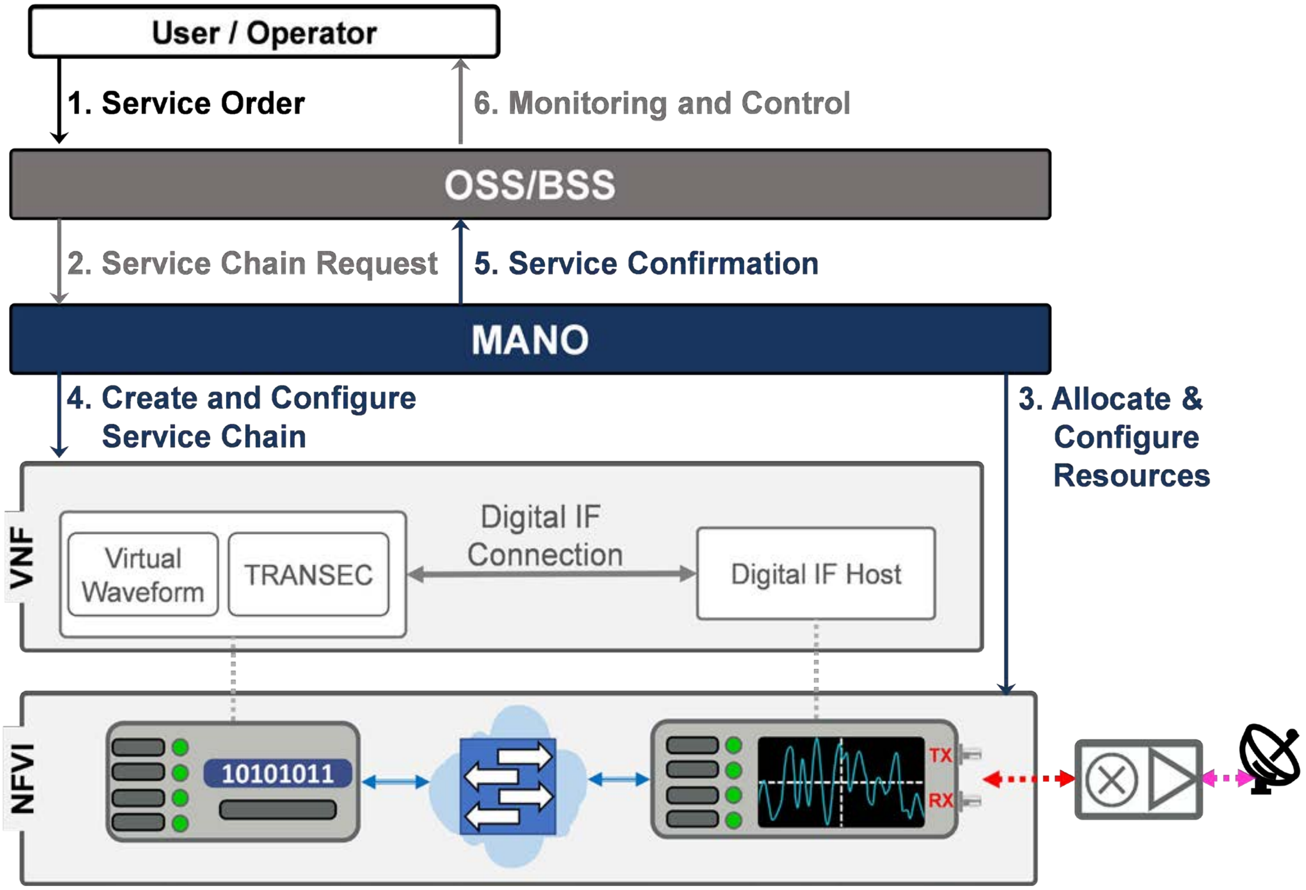

Figure 4-5: OSS/BSS Deploys Virtual SATCOM Functions on Demand.

Key Demand-1: Freedom From Vendor Lock-In
Since virtualization untethers hardware from SATCOM functions, best-in-class SATCOM functions can be selected independently from distinct application vendors. In this new paradigm, application vendors could offer VNFs like the apps offered in smartphone ecosystems. Additionally, pure software entrants are encouraged to compete since there is no need to develop hardware to enter the market. Virtualized architectures accelerate speed of innovation by fostering a larger pool of competitors, where superior functions can be selected and deployed together.

Key Demand-2: Reduction in TCO
When VNFs are deployed, hardware migrations generally are turned into software migrations. Rather than replacing racks of purpose-built modems, migrations with virtualized architectures require only deploying new VNFs. Because common hardware can be used for multiple architectures, new purpose-built hardware does not need to be purchased or managed. Additionally, consolidation allows more efficient use of existing hardware resources, which can support a multiplicity of functions and simultaneously take advantage of hardware and software economies of scale enabled by larger telecom and information technology sectors.

Key Demand-3: Ground Segment Sustainability
When VNFs are deployed, hardware migrations generally are turned into software migrations. Rather than replacing racks of purpose-built modems, migrations with virtualized architectures require only deploying new VNFs. Because common hardware can be used for multiple architectures, the logistical footprint of multiple purpose-built hardware systems is no longer required. Additionally, with purpose-built modems, the design-integrate-deploy lifecycle is costly and time consuming. These lifecycles will stifle the deployment of new technologies. With a rapidly changing and diverse space layer shortening lifecycles, purpose-built systems will create evolutionary bottlenecks.

Key Demand-4: Terminal/Modem Agility and System Agility/Resiliency
The rapidly changing space layer requires the SATCOM network to quickly reconfigure itself to deploy new waveforms or capabilities and connect with multiple, different orbits. With VNFs, these functions can easily be prototyped, tested, and deployed, with minimal impacts to network hardware.

Key Demand-5: System Agility/Resiliency
With consolidation of hardware, data handoffs could occur between orbits, waveforms, and constellations. Leveraging existing infrastructure, on-demand services with VNFs can deploy flexibility. Additionally, with digital IF and virtualization, other different mission needs, such as information operations and electronic warfare (EW), could be served with the same equipment [18].

Key Demand-6: High Computational Density/ Efficiency
Virtualization allows consolidation of hardware, which leads to more efficient hardware utilization means reduction in SWaP. Purpose-built appliances, by nature of development, have only the computing capability required for their application. Purpose-built modems have compounded the complexities and costs of managing SATCOM networks. In an exponentially growing SATCOM market, managing purpose-built modems has scalability constraints due to rack space, power, and operation knowledge necessary for managing many different models and vendors. A network with N different modems means a network with N times more rack space, switching equipment, network cost, and complexity.

4.4 EMERGING TECHNOLOGIES

Emerging technologies in the virtualization of SATCOM fall into many different categories. Among the most significant are (1) virtual and containerized network functions (VNFs and CNFs), combined in different network services, and (2) management and orchestration solutions—NFV orchestrators and VNF managers. The following subsections briefly describe some of the key players and their roles.

4.4.1 VNFs/CNFs

- **Kratos** – Kratos OpenSpace is a family of solutions that enables the digital transformation of ground systems. Three product lines in the

OpenSpace family support a variety of paths, goals, and business models, including OpenSpace SpectralNet, OpenSpace Quantum, and the OpenSpace Platform. Kratos leverages key standards, such as Metro Ethernet Forum (MEF) Lifecycle Service Orchestration (LSO), YANG, and VITA 49.

- **Amerigent Solutions** – All Amerigent systems are built upon SOFTLINK, Amerigent's flexible and configurable software-defined architecture. SOFTLINK leverages a vetted library of modular, scalable software applications (called "Apps") to tailor and evolve system capabilities with minimal risk and cost. SOFTLINK's open architecture and open applications programming interface (API) enable Amergint Apps to be truly "platform agnostic," meaning Apps can run on premise (our hardware or yours), on virtual machines, in containers, or natively in the Cloud.

4.4.2 Management and Orchestration Solutions

- **ONAP (Open Network Automation Platform)** – ONAP is a comprehensive platform for *orchestration, management, and automation* of network and edge-computing services for network operators, Cloud providers, and enterprises. Real-time, policy-driven orchestration and automation of physical and virtual network functions enables rapid automation of new services and complete lifecycle management critical for 5G and next-generation networks.
- **OpenNFV (OPNFV)** – reduces time to integrate and deploy NFV infrastructure and onboard VNF/CNFs for those who supply components and those who operationalize these platforms. The OPNFV community does this by *implementing, testing, and deploying tools for conformance* and performance of NFV infrastructure, aligned with industry reference architectures. Overall, OPNFV can be seen as a platform based on open standards.
- **Amdocs NEO** – Amdocs' pre-integrated NFV SD-WAN package is based on the Cloud-native, open, and modular Amdocs Service & Network Automation platform (NEO). NEO is a unified yet modular platform that encompasses traditional service activation and fulfillment functionality, along with Cloud and NFV orchestration and advanced network automation capabilities. Leveraging ONAP components and service modeling practices, NEO empowers service providers to deploy and manage VNF ecosystems.

4.4.3 Edge Devices

- **Amerigent satTRAC** – satTRAC modems provide RF conversion and modem processing for tracking, telemetry, and control and payload links with support for all commonly used frequencies and waveforms. satTRAC modems offer extensive configurability and are compatibility tested with most GEO spacecraft buses and LEO small satellite radios. An ethernet-attached RF digitizer connects to the modem's software application running on commercial servers.
- **Kratos SpectralNet** – SpectralNet is a carrier-grade digitizer for assuring QoS and service-level agreements. SpectralNet provides the ability to transmit digitized data over a standard WAN without any distance limitations, maximize network performance for distributed transport with multi-cast capabilities, and optimize operations with a reduced infrastructure footprint and less expertise needed for antenna sites.

4.4.4 Other Supporting Virtualization Technologies

- **MEF LSO** – MEF LSO defines the reference points between key functions within the service provider and extending out to the enterprise and the Cloud. MEF standardizes these reference points, developing information models, business requirements and use cases, and data schemas, packaged within SDKs that enable developers to build open APIs to support each reference point. These APIs leverage work from the entire industry ecosystem, including ONF, tmforum, ONAP, and more. The LSO reference architecture incorporates seven reference points—two focus on customer-to-service-provider interactions, two focus on interprovider interactions (east-west APIs), and three focus on intraprovider interactions (north-south APIs).

- **OpenStack** – OpenStack is a Cloud operating system that controls large pools of compute, storage, and networking resources throughout a data center—all managed and provisioned through APIs with common authentication mechanisms. A dashboard is also available, giving administrators control while empowering their users to provision resources through a web interface. Beyond standard infrastructure-as-a-service functionality, additional components provide orchestration, fault management, and service management, among other services, to ensure high availability of user applications.

4.5 SUMMARY AND CONCLUSION

We introduced and discussed virtualization from two perspectives. The first perspective was just the concept of virtualization in general. The second perspective was the second major component of the digital transformation. The virtualization component of the digital transformation had several dependencies. The first dependency was the reliance upon common hardware, which was provided through digitization network of the ground segment. The other dependencies were with NFV, OSS/BSS, and MANO system frameworks. These dependencies allow service orders and translation of those orders into virtualized service chains. Those service chains comprise virtual SATCOM functions, which can be deployed on demand. We closed with a summary of how virtualization meets the key demands and current technologies used in SATCOM virtualization.

SECTION 05

ADVANCED ANTENNAS

5.1 INTRODUCTION

While most of this SOAR discusses modems and IF transmission systems, we have not discussed advanced antennas, which remain important because they are the method by which the ground segment interacts with the space segment. However, we note that a thorough survey on future SATCOM antenna systems could be its own SOAR.

In this section, we present existing antenna technologies for realizing multi-band, multi-orbit, and multi-beam capabilities. We first discuss new spectrum and constellations in the V band. Subsequently, we define multi-band, multi-orbit, and multi-beam capabilities and provide examples of technologies for that category. We close with a summary of challenges for the digital transformation.

5.2 BANDS AND SATELLITES

RF spectrum is the medium by which signals are sent between terminal, ground, and space segments. Commonly used bands of interest are shown in Table 5-1 [35]. Previous sections discuss how L band is used as an intermediate frequency for transporting analog signals within gateways. However, there are some SATCOM satellites which use L band as RF frequency. The most commonly used SATCOM RF frequencies are X, Ku, and Ka. Additional bands above 33 GHz are being used more on newer constellations called the Q and V bands [36]. While the exact frequencies of Q/V changes based on context of discussion and these Q/V are sometimes used interchangeably, new V-band frequencies recently approved by the Federal Communications Commission (FCC) have been approved between 37.5 GHz and 51.4 GHz.

Table 5-1: Satellite Bands

Designations	Frequencies	Band Name
P	225–390 MHz	VHF/UHF
L	1–2 GHz	UHF
C	4–8 GHz	UHF/SHF
X	8–12 GHz	SHF
Ku	12–18 GHz	SHF
K	18–27 GHz	SHF
Ka	27–40 GHz	SHF/EHF
Q	33–50 GHz	EHF
V	50–75 GHz	EHF

Table 5-2 shows some of the most recent LEO/MEO satellite constellations that have been proposed to the FCC in 2018. Many of these constellation plans have been approved as is, with some slight modifications. However, the overall trend for these networks has been to move to higher V-band frequencies. While the availability of an open spectrum is the primary motivation for moving to the V band, more significant atmospheric, path loss, and differences in antenna approaches remain challenges due to the small wavelength of higher frequencies. In addition to the bands listed, the FCC approved V-band operation for O3b, Audacy, SpaceX, and Telesat in 2020. With these changes in the space layer, more antennas in the V bands are likely to be seen [37].

Table 5-2: Three Proposed LEO Constellations in V Band

	OneWeb-V	Boeing-V	Telesat-V
#satellites	720+1280	147	117
Orbit	LEO-MEO	LEO	LEO
Band	V	V	V
Service			
User-Sat (GHz)	48.2 – 50.2	47.2 – 50.2 50.4 – 51.4	47.2 – 50.2 50.4 – 51.4
Sat-User (GHz)	40.0 – 42.0	37.5 – 40 40 – 42	37.5 – 42.0
Feeder			
Sat-GW (GHz)	37.5 – 42.5	37.5 – 40 40 – 42	37.5 – 42.0
GW-Sat (GHz)	42.5 – 43.5 47.2 – 50.2 50.4 – 51.4	47.2 – 50.2 50.4 – 51.4	47.2 – 50.2 50.4 – 51.4

5.3 MULTI-BAND/MULTI-ORBIT/MULTI-BEAM ANTENNAS

We define the multi-band, multi-orbit, and multi-beam antennas and briefly explain their operation and limitations. In each of the subsections, we also provide a table summary of select examples of existing antenna technologies that fit into this category.

5.3.1 Multi-band

Multi-band refers to an antenna system that can operate on multiple frequency bands simultaneously. Figure 5-1 shows an example of a multi-band antenna system. While many antennas support multiple frequencies, the RF transmission systems must also support multiple frequencies in conjunction with the antenna. To this end, multi-band systems typically will have multiple RF transmission systems to support these multiple bands since these systems have designs optimized for specific frequencies. These functions are tightly conjoined since both the antenna and RF transmission systems are required to provide a useful function. These systems tend to be large due to the multiple RF transmission systems required.

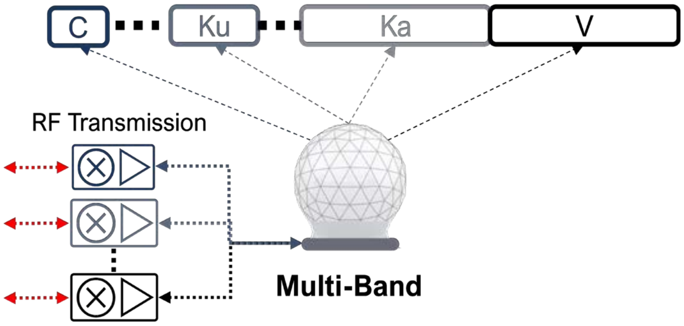

Figure 5-1: Multi-band Antennas Allow the Capability to Transmit on Multiple Frequencies.

The most common case for multi-band applications is with a GEO satellite that supports those multiple bands. In this case, there is no need for steering capabilities. The L3Harris MAQA is an example antenna of this category. Wideband Global Satellite Communications is an example satellite constellation that uses both X and Ka bands. As a result, there are antenna systems which support simultaneous multi-bands and others being developed.

When terminals are mobile, steerable antenna systems are required for GEO systems. These mechanically steered systems can also easily translate to multi-orbit, systems. Maritime operations are the most common application for these multi-band and multi-orbit mechanically steerable antennas. There are multiple examples of these systems, such as the Cobham Sea Tel 2400 and 9711 Series and the Intellian V240MT, that support multi-band and multi-orbit operations (Table 5-3).

5.3.2 Multi-orbit

Multi-orbit refers to antenna systems which may operate at LEO, MEO, or GEO orbits. This requires an antenna system with a steering and tracking capability. We discussed multi-band and mechanical steering capabilities in the previous section. Figure 5-2 illustrates a multi-orbit antenna capability supported by an antenna control unit (ACU). The purpose of the ACU is to direct the pointing mechanisms toward the satellite. To track satellites, antenna steering and tracking capability require three pieces of information: (1) satellite ephemeris,

Table 5-3: Examples of Multi-band Antennas

ANTENNA:	L3HARRIS MAQA	Cobham Sea Tel 9711	Cobham Sea Tel 2400	Intellian V240MT
STEERING:	None	Mechanical	Mechanical	Mechanical
BAND:	X/Ka	C/Ku	C/Ku/Ka	C/Ku/Ka
RX FREQ (GHz):	X: 7.25-7.75 Ka: 20.2-21.2	C: 3.4-4.2 Ku: 10.7-12.75	C: 3.625-4.2 Ku: 10.7-12.75 Ka: 17.7-20.2	C: 3.625-4.2 Ku: 10.7-12.75 Ka: 17.7-20.2
TX FREQ (GHz):	X: 7.9-8.4 Ka: 30.0-31	C: 5.85-6.725 Ku: 13.75-14.5	C: 5.85-6.425 Ku: 13.75-14.5 Ka: 27.5-30.0	C: 5.85-6.425 Ku: 13.75-14.5 Ka: 27.5-30.0

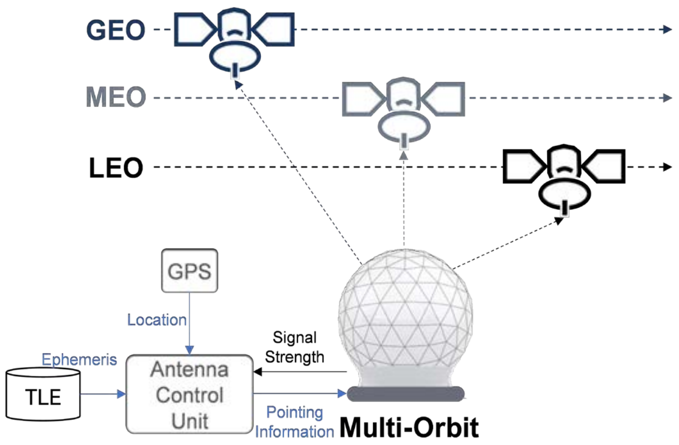

Figure 5-2: Multi-orbit Antennas Require Tracking Capabilities.

(2) initial or continuous location of the antenna, and (3) signal strength of the received signal. The satellite ephemeris is the orbital prediction parameter data for the satellite. This information is contained in a two-line element (TLE), which are two strings of text that define these parameters. This information is periodically updated in a public database and used by the ACU. The location of the antenna is required to then define the pointing vector to the predicted satellite location to establish initial contact. After initial contact is made with the satellite, signal strength monitoring and pointing dithering are performed for precision tracking.

Actual beam-pointing mechanisms come in various types. Mechanical tracking systems are used by most systems with a parabolic reflector. Systems of this type are typically larger and expensive (which we addressed in the previous section). However, due to their size and weight, mechanical steerable dishes are not practical for many applications. Thus, new flat panel antennas technologies have been recently marketed to support terminal and other similar mobile applications [38]. Some examples of flat antennas using phased array technology are the Kymeta u8 and GETSAT Sling series antennas (Table 5-4). These antennas are referred to as electronically steerable arrays (ESAs). Due to their intrinsic design, most of these antennas will operate at fixed frequency and do not support multi-band operation. However, Isotropic is planning on a Ka/Ku multi-band ESA for 2024 [39].

5.3.3 Multi-beam

Multi-beam refers to antenna systems that may transmit to two or more satellites simultaneously. Figure 5-3 shows an example of a multi-beam antenna that supports two simultaneous RF inputs and connections to multiple satellites. These multi-beam satellites are especially needed for LEO and MEO satellites for handoffs, where one satellite experiences a loss of signal while another is experiencing an acquisition of signal. When multi-waveform capability is enabled with digitization and virtualization, multi-beam antennas allow additional operational scenarios between LEOs, MEOs, and GEOs to maintain connectivity. Finally, in the simplest case, multi-beam operation allows

Table 5-4: Examples of Flat Antennas

ANTENNA:	**Kymeta u8**	**Kymeta KyWay u7**	**GETSAT Milli/Micro Sling Blade**	**GETSAT Sling Blade**	**ThinKom ThinWave Ku13**	**ALCON NGSO**	**GSAN Scout-P**
STEERING:	ESA	ESA	ESA	ESA	VICTS Mechanical	ESA	ESA
BAND:	Ku	Ku	Ka	Ka	Ku	Ka	Ku
RX FREQ (GHz):	10.7-12.75	11.4-12.4	17.7-21.2	17.7-21.2	10.7-12.75	17.7-20.2	10.95-12.75
TX FREQ (GHz):	13.75-14.5	13-14.5	27.5-31	13.75-14.5	13.75-14.5	27.5-30	13.75-14.5

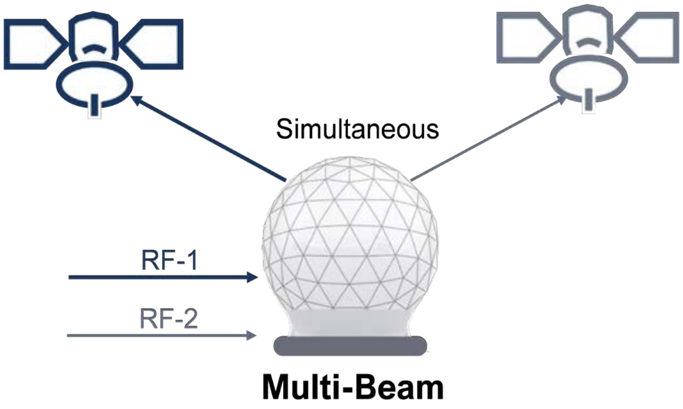

Figure 5-3: Multi-beam Antennas Allow Connections to Multiple Satellites.

multiple waveforms or carriers to operate on the same antenna. A multi-beam antenna does not currently exist on the market. In the future, Isotropic is planning to release the first multi-beam Ka-band antenna in 2022. However, it is likely that Starlink's Dishy McFlatface and McSquarepants are performing multi-beam operations for continuous coverage for existing customers, which is at the V-band frequencies.

5.4 SUMMARY AND CONCLUSION

We defined multi-band, multi-orbit, and multi-beam antenna terms. We also provided examples of those associated technologies. Multi-band technologies have been deployed with GEO satellites using fixed antennas, where the GEO satellite operates on multiple frequencies. Multi-band systems also require multiple RF transmission systems, which increase SWaP. With maritime applications, mechanical steering is required with multi-band solutions, and these have been adapted to create multi-orbit solutions. Mechanical steering, multi-orbit solutions do not meet SWaP requirements for many applications. Thus, ESA antennas have been making a push into the market to address that gap. Although ESAs have the most potential for creating a multi-beam solution, they are still limited to single-band applications since their multi-element design depends on frequency.

SECTION 06 USE CASES

6.1 INTRODUCTION

In this section, we present operational use cases for a digitally transformed (DT), i.e., fully digitized and virtualized, SATCOM ground and terminal segments. In these use cases, we make two critical assumptions. First, each example is satellite constellation agnostic, where we assume satellite constellations to be a network that provides the connection between gateways and terminals. These operational use cases focus on the two key demands—terminal/modem agility and system agility/resiliency. The scope of these use cases is not an exhaustive list but represents a view of the potential capabilities realized through DT SATCOM segments.

6.2 MODEM/TERMINAL AGILITY

6.2.1 Dynamic Applications and Waveforms

Waveform and application virtualization is a key function provided with DT SATCOM networks. This operational use case illustrates how DT SATCOM ground and terminal segments would use dynamic applications and waveforms. Figure 6-1 shows three DT SATCOM elements—a ground station (shown on the left) and two terminals (shown on the right). The gateway NFVI comprises a DMB, DIL, and two digital transmission systems (DTSs), which further comprise an edge device, RF transmission, and antenna systems. Similarly, each terminal comprises a DM, DIL, and DTS. For both the ground and terminal segments, the VNF layer shows deployed

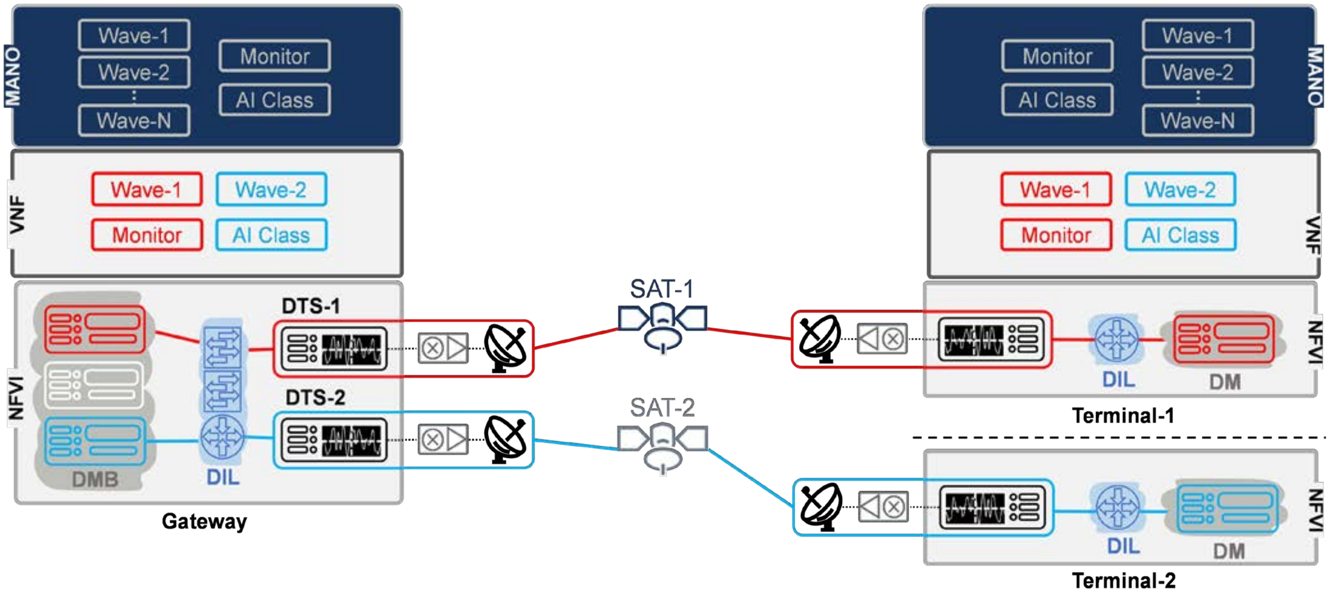

Figure 6-1: A Digitized and Virtualized SATCOM System Can Deploy a Panoply of Waveforms and Applications.

VNFs, which show color-coded resource allocations in the DMB. The MANO layer shows the potential VNFs that can be deployed. The VNFs considered in this use case are waveforms, spectrum monitoring, and artificial intelligence (AI) classifier application. The terminal segment in Figure 6-1 (right) shows two terminals with the same VNF and MANO layers as the gateway.

We discussed how virtualization fulfills the key demands of ground segment sustainability and freedom from vendor lock-in through common hardware for the DMB. Since the DMB is based on common hardware, resources can be dynamically assigned and allocated. In this use case, two different waveforms are deployed on common hardware, along with other applications. The same hardware supporting waveform-1 (shown in red) is also supporting a spectrum-monitoring function. Likewise, the same hardware-supporting waveform-2 is also supporting an AI classifier for the spectrum received (shown in cyan). In other words, each digital modem resource in the gateway can support multiple VNFs if there are sufficient resources.

6.2.2 Waveform Diversity

With dynamic waveform deployment, DMs could deploy multiple waveform link combinations to create waveform diversity. In a SATCOM context, diversity is the ability to provide improved signal quality, throughput, and resilience through using multiple transmission paths. In the case of multiple waveforms, two waveforms could be used to form redundancy, data obfuscation, or throughput optimization. The key characteristics of waveform diversity are the data source is split into multiple streams using multiple waveforms and recombined into a single data source. Waveform diversity is not unique to DT SATCOM systems. However, in a DT SATCOM system, waveform diversity requires less hardware and is much easier to implement.

Figure 6-2 shows an example of waveform diversity. While similar functionality can be realized using multiple antennas, we show multi-band, multi-orbit, multi-beam antenna system in this example on the terminal side. Both the gateway and terminal contain a single DM in red and cyan; this DM supports the transmit and receive functions for the two waveforms. Although not required for waveform diversity, two waveforms using two different satellite networks are shown. Waveform diversity could also use the same satellite.

6.2.3 Satellite Link Diversity

Similar to waveform diversity, the objective of satellite link diversity is to provide additional resilience or throughput by leveraging multiple satellite links. While we used Figure 6-2 to explain waveform diversity, technically, it is also leveraging satellite link diversity. We provide an additional example in Figure 6-3 that shows the same terminal but a connection to two different gateways instead. Since capabilities are not restricted to purpose-built hardware, waveforms can be freely deployed among resources in gateways and terminals.

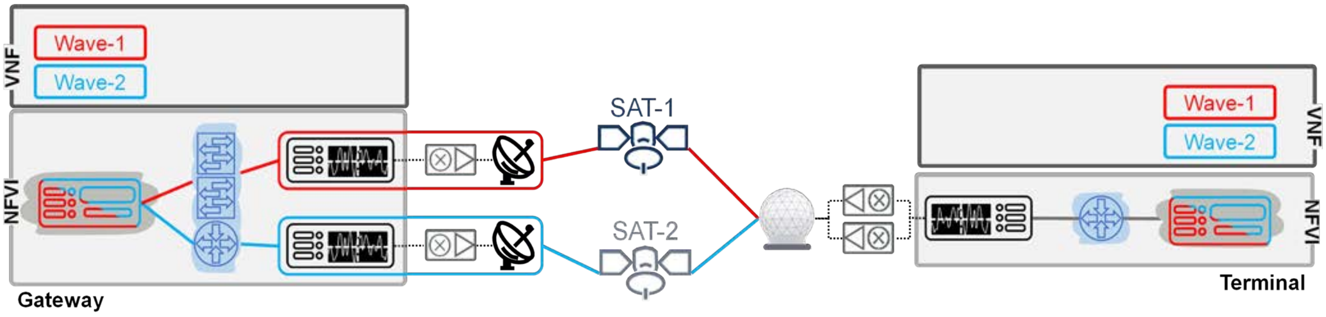

Figure 6-2: A Waveform Used to Improve Throughput and Resilience by Using Multiple Waveforms for Data Sources.

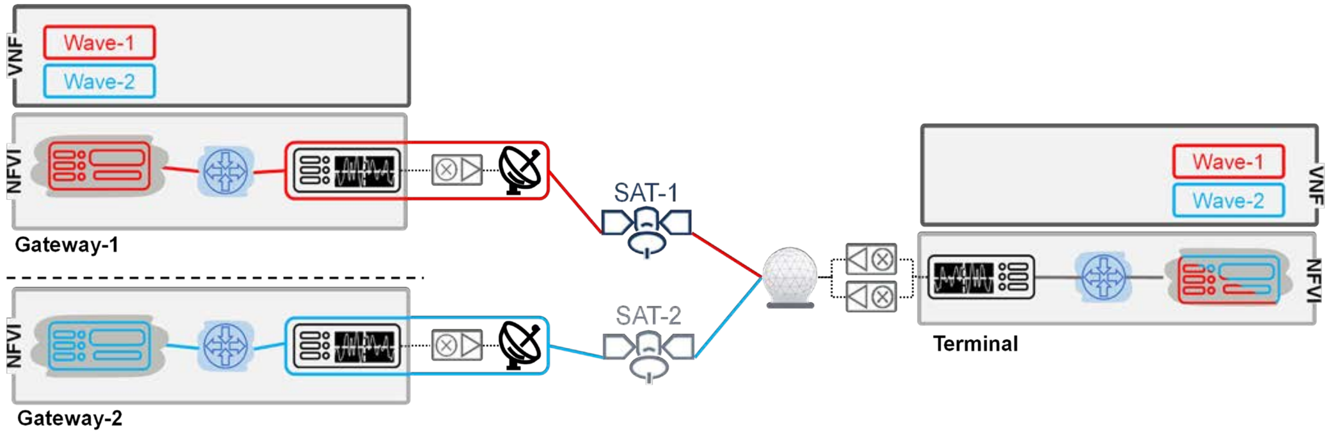

Figure 6-3: Link Diversity Improves Throughput and Resilience by Using Multiple Satellite Links.

6.3 SYSTEM AGILITY/RESILIENCY

6.3.1 Gateway Resource Sharing

System agility and resiliency is a key demand from the DoD, which serves as the basis for our second set of use cases. Figure 6-4 illustrates three independent transmission paths using two gateways—local and remote. In our use case, we assume available NFVI resources at a local and a remote gateway. Figure 6-4 (right) shows three different terminals as communications endpoints for the gateways. To support each of the three different terminals, there are three independent paths indicated in red, cyan, and violet. The red path shows communications between the local gateway and terminal-1, which is an equivalent standard path for normal SATCOM networks. The cyan path travels through the DIFL, which connects to the remote gateway DIL and DTS to connect to terminal-2. Finally, the violet path originates in the DMB of the remote gateway and travels through the DIFL to the local gateway's DIL and out the DTS to connect to terminal-3.

The purpose of this use case is to illustrate that connections are not limited to DMBs and DTSs of the same locations. In the case of the cyan path, there are multiple reasons for leveraging a remote gateway. First, the local gateway could not have adequate DTS resources. Second, a local gateway's DTSs may not be able to connect to SAT-3 due to a weather event. Thus, leveraging a DTS at remote

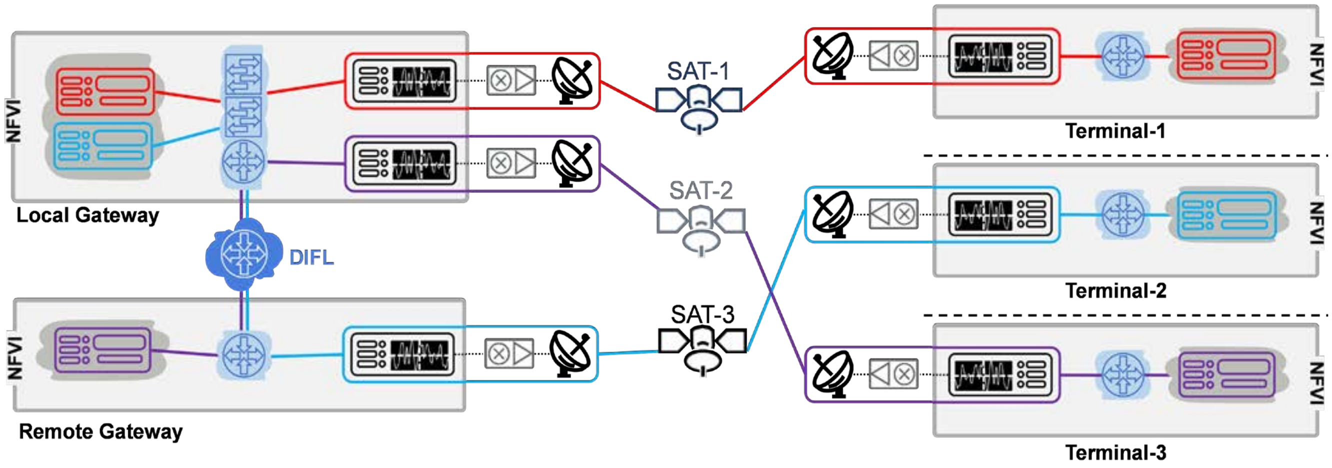

Figure 6-4: Gateways Can Share Multiple Transmission Paths Using the DIFL.

gateway enables the network to establish service for the terminal. In the case of the violet path, the NFVI at the local gateway could be lacking required DMB resources and require them from the remote gateway. This creates an interesting scenario with what is called a hybrid Cloud, which is our last component of the digital transformation. In short, this means that NFVI resources do not necessarily need to exist in a gateway. They can be a Cloud computing center's resources, which leverage the DIFL to access the local gateway's DTS resources. This Cloud architecture creates a new dynamic use for Cloud computing resources that supports local gateways in a more distributive manner. Finally, the significance of this use case is that global management of DoD SATCOM resources is possible.

6.3.2 Gateway Network Routing

In addition to increasing resilience through gateway resource sharing, DT SATCOM gateways are also able to act as routers, allowing different satellite systems to connect terminals. Figure 6-5 illustrates how a gateway may act as a router using digital IF interfaces. In the figure, terminal-1 is connected to the gateway via DTS-1, and the waveform samples are converted into a digital IF signal and then routed to DTS-2 and terminal-2. This use case assumes that terminal-1 and terminal-2 communicate using the same waveform and using the gateway as a router.

6.4 SUMMARY AND CONCLUSION

We illustrated potential capabilities of the DT SATCOM systems using two set of use cases based on key demands—terminal/modem and system agility and resiliency. For terminal/modem agility, we showed that operating dynamic waveforms and applications, waveform, and link diversity could provide for SATCOM networks. For the system agility/resiliency, we showed the operations of gateway resource sharing and gateway routing. Gateway resource sharing supports hybrid Cloud capabilities, which is one of the final characteristics of the digital transformation. These use cases show DT SATCOM systems provide significant capabilities to meet key demands of future SATCOM networks.

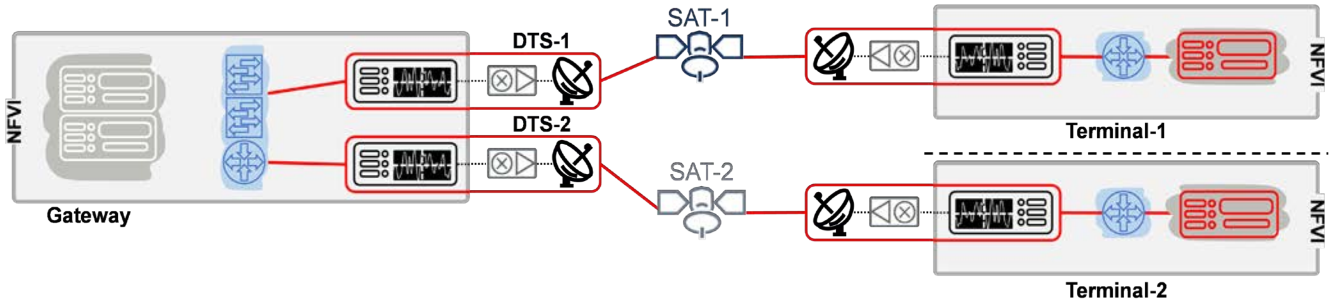

Figure 6-5: Gateways Act as Routers Between Satellite Networks Using Digital IF.

REFERENCES

1. Satellite Industry Association. "State of the Satellite Industry Report." Annual Report, https://bit.ly/3aBdkWe, 2021.
2. Vigil, A. J., and M. D. Rhoades. "Communications Performance Based Specification of Phase Noise for SATCOM Systems." Presentation, MILCOM, 2018.
3. United States Space Force. "United States Space Force Vision for Satellite Communications." Vision Document, https://bit.ly/3nr4mQJ, January 2020.
4. Dean, M. "DoD's Digital Modernization of Modems." Satellite 2021 Panel: The Future of Modem Architectures, 2021.
5. U.S. DoD. "Managed Services – SATCOM (with terminals) As A Service (SAAS)." Request for Information, https://bit.ly/3myTh1x, 2021.
6. U.S. DoD. "SATCOM Modernization." BAA-21-R-NCFT, White Paper Call, 2020.
7. U.S. Department of the Army. "Virtualization of Satellite Modems and Waveforms." Request for Information, https://bit.ly/3iGouxh, 2021.
8. PM DCATS. "Draft System Specification for the Enterprise Digital If Multi-carrier (EDIM) Modem." Revision 0.8, September 2021.
9. U.S. DoD. "Next Generation of Tactical Terminals for Resilient Tactical SATCOM." White Paper Call 0011, https://bit.ly/3bpdKQ8, 2021.
10. Daehnick, C., I. Klinghoffer, B. Maritz, and B. Wiseman. "Large LEO Satellite Constellations: Will It Be Different This Time?" McKinsey Industry Insights, https://mck.co/3jFK9o3, 2020.
11. Pachler, N., I. del Portillo, E. F. Crawley, and B. G. Cameron. "An Updated Comparison of Four Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband." International Conference on Communications Workshops, https://bit.ly/3lzPQHv, 2021.
12. Henry, C. "SES Details LEO Constellation and Expanded MEO Constellation to FCC." *Space News*, https://bit.ly/3BI9SoL, 2020.
13. Henry, C. "Geostationary Satellite Orders Bouncing Back." *Space News*, https://bit.ly/3aBqW3M, 2020.
14. NSR. "Satellite Ground Network Virtualization." White Paper, https://bit.ly/3lnTD7G, 2020.
15. CPRI Committee. "eCPRI Specification V2.0." Common Public Radio Interface: eCPRI Interface Specification, https://bit.ly/3phHV0z, 2019.
16. ETSI. "Network Functions Virtualization (NFV) Architectural Framework." ETS GS NFV 002 V1.1.1, https://bit.ly/3kWfenR, October 2013.
17. Vigil, A. J., and J. Hicks. "The Case for an All-Digital Military Satellite Communications Earth Terminal." MILCOM, https://bit.ly/3dfJXdT, 2010.
18. Vigil, A., et al. "Migration of DOD SATCOM Earth Segment Architectures to Digital IF." MILCOM, 2021.
19. Cooklev, T., R. Normoyle, and D. Clendenen. "The VITA 49 Analog RF-Digital Interface." *IEEE Communications Magazine*, https://bit.ly/2KOYd29, 2012.
20. VITA. "VITA Radio Transport (VRT) Standard for Electromagnetic Spectrum: Signals and Applications." ANSI/VITA 49.2-2017, 2017.
21. Beljour H., et al. "FAST Digital IF Architecture and Open Standard Digital IF Interfaces." IEEE Military Communications Conference, https://bit.ly/2SNfYQ5, 2014.
22. TIA. "Future Advanced SATCOM Technologies (FAST) Open Standard Digital – If Interface (OSDI) for SATCOM Systems." ANSI/TIA-5041-2016, 2016.
23. PM DCATS. "Draft System Specification for the Enterprise Digital IF Multi-carrier (EDIM) Modem." Revision 0.8, October 2021.
24. Vigil, A. J. "SATCOM Earth Segment Migration to Digital IF." Satellite 2021 Panel: The Future of Modem Architectures, 2021.
25. Prechtel, M., and J. Klepper. "Smallsat Ground Systems, a C2 to RF Integrated Approach." Kratos White Paper, https://bit.ly/3sqRZFC, 2016.
26. Wood, S. H. "Trade Study of Commercial Software Defined Radio Technologies for Small Satellite Ground Station Network Command and Control Applications." Master's thesis, https://bit.ly/3HtUSOL, 2020.
27. Project Manager, Defense Communications and Army Transmission Systems. "Draft System Specification for the Enterprise Digital If Multi-carrier (EDIM) Modem." Revision 0.8, September 2021.
28. DIFI Consortium. "Digital IF Interoperability Standard V1.0." IEEE Standard 4900-2021, https://bit.ly/3gwVlnw, 2020.
29. Sharabayko, M. P., M. A. Sharabayko, J. Kim, and J. Kim. "https://bit.ly/3dXbQry." IETF RFC draft, https://bit.ly/3dXbQry, 2021.
30. Rizzo, L. "Effective Erasure Codes for Reliable Computer Communication Protocols." ACM Computer Communication Review, https://bit.ly/3lNmeH7, 1997.

REFERENCES, *continued*

31. Desai, A., R. Oza, P. Sharma, and B. Patel. "Hypervisor: A Survey on Concepts and Taxonomy." *International Journal of Innovative Technology and Exploring Engineering,* https://bit.ly/2Sk8BCM, 2013.
32. ETSI. "Network Functions Virtualization: An Introduction, Benefits, Enablers, Challenges & Call for Action." SDN and OpenFlow World Congress, https://bit.ly/3amI266, 2012.
33. ETSI. "Network Functions Virtualization (NFV) Architectural Framework." ETS GS NFV 002 V1.1.1, https://bit.ly/3kWfenR, October 2013.
34. ETSI. "NFV & MEC Plugtests." ETSI Plugtests Report V1.0.0, https://bit.ly/3mSR12j, September 2020.
35. U.S. Army. "Techniques for Satellite Communications." ATP 6-02.54, https://bit.ly/3eJfZQj, 2020.
36. Portillo, I., B. Cameron, and E. Crawley. "Ground Segment Architectures for Large LEO Constellations With Feeder Links in EHF-Bands." IEEE Aerospace Conference, https://bit.ly/3ynKK5J, 2018.
37. FCC. "Report No. SAT-01473." Public Notice, https://bit.ly/3mniyeJ, 2020.
38. Gupta, U., A. Tan, J. Liu, and W. Lohmeyer. "Modern Flat Panel Antenna Technology for Ku-/Ka-Band User Terminals in LEO Satellite Communications Systems." *Microwave Journal*, https://bit.ly/3mb16tG, 2021.
39. Satellite Mobility World. "Isotropic's New Multi-beam, Multi-Frequency ESAs." https://bit.ly/3eiGN9e, 2021.

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CSIAC-BCO-2021-189