Integrating 5G Capability into Marine Corps Live-Virtual-Constructive Prototyping and Experimentation

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ABSTRACT

The Department of Defense (DoD) has established the "5G to Next G" initiative to accelerate the use of 5G networks and associated 5G technologies in support of DoD use cases. In particular, the US Marine Corps (USMC) is interested in exploring the suitability of 5G networks and technologies for its expeditionary operations. This paper presents a use case of applying Network Digital Twin technology to investigate the addition of 5G capabilities to the Marine Corps Enterprise Network (MCEN) to support a Forward Arming and Re-Fueling Point (FARP) mission thread.

Currently, FARP missions are supported by legacy VHF/UHF voice communication radios to provide security, command and control. Newer technologies in radars, cameras, and a wide range of short-to-midrange sensors (acoustic, seismic, magnetic, and infrared) can greatly aid FARP mission execution, but they also present significant challenges to communication and coordination during FARP operations. 5G is a promising emerging solution to provide high bandwidth and low latency communications to meet future FARP information exchange requirements driven by increasingly capable sensor deployments to counter advanced threats. This study uses a Network Digital Twin model of the MCEN integrated with a high fidelity 5G simulation model to investigate the feasibility of prototype 5G expeditionary operations to conduct FARP missions.

Live-virtual-constructive prototyping and experimentation using Network Digital Twin technology offers significant value to mission and network planners as it provides for integration of new network components and capabilities such as 5G with a digital replica of existing network infrastructure such as the MCEN. Network Digital Twin can provide a high fidelity emulation of the communication network integrated with its operating environment and the application traffic carried by it, leveraging real-world data about a physical network as input and producing accurate predictions regarding how that physical network will be affected by the addition of new capabilities and requirements. Increased network traffic loading from newer radar, electro-optic, infrared and other sensor technologies can then be modeled to better understand their contributions to mission execution while simultaneously evaluating their impacts to existing network infrastructure.

ABOUT THE AUTHORS

Dr. Ha Duong is Principal Engineer at SCALABLE Network Technologies where he has worked on modeling JTRS waveform for the Future Combat System (FCS) and Brigade Team Modernization (BCTM) programs. Over the past several years, Dr. Duong has focused on modeling vulnerabilities and cyber attacks in both IT and OT networks, and on how to use those models to understand and evaluate impact of cyber attacks on mission and operation execution. Recently, he works on methods and tools to create Network Digital Twin of various physical networks that will take simulation and emulation to the next level in meeting requirements of cyber and network testing. His current research interests include LVC-based cyber-attack representation, modeling and simulation techniques to represent complex operations in simulation environments, and analysis of cyber effects on IT and OT networks.

Captain Jeff Hoyle (US Navy, Retired) leads SCALABLE Network Technologies communications and networking developments for the Department of Defense and Intelligence communities. Prior to joining SCALABLE, he served as Director of Advanced Maritime Programs for Northrop Grumman Aerospace Systems, a leading provider of military autonomous systems, and Director of Technology and Navy Programs for AtHoc, Inc., a leading provider of crisis communications capabilities to multiple Federal agencies. While on active duty, Captain Hoyle supervised all aspects of US Navy operations on five submarines and one aircraft carrier, including command of USS MAINE (SSBN 741) and ten deployments to forward operating regions on missions vital to national security. As a Defense Acquisition Program Manager, he led development of submarine exterior communications systems and joint tactical networking capabilities for the Army, Navy, Air Force and Marine Corps.

Luis E. Velazquez is Chief Technology Officer (CTO) United States Marine Corps Command with over 35 years of System Engineering related experience in the Marine Corps, Navy, and Industry. Serving on active duty in both the Navy and Marine Corps, followed by Industry and then as a Marine Corps Civilian, Luis has continually worked in complex, technically sophisticated assignments, from sonars to software development, network engineering to M&S, data base design to electrical systems.

His career includes assignments as a Professor of Computer Science at the U.S. Naval Academy, CIO for two Defense Industry companies, TECOM's Technology Division Director, Chief Engineer for the US/Japan High Water Speed Program, Branch Head for the MCSC Framework for Assessing Cost and Technology (FACT) effort, DoN International Exchange Agreement Officer, and the MCSC Modeling and Simulation (M&S) Lead. His most recent assignment has been Division Head, Systems Engineering Directorate, SEAL.

The recipient of multiple awards, Luis has been recognized with the DON Acquisition Excellence Award, the Team Lead for the Innovation Excellence Acquisition Team of the Year award, the Office of Naval Research Technology Transition Award, the Commander's Innovation Award, the Excellence in MAGTF Engineering Award, and the DoD National Image Award. Luis has also published several articles in the Marine Corps Gazette and Interservice/Industry Training, Simulation and Education forums.

Luis has earned a Master of Computer Science from the US Naval Postgraduate School, Monterey, CA, and a B.S., Computer Science from Jacksonville University, Jacksonville, FL, and is a Microsoft Certified Systems Engineer. DAWIA Level 3 certified in Engineering, he is a longtime Defense Acquisition Corps Member, and a graduate of the DoD Executive Potential Program. He also earned the Lead Systems Integrator (LSI) designation from the US Naval Postgraduate School.

Captain Kevin Ayres (US Marine Corps) is a Modeling and Simulation Officer at Marine Corps Systems Command, where he executes and coordinates M&S analysis, market research, and simulation tool assessments to support Marine Corps program offices and portfolio managers. He supports simulation data exchanges, standards, and protocols across multiple external agencies to include academia, industry, and other governmental agencies in support of simulation requirements and future Naval operating concepts. Recently, he has worked on several acquisitions initiatives to enhance Marine Corps wargaming and network modeling capabilities. Captain Ayres also provides advance collaboration and discussion across the M&S community of interest to improve identification, selection, and execution of research that will directly benefit the Fleet Marine Force. Captain Kevin Ayres is a Logistics Officer and Naval Postgraduate School graduate with a Master of Science in Modeling, Virtual Environments, and Simulation.

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Introduction

The Department of Defense (DoD) has established the "5G to Next G" initiative to accelerate the use of 5G networks and associated 5G technologies in support of its wide range of missions and operations. In particular, the US Marine Corps (USMC) is interested in deploying 5G networks and technologies for its expeditionary operations. The DoD community is continuously investigating better ways to meet communication needs for mission operations. Leveraging COTS (Commercial-Off-The-Shelf) products, whenever possible, greatly benefits DoD by effectively sharing development costs with private industry and consumers. Additionally, COTS products, by the nature of their distribution, have undergone extensive and real-world testing that ultimately provides a proven and reliable platform. In particular, commercial 5G technology is considered a great candidate for tactical communication due to its attractive high bandwidth and extremely low delay, generating a great interest in evaluating 5G's ability to support military missions.

However, large-scale 5G deployments for prototyping and experimentation require significant time and resources. Additionally, 5G tactical networks will ultimately need to be connected to existing military-specific networks for command and control, posing additional requirements to plan for and evaluate integration between disparate networks. In this paper, we describe a novel approach to integrate a high fidelity 5G simulation model with a Network Digital Twin of backbone enterprise network to provide an effective test environment. To illustrate the approach, the paper will present a use case of augmenting the Marine Corps Enterprise Network (MCEN) with 5G capabilities using a Network Digital Twin approach to support a Forward Arming and Re-Fueling Point (FARP) mission thread [*MCWP 3-21.1 Aviation Ground Support*]. Through the use case, our approach will be shown as a good tool to quickly and effectively assess 5G network and its technologies for military missions of interest.

The first two sections below discuss the application of Network Digital Twin and 5G network simulation in supporting Live-Virtual-Constructive (LVC) based test and evaluation. The next section describes the challenges and opportunities associated with the integration of 5G capabilities to support Marine Corps FARP operations. The main section presents a proof of concept that integrates a 5G model simulation with a Network Digital Twin of and existing MCEN network to evaluate a complete FARP mission rehearsal. Finally, we summarize the paper and suggest possible directions for further work.

Network Digital Twin

Digital twin technology offers significant value to an organization as it allows continuous access to the digital replica of a physical object or process throughout its lifecycle. The digital replica can be used for analysis that provides insights and actionable information to improve the process or product in terms of optimized performance, cost effectiveness, readiness, or maintenance.

A particularly strong use case for the digital twin approach is its use in communications and networking, commonly referred to as a Network Digital Twin, a computer simulation model of the communication network integrated with its operating environment and the application traffic carried by it. To satisfy its intended purpose, the Network Digital Twin must have sufficient fidelity to accurately reflect the network dynamics due to the interplay between the communication protocols, topology, traffic, and physical environment. A Network Digital Twin can be enhanced by incorporating cyber vulnerabilities and defenses. The cyber-enhanced Network Digital Twin can be used to assess the cyber resilience of the target system by subjecting the digital twin to live or simulated cyber attacks and analyzing its behavior.

Figure 1 depicts how a Network Digital Twin can be created from different data sources on topology, traffic and device configurations.

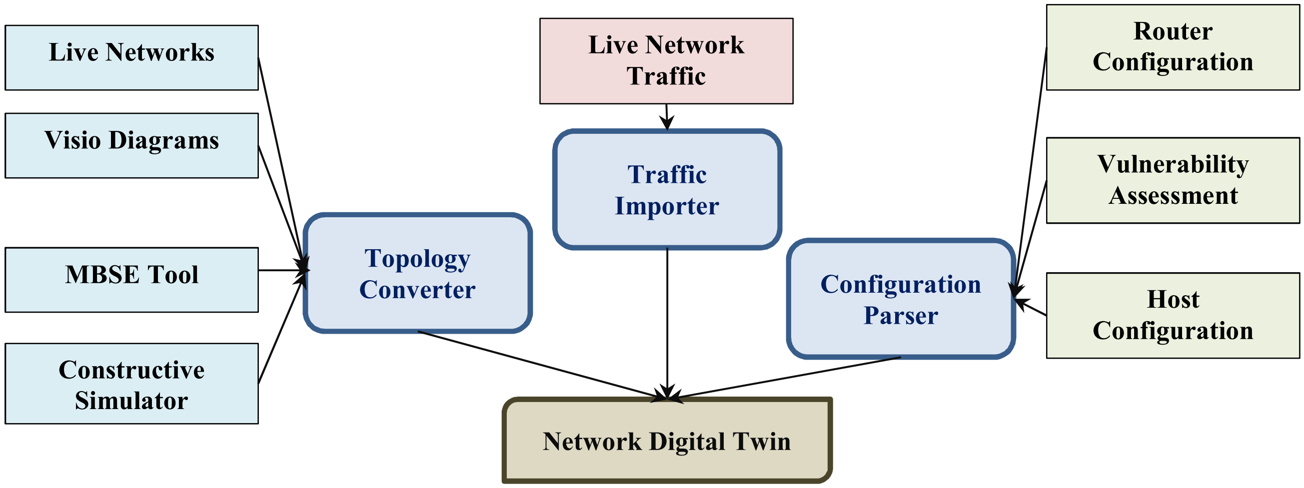

Figure 1. Creating Network Digital Twin

Network Digital Twin technology applications include network deployment life cycle engineering support, network performance testing and analysis [*Luis E. Velazquez, et al, 2018*], cyber resilience assessment [*Ha Duong, et al 2018*], prototyping and experiment. This paper focuses on the last use case, where we built a prototype using Network Digital Twin and then extended with high fidelity simulation models. Thus, the prototype consists of two parts: an "as-is" (or existing network) and a "to-be" network (or future network).

Now, we can use this prototype through a cycle of development, testing and deployment to:

- Evaluate performance of potential hardware and software components of the "to-be" network
- Test new services, applications, operations or missions offered by the "to-be" network
- Plan new deployments of the "to-be" network, assess the impact of adjusting operational and environmental conditions, and perform after action review

In this manner, experimenting with the prototype can cost-effectively answer questions such as:

- Do potential hardware/software components meet requirements of the "to-be" network?
- Can new services, applications, operations or missions be supported on the "to-be" network?
- How does the "to-be" network impact the operation of the existing "as-is" network?
- Do any configuration parameters of the "as-is" network need to be adjusted to accommodate the "to-be" network?
- Does the "to-be" network introduce a new cyber vulnerability to the "as-is" network?

In this paper, the "to-be" network encompasses the 5G model (core, gNBs and handsets) as described in the next section.

LVC Prototyping and Experimentation of 5G Networks

5G [*5G*, https://en.wikipedia.org/wiki/5G,] consists of digital cellular networks that, like its predecessors, are divided into small geographical areas or cells that allow spectrum reuse and increase service capacity. Moreover, 5G includes some breakthrough technologies that offer more and better services such as enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC), and ultra-reliable low latency (URLLC). As with Network Digital Twin, 5G services and capabilities are very attractive for many DoD applications, such as networked sensors for force protection and persistent ISR, edge computing using ML/AI, connected vehicles / autonomous platforms and Command and Control / Situational Awareness (C2/SA). In order to investigate the feasibility of using 5G networks to support military operations, testbed infrastructure needs to be developed to support development, experimentation and deployment. Often, this process is repeated multiple times to allow for maintenance, upgrade or new requirements as shown in Figure 2.

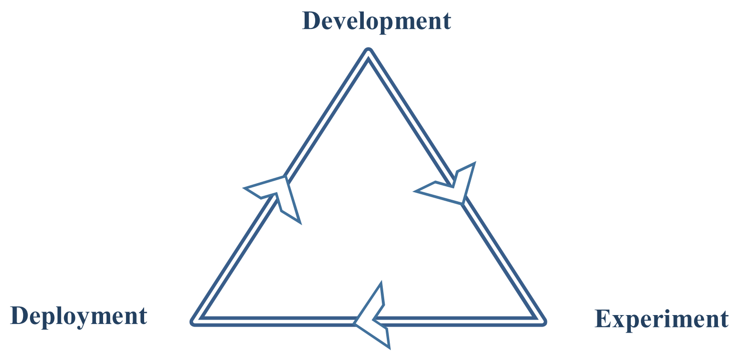

Figure 2. Testbed Process

In each of the above steps, Network Digital Twin, as described in the previous section, can be a valuable tool as it represents the entire prototype 5G communication networks, accurately modeling the devices, communication links, operating environment, and applications running on the network. Moreover, Network Digital Twin can interface with physical hardware and/or real applications to establish a LVC prototype for testing. In other words, Network Digital Twin is a digital counterpart of the physical testbed.

In the testbed development step, we can use Network Digital Twin to evaluate the performance of potential hardware and software components and configurations in simulations of expected exercise scenarios. Once candidate components are selected and procured, the LVC prototype will enable rigorous assessment of 5G network testbed infrastructure capabilities in the laboratory prior to the next step.

During experimentation in the testbed, we can select certain applications to be tested using the same systems engineering approach as in the previous step. Each of the selected applications will be integrated with the LVC prototype to evaluate its performance in multiple mission scenarios under variable conditions. In particular, the application will be tested against 5G resources such as gNB coverage or 5G network slicing. "What-If" analysis can be performed to make recommendation on gNB coverage (i.e. RF power, location) or network slicing configuration. With the advantage of a controlled testing environment provided by simulation capabilities and realism provided by live/virtual capabilities, LVC testing can quickly and thoroughly evaluate an application's performance and operation, ensuring its technical readiness before deployment.

In the final step, where the testbed is being deployed to the field for experimentation, operators can run mission rehearsals on the LVC prototype to understand expected behavior during the planned deployment and to adjust exercise plans when needed. Additionally, operators can leverage the LVC prototype to evaluate potential impacts of changing operational and environmental conditions in real-time using available sensors and observations. Finally, in after action review, using the LVC prototype operators can investigate any issues that occurred during the exercise and ensure that future exercise plans take them into account. Network traffic captured during the exercise can be played back through the Network Digital Twin emulation to identify root causes of any observed anomalies or message transmission failures.

Forward Arming and Re-Fueling Point (FARP) Mission

In a FARP mission, Marines are inserted forward in the battle space and quickly establish or occupy an existing expeditionary landing field to support rearming and refueling of manned and unmanned aviation assets. This site includes an Operations Facility (OPFAC) and support functions such as ASC (Air Support Center), logistics, and force protection. The logistics entities include OIC (Officer-In-Charge), fuel team, maintenance team, ARFF (Aircraft Recuse Firefighting) team, and ordnance team. Force protection, including perimeter security and entry control point (ECP) operations, can be challenging as the FARP mission calls for the absolute minimum number of personnel to be deployed. With the incorporation of 5G network technologies, this challenge can be mitigated through the employment of a diverse range of high-fidelity, networked sensors around the perimeter, at ECPs, and along likely avenues of approach.

Figure 3 shows example of possible FARP mission sequence events, starting with “OIC directs an inbound aircraft”.

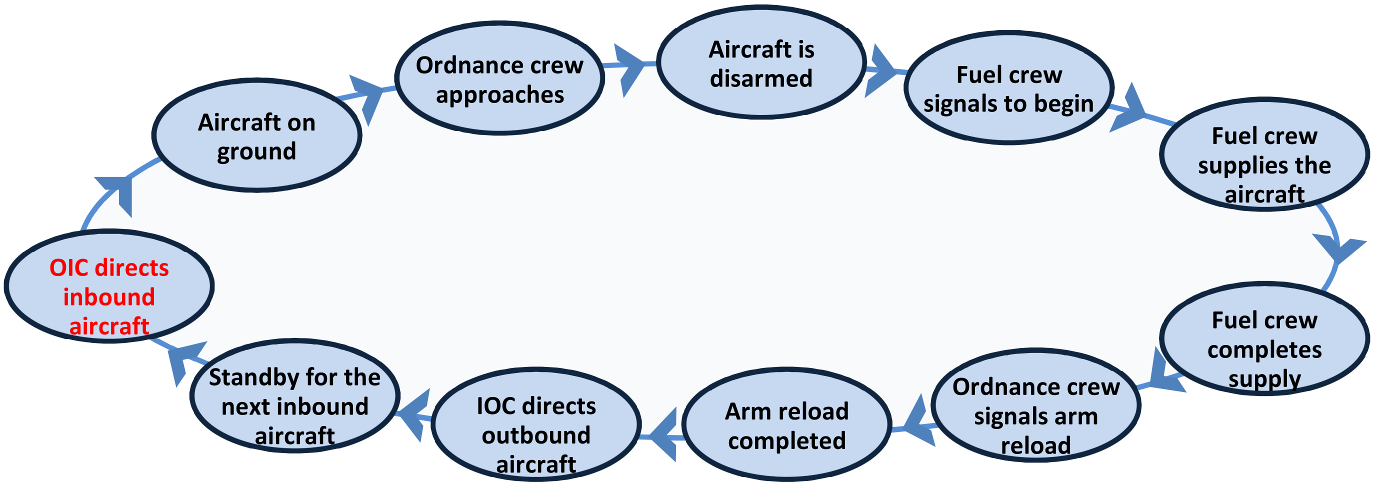

Figure 3. FARP Mission Sequence Events

Like any military mission, communication is a vital part of FARP that requires external and internal communications for various entities. While each team uses internal communication to perform its specific functions, external communication is required to coordinate the entire mission. Currently, FARP communication relies primarily on UHF and VHF voice radios, limiting data exchange and creating highly detectable electromagnetic signatures. Even using more advanced networking radios (for example, PRC-117G with SRW and ANW2), FARP communications capabilities cannot support the diverse range of networked devices such as radars, cameras, and a wide range of short-to-midrange sensors (acoustic, seismic, magnetic, and infrared) envisioned for future expeditionary advanced base operations, thus requiring more capable communication technologies such as 5G to ensure adequate bandwidth with guaranteed QoS communication while enabling more advanced options for low probability of detection and interception.

Proof of Concept: Integrating 5G Capability into Marine Corps Live-Virtual-Constructive Prototype

In this section, we will demonstrate a proof of concept where the prototype is built, starting with a Network Digital Twin of existing or “as – is” MCEN network, then adding a simulated 5G model to create the “to-be” network. The prototype is then used to conduct FARP mission rehearsal, analyzing RF coverage and network performance.

Figure 4. Workflow for Proof of Concept

Network Digital Twin Creation/Analysis ("As-Is" Network)

To ensure accuracy of the Network Digital Twin representation of the "as-is" network, it is best to use existing system artifacts as much as possible. In most cases, system artifacts of network topology and traffic profile are likely available and can be leveraged to develop most of the Network Digital Twin. For this proof of concept, we imported the MCEN network topology in the form of a Visio file using a Topology Converter utility. Since the Visio file describes the network via shapes and connections between them in XML format, the Topology Converter utility processes the XML elements and builds the equivalent Network Digital Twin.

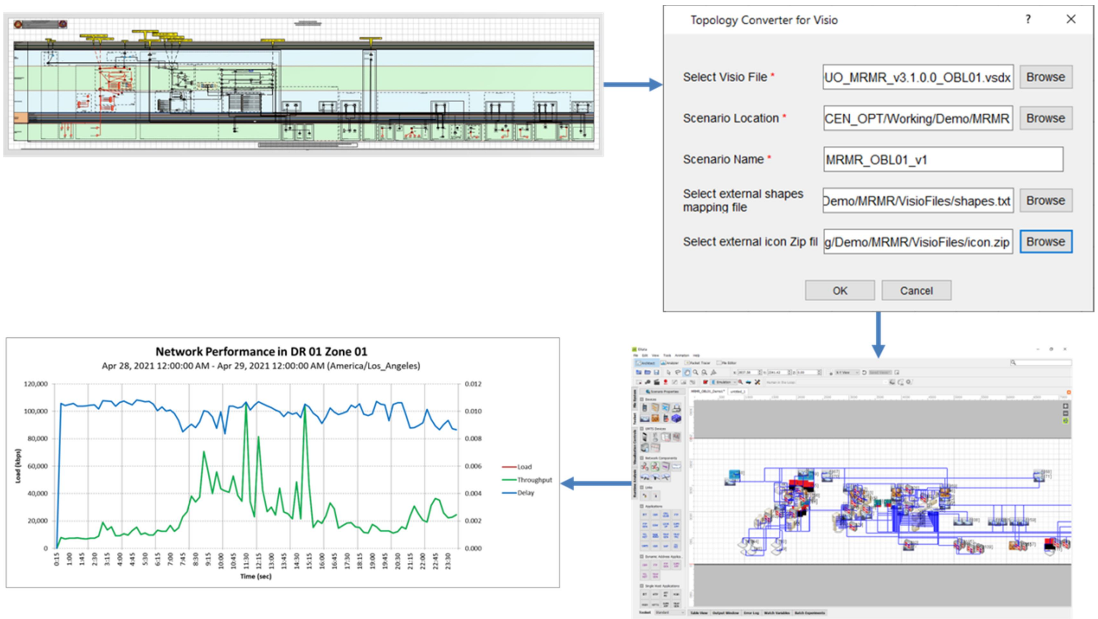

Figure 5. Creating and Analyzing Network Digital Twin for MCEN Network

Traffic profiles are available in different forms such PCAP (Packet CAPture) file or NetFlow records. Introduced by Cisco around 1995, NetFlow has become a de facto standard for traffic collection protocol, and has been used in popular network manager tools to monitor and analyze network traffic. In our use case, the MCEN network is monitored and managed by Network Node Manager [*Network Node Manager - Monitor Network Traffic 2021*], one of its functions is to collect traffic data through NetFlow, analyze and build traffic profiles for each network device.

Figure 6 shows graph of live data on one Distro Router of MCEN network for which traffic data are collected for 2 hours with granularity of 1 minute. This router acts as gateway between network segment and backbone segment.

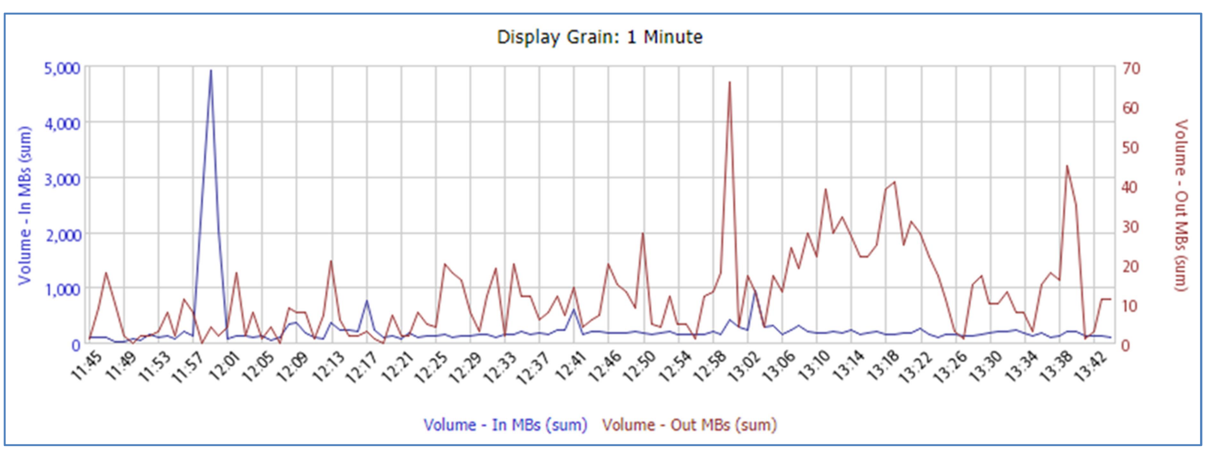

Figure 6. Collection of Live Traffic on Distro Router

Then, the live data were imported into Network Digital Twin that generates similar load (as shown Figure 7)

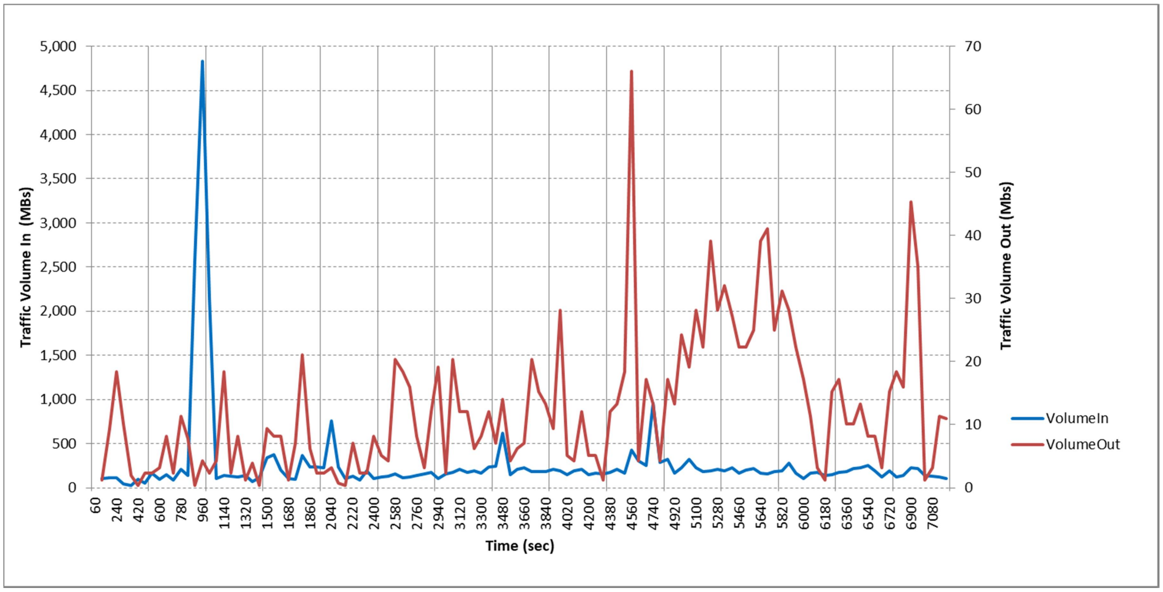

Figure 7. Traffic Volume Generated In Network Digital Twin

Given the above traffic volume, we executed Network Digital Twin of the "as-is" network to obtain baseline performance of load, throughput and delay as shown in Figure 8.

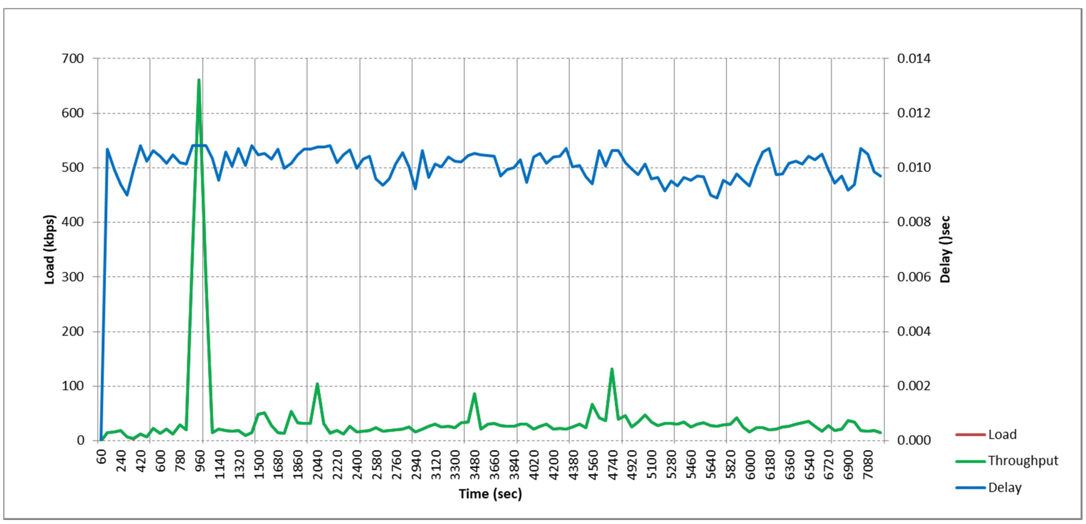

Figure 8. Baseline Performance In Network Digital Twin

Network Digital Twin Expansion ("To-Be" Network)

Next, we expanded the Network Digital Twin of the "as-is" MCEN network by adding simulated 5G network components. This high fidelity simulated 5G model includes a 5G network core, 5G gNBs and 5G handsets that are equipped for various FARP personnel and mission assets.

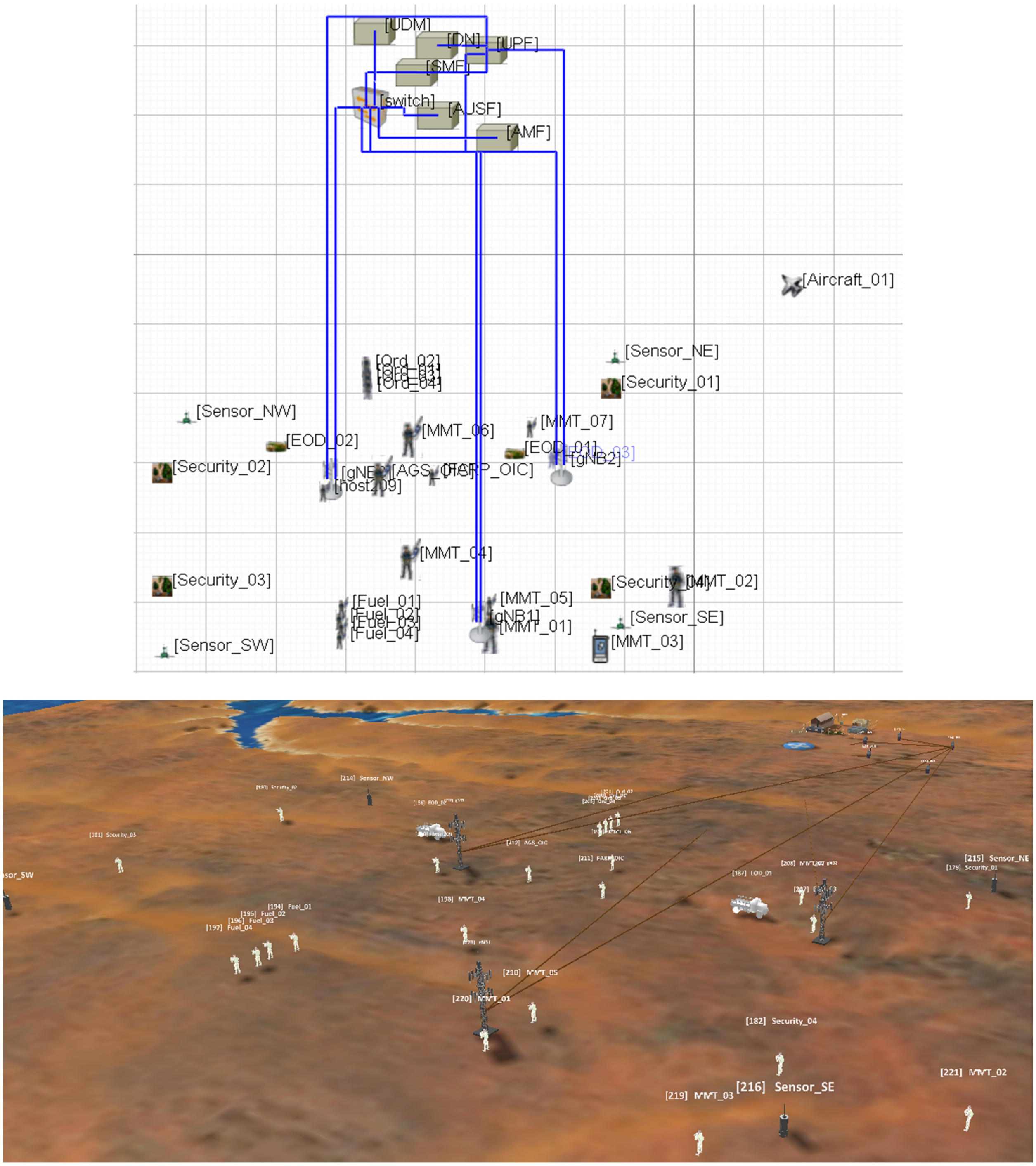

Figure 9. 5G Network and Components in FARP Mission

To analyze the additional capability provided by the 5G-enhanced "as-is" Network Digital Twin, we first need to ensure adequate RF coverage for the planned FARP mission site. The simulated 5G model can accurately portray RF transmission, propagation and reception, given 5G radios' characteristics such as transmission power, antenna (MIMO, beamforming), coding & modulation schemes and terrain of the FAPR site. Based on simulation runs, a heat map is generated to visualize RF signal reception quality throughout the entire FARP site, where RF signals are transmitted by one or multiple gNBs.

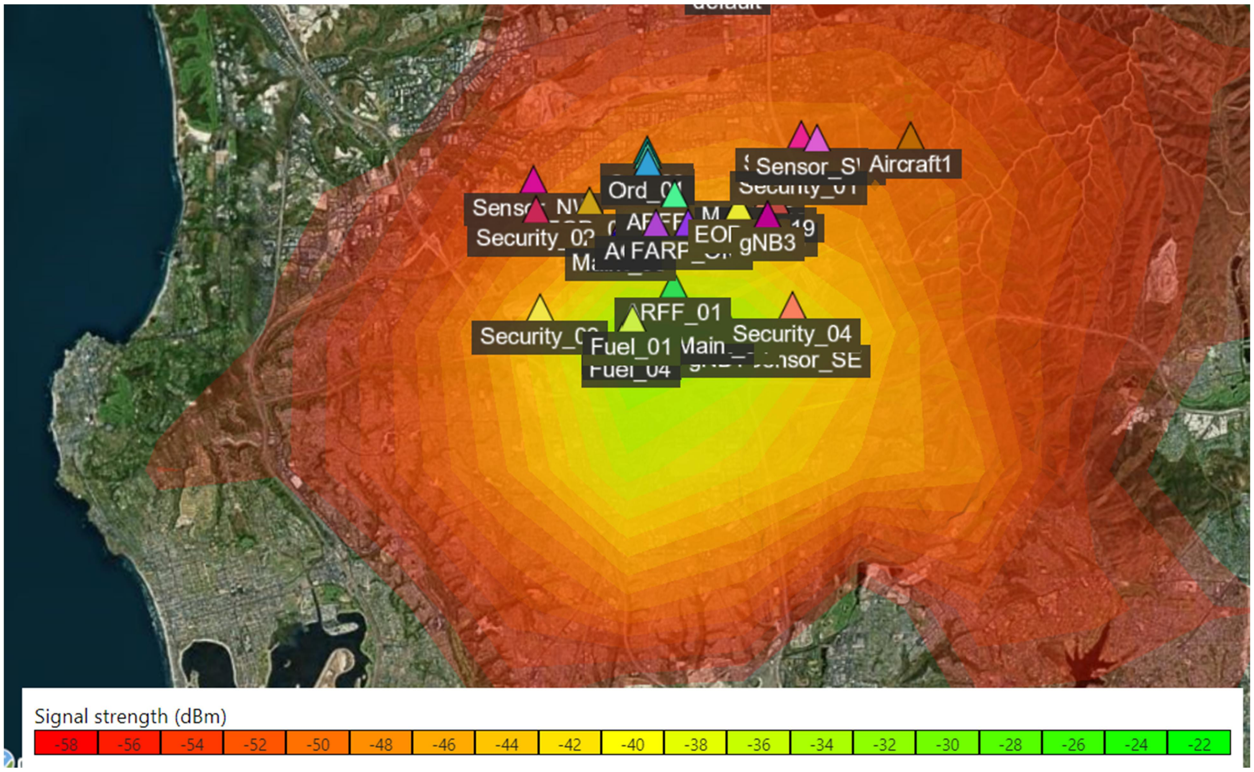

Figure 10. Using Heatmap to Analyze RF Coverage

FARP Traffic Profile

The FARP mission requires voice, data and video streaming. Each group (disarm, refuel, rearm and security) requires high quality voice communications, for which it is assumed that each voice call generate a load of 180 kbps. Security sensors are continuously monitoring their designated area, generating medium resolution video stream of 1 Mbps. If a sensor detects a possible threat, a security sensor can switch to higher resolution video stream (3 Mbps) to enable better assessment of the threat. As the FARP teams are serving the aircraft, a high resolution video stream is generated to monitor tasks performed and provide for visual inspection. In parallel, data from the previous mission are downloaded from the aircraft to OPFAC, and data supporting the next mission are uploaded. Those data transfers are assumed to be 10 Mbytes in each direction.

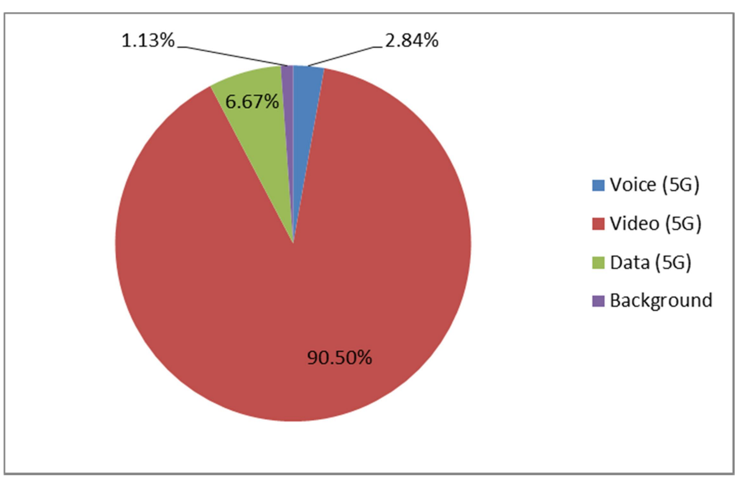

Figure 11. 5G Traffic Profile for FARP Mission

As shown in Figure 11, video traffic makes up most of the FARP traffic profile, data traffic comes in second; and voice traffic in third. The background traffic is actually live traffic already present in the "as-is" network as determined by the data collection discussed above, and it represents a small fraction of the overall traffic profile.

Network Digital Twin Simulation (Mission Rehearsal)

Adding the simulated 5G model to the Network Digital Twin of the "as-is" network is easily accomplished by connecting the 5G network core to the OPFAC located within MCEN network. The connection type could vary depending on how and where the mission rehearsal is planned. For example, if the mission rehearsal is planned on an existing Marine Corps Base using one of network segments from the base network as the OPFAC, we can simply assume a wired connection between 5G network core and the OPFAC location.

The FARP mission is executed with F-35B landing, being re-fueled and re-armed. During the mission, security sensors monitor the surrounding areas to detect possible threats. Using the developed FARP traffic profile described in the previous section, Network Digital Twin simulation of "to-be" network was executed with the resulting performance metrics as shown in Figure 12. The FARP mission lasts approximately 50 minutes, and during that period the network traffic load is significantly increased. However, it is shown that the "to-be" network is able to handle the increased load with delivery ratio of 100%. While the traffic delay was increased during this period, it was mostly under acceptable range of 100 milliseconds.

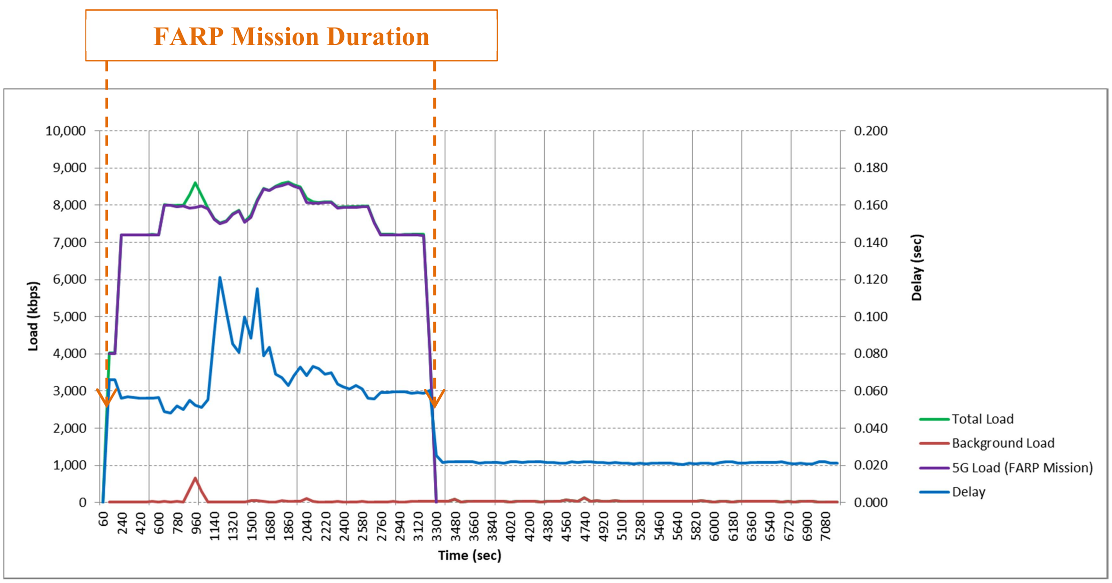

Figure 12. Network Performance for FARP Mission

Analysis of many different scenarios is now possible using the FARP traffic profile with appropriate modification. For example, during the FARP mission, a security sensor could detect suspicious vehicles as a possible threat and switch from medium to high resolution mode, resulting in additional traffic load of 2 Mbps. Then, as the threat is assessed as imminent, the OPFAC decides to insert a mobile security team into the area to eliminate the threat, resulting in additional traffic load of voice calls between the OPFAC and the mobile security team. We can easily modify the FARP traffic profile to account for those additional traffic loads. Then, we execute the Network Digital Twin simulation again with the modified FARP profile to generate a revised set of network performance metrics to assess the FARP mission under imminent threat of kinetic strike.

In another use case, the prototype can investigate if existing networking radios such as ANW2 can support the FARP traffic by adding the simulated ANW2 model to the Network Digital Twin of the "as-is" network and re-running the FARP mission on this new "to-be" network. Since ANW2 radios operate on 2 Mbps channels, the FARP mission requires multiple channels to support voice, data and video applications. However, ANW2 radios are still not able to handle heavy traffic type such as high resolution video (3 Mbps). Therefore, ANW2 throughput is significantly lower than 5G as shown in Figure 13. Then, the analyst can conduct further "what if " analysis such as replacing high resolution video with medium resolution in order to meet ANW2 bandwidth constrains, knowing that this type of video does not give the best visual assessment on the threat.

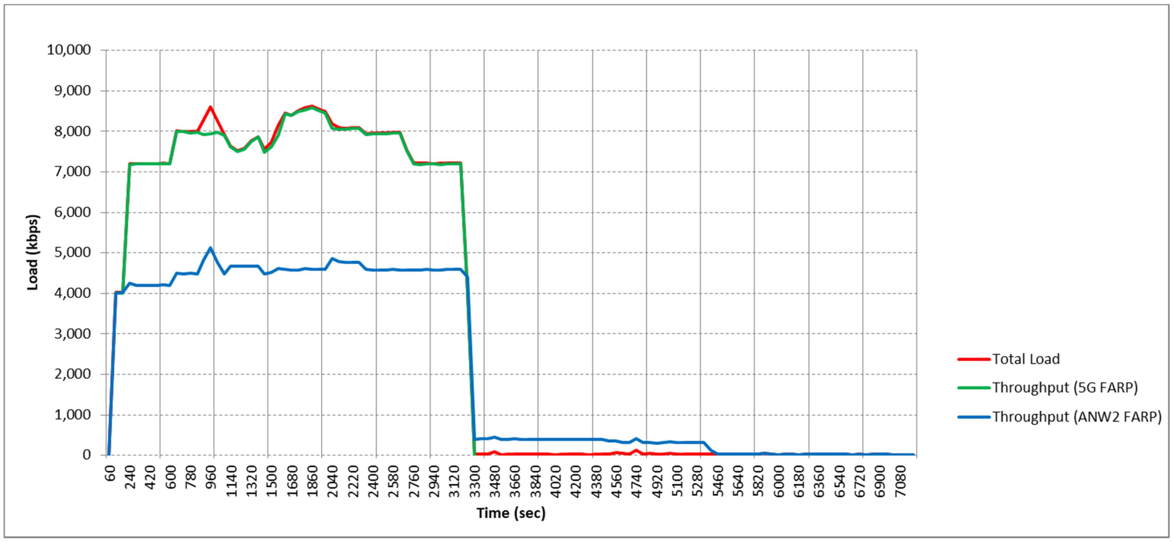

Figure 13. Comparison of Network Performance for FARP Mission Using 5G and ANW2

CONCLUSION

In this paper, we discussed integrating 5G capabilities into Marine Corps Live-Virtual-Constructive prototyping and experimentation using Network Digital Twin technology. The FARP mission was selected to demonstrate usefulness and effectiveness of the prototype in assessing how 5G capabilities can enhance mission execution in various operational conditions. Network Digital Twin technology was used to build a digital replica of an existing network that was then extended with a 5G network segment. Live traffic was also imported into the "as-is" Network Digital Twin to serve as baseline traffic. A FARP mission traffic profile was constructed and together with the baseline traffic, represented all operational traffic during the FARP mission. Network Digital Twin simulation was executed to generate performance metrics such as load, throughput and delay that were used to assess communication performance during the mission. Network Digital Twin simulation can also be executed in various "what-if" mission scenarios, such as additional traffic loading that results from an imminent hostile kinetic attack.

The Network Digital Twin prototype developed for this paper can be easily extended in multiple ways. For example, different 5G network configurations can be established and tested to determine optimal settings to meet specific mission requirements. Similarly, as configuration adjustments in the "as-is" network might be required to satisfy a new application class (e.g., FARP mission), testing those adjustments on the prototype can be quickly and cost-effectively accomplished before deploying them in the physical network. One particularly interesting configuration that warrants further investigation is how QoS (Quality of Service) in the MCEN network can operate with 5G network slicing [*5G Network Slicing*] to ensure end-to-end QoS for mission critical data. The Network Digital Twin prototype can also determine RF characteristics and optimal location of gNBs (i.e., 5G base station) to ensure best RF coverage in the area of operation. Jamming and other EW capabilities can be added to the prototype to investigate their impact on 5G spectrum availability and mission accomplishment.

Cyber resiliency assessment is another important area of assessment for the "to-be" network. With Network Digital Twin technology, it is possible and safe to perform active cyber attacks such as vulnerability exploitation, virus/worm propagation, or DDoS (Distributed Denial of Service) to actively and effectively assess defense measures against those types of attacks.

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