DEPLOYMENT OF A 5G NETWORK TESTBED TO SUPPORT DRONE OPERATIONS

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1 INTRODUCTION

In this paper, the MITRE Engenuity Open Generation 5G Consortium describes efforts related to the recent deployment of our first outdoors 5G private testbed, designed to support experimentation with drone operations. We also present early results obtained from the initial assessment of command and control (C2) link performance over this network.

1.1 Background on Open Generation and Objectives

The Open Generation 5G Consortium is a research and development collaborative launched by MITRE Engenuity in 2020. The consortium brings together diverse technical viewpoints and domain expertise from across multiple industries and market verticals to design, develop, demonstrate, and validate solutions that may be uniquely enabled by 5G capabilities.

The first area of focus selected by the consortium members for research and experimentation is Uncrewed Aircraft Systems (UAS), with the goal to enable use cases that safely operate beyond visual line of sight (BVLOS) and, therefore, can benefit from the connectivity provided by cellular networks. Examples of BVLOS use cases selected by the consortium for investigation include emergency response, package delivery, static infrastructure inspection, indoor warehouse operations, and Urban Air Mobility (UAM) or Advanced Air Mobility (AAM).

BVLOS operations face some common challenges that may be addressed by 5G and beyond:

- **Reliable and uninterrupted communications:** A key challenge is the need to provide C2 connectivity ensuring consistent quality and continuous availability to receive telemetry from and send commands to the small uncrewed aircraft, sUA (drone)[1].

- **Collision avoidance:** A key challenge is the need to improve the ability for sUA to detect and avoid (DAA) other aircraft (crewed and uncrewed) and obstacles. Current approaches for avoiding collisions utilize a varied set (or combination) of techniques, which may include onboard and ground based surveillance sensors. Several ground-based DAA approaches rely on the C2 link; for instance, with sUA transmitting airborne surveillance data to ground, and ground station transmitting ground-based surveillance data and commands to sUA. Ground-based DAA approaches are not capable of supporting automatic avoidance maneuvers during an interruption of the C2 link. As the utilization of 5G is expected to improve C2 link throughput, latency, and availability, it also has the potential to increase DAA reliability. The use of 5G may also allow new methods for sUA position broadcasting, including sUA-to-sUA communications and potential utilization of the cellular 5G network as a ground-based DAA processor. Additionally, cellular 5G networks can be used to provide localization where Global Positioning System (GPS) signal is not available (e.g., indoors) or as backup to GPS in case of outage.

[1] The terms small uncrewed aircraft (sUA) and drone are used interchangeably in this report. The term uncrewed aerial vehicle (UAV) is also used to describe sUA in 3GPP documents.

- 5G also addresses requirements for more advanced capabilities that can benefit UAS missions, such as high video throughput, low latency, and user data processing/learning capability in support of complex operations in dynamic and high-density environments.

The consortium has identified a path towards developing a set of experimental "sandboxes" to help accelerate deployment of the selected use cases. As part of this effort, we have recently deployed our first private 5G network at a Federal Aviation Administration (FAA) designated UAS Test Site located in central New York, which is now operational. With a 65 square mile operation area, the aviation range is managed by Northeast UAS Airspace Integration Research Alliance, Inc. (NUAIR), and supports BVLOS operations.

The Open Generation team has started to perform experiments at the Test Site and to collect and assess data to help quantify performance, both for C2 and mission payload, and plans to test solutions and approaches to improve the achievable performance for the selected use cases.

1.2 Document Scope

In Section 2, we provide an overview of the testbed and end-to-end network design, including network topology and architecture, the solutions adopted to add 5G connectivity to drones, and applications utilized in the initial setup. We also describe the metrics of interest; assess expected system performance based on system predictions; and present the approach, test equipment and data capture, and processing and visualization applications utilized to collect those metrics in the field and to characterize actual performance.

In Section 3, we share with the reader a few insights from our collective experience of deploying and managing a private outdoor 5G testbed for drones, including highlights of important steps, challenges faced, and recommendations learned from the process. We cover topics from pre-deployment to installation and operation, including integration efforts, network validation, and performance assessment.

In Section 4, we present, preliminary findings and Key Performance Indicators (KPIs) obtained from drive and flight tests in the field, comparing with prediction results when equivalent circumstances apply.

In Section 5, we discuss plans to perform additional experimentation for the use cases identified for this testbed. This section presents a summary of upcoming experiments to enable, assess, and improve performance for the selected use cases.

2. Testbed Design and Components

2.1 New York UAS Test Site Overview

The New York UAS Test Site is one of seven FAA-Designated UAS Test Sites in the United States. Owned by Oneida County and managed by NUAIR, the New York UAS Test Site consists of a highly instrumented UAS testing facility at Griffiss International Airport in Rome, New York (KRME). NUAIR is a New York–based nonprofit organization that provides expertise in uncrewed aircraft systems operations, aeronautical research, safety management and consulting services, and limited Flight Test Operations from the FAA-designated New York UAS Test Site under BVLOS conditions with sUAS less than 55 lbs. Griffiss (KRME) FAA Contract Tower is the responsible Air Traffic Control facility. KRME is within the specified boundaries of this airspace. Operations, subject to FAA approval, will include a combination of Visual Line of Sight, and BVLOS flights, comprising multiple sUAS operating concurrently. Flights will initially be conducted in Classes D, E, and G airspace at a max altitude of 400 ft above ground level (AGL) with an operating area of approximately 65 square nautical miles (9.9 NM x 6.6 NM) around Griffiss International Airport (KRME), New York, as shown in Figure 1.

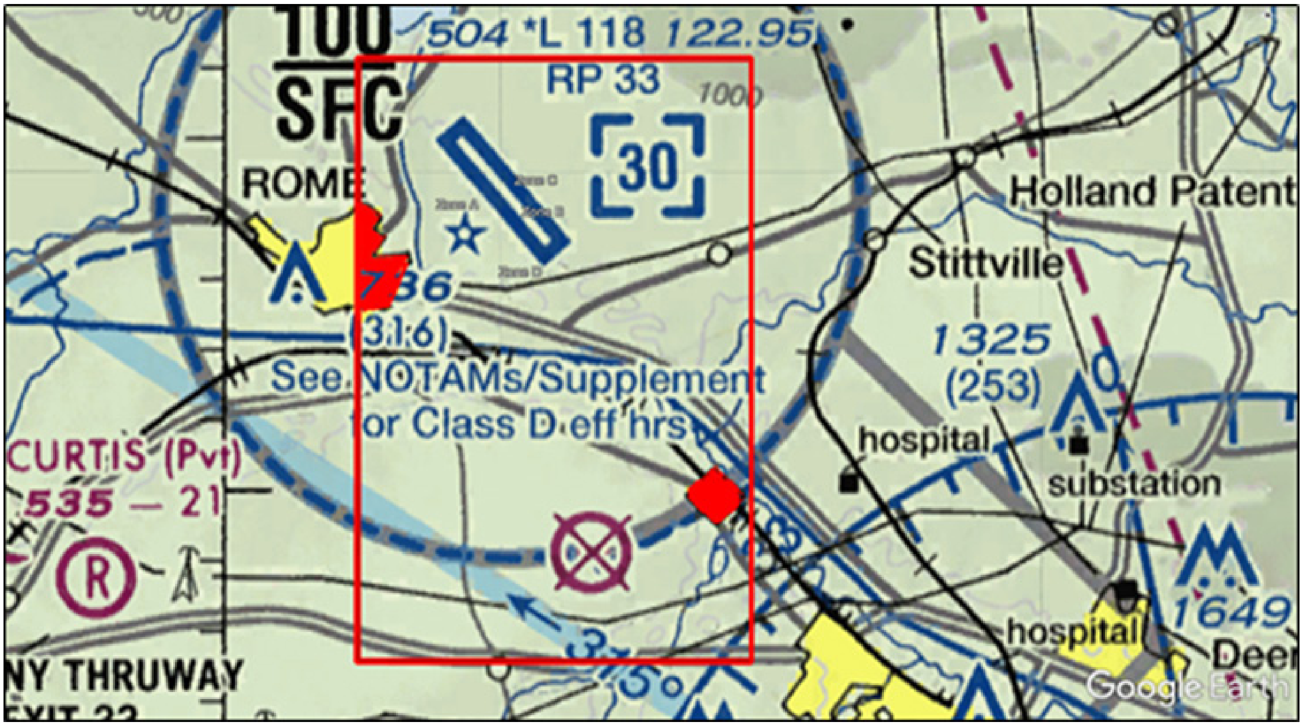


FIGURE 1: OPERATING AREA – RED ZONES ARE EXCLUDED

2.2 Network Architecture and Setup

Our private 5G cellular network solution, Nokia Digital Automation Cloud (DAC) was deployed outdoors using commercially leased spectrum at the New York UAS Test Site for experimenting with prioritized BVLOS use cases of UA operating over the 5G network. A high level diagram of the network architecture is illustrated in Figure 2.

Key highlights of the Nokia DAC solution are listed below:

- 5G Stand-Alone (SA) network
    - Only 5G New Radio (NR) Radio Access Technology is deployed, and Next Generation Radio Access Network connects to 5G Core (5GC).
    - Private 5G network deployment to quickly enable advanced, low latency, and robust wireless connectivity solutions for sUAS vertical market and many more in the future without relying on public cellular networks.
        - Public Land Mobile Network (PLMN) code 999-40.
    - 3rd Generation Partnership Project (3GPP) Release 15 based 5GC supports cloud native architecture, network functions are containerized on a single-server solution. The following functions are available:
        - Access and Mobility Management Function (AMF) handles network registration, connection, and mobility management related procedures.
        - Session Management Function handles Protocol Data Unit (PDU) session management and User Equipment (UE) IP address management procedures.
        - User Plan Function (UPF) handles user plane packet routing and forwarding as a mobility anchor point and provides interconnection to the external Data Network and handles Quality of Service (QoS).
        - Authentication Server Function provides UE authentication service.

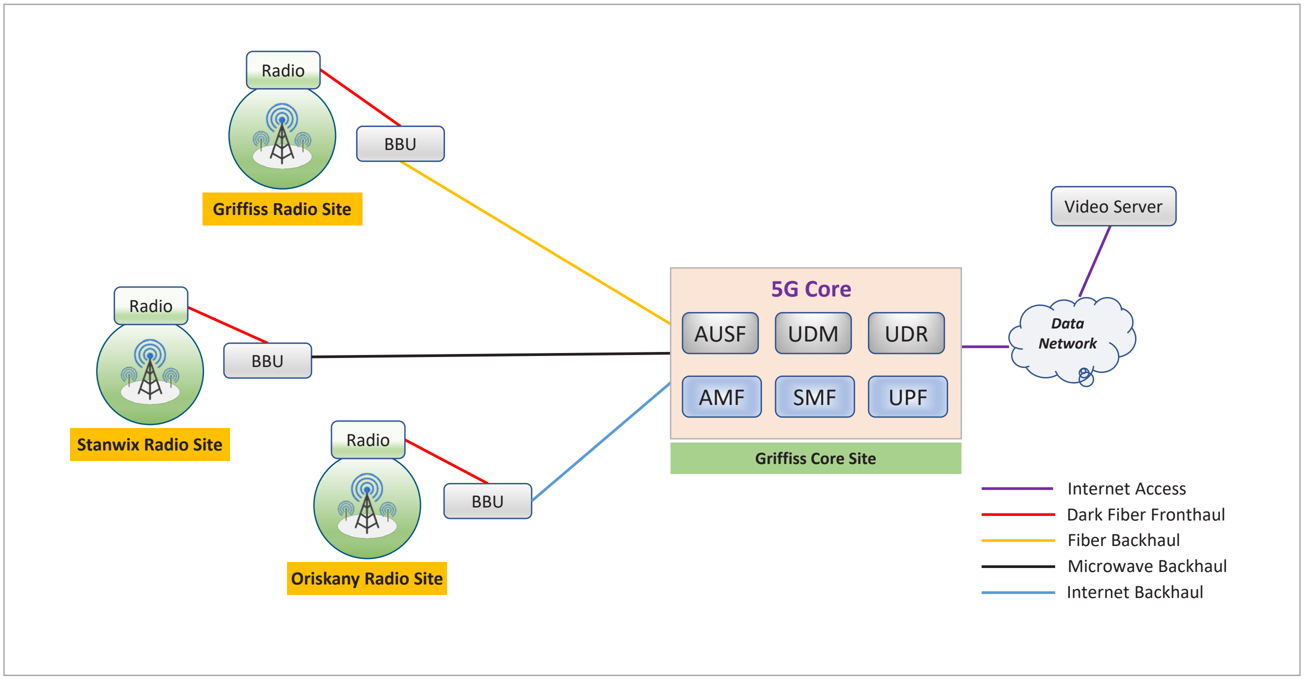


FIGURE 2: 5G STAND-ALONE NETWORK AT TEST SITE

   - Unified Data Management (UDM) manages subscription and generates 3GPP Authentication and Key Agreement credentials.
   - Unified Data Repository stores subscription data used by UDM.
 - Classical gNB architecture includes Remote Radio Head (RRH) and Baseband Unit (BBU) on a proprietary hardware.
   - Digital Common Public Radio Interface (CPRI) is supported as front haul transport between RRH and BBU.
   - Ethernet or Fiber interface is supported as backhaul transport between BBU and AMF/UPF for terminating N1/N2 and N3 interfaces, as defined in 3GPP.
   - Ethernet or Fiber interface is supported between two BBU for terminating X2 interface.
- 5G NR Band:
  - Frequency Division Duplex Band n66.
  - Bandwidth 5 MHz.
- Radio Edge sites
  - After performing a site survey with local field engineers, careful network planning with the Nokia DAC team, and performing an Radio Frequency (RF) study with radio planning software; radio edge sites were selected to provide ubiquitous 5G coverage to UA on the ground (for UA takeoff, landing, and emergency landing) and in the air for supporting BVLOS operations (for the intended flight path shown in purple in Figure 3) and conducting experiments for identified high priority use cases.
  - Each radio edge site needs to support the installation of a RRH on the Tower, the BBU in an environmentally controlled server room or outdoor cabinet, Alternating Current (AC) power source with a rectifier to power the Direct Current (DC) powered RRH and the BBU, a fronthaul dark fiber connection between the RRH and the BBU for CPRI interface, a backhaul transport to the 5GC Network for 5G control and user plane traffic between the Radio Access Network (RAN) and the 5GC.

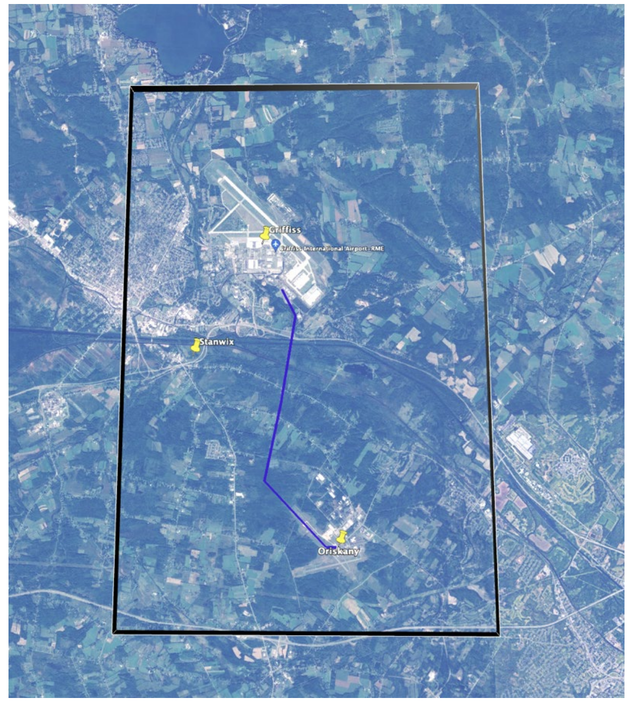


FIGURE 3: 5G RADIO SITES LOCATIONS AT NUAIR TESTBED

- Centralized Core Site:
  - The Griffiss location was also selected as the centralized core site to host the 5G Core network. This site provides fast and reliable connectivity to the Internet for:
    - 5G network operation and configuration management
    - Supplementary services (such as Domain Name System and Network Time Protocol) for cloud infrastructure
    - Routing application traffic to the internet or local servers for 5G User Equipment (UE).
  - This site also provides an environmentally controlled server room with a 19” rack for

installing server, router, and firewall. AC power source with option to use rectifier for DC-powered units. This site connects to each radio edge site using a backhaul transport for 5G control and user plane traffic between RAN and 5GC.

2.3 Drone Integration With 5G Connectivity

Flight tests were conducted with an Aurelia X6 Pro. MITRE Engenuity has previously designed, built, and flown several drones, and the X6 Pro matched many of our preferred design considerations:

- **Pixhawk Orange Cube Flight Controller:** Updated Free Software ArduPilot platform with "ADS-B in" support.
- **RFD900+ 915 MHz radios:** Excellent range with a combined telemetry and radio-controlled module for lighter weight and lower power.
- **Hexcopter design:** Allows for at least one motor failure without loss of control.
- **Over 10 lb. payload capacity:** Allows for a flexible range of mission payloads.
- **Over one hour endurance:** Required for the BVLOS missions that are planned.
- **Typical components integrated in a standard manner:** Nothing too exotic or novel for high reliability via operational experience.

The mission payload consists of a Raspberry Pi 4B as the mission computer with a TechShip MU201 USB-to-M.2 adapter interface board and Telit FN980m M.2 modem module. Raspberry Pi is a small light platform with millions of units shipped assuring good Free Software support and generally hardware reliability. We originally used a development kit from Telit to hold the FN980m, but it was very large and not conducive for any application outside of a lab environment. Instead, we are using the TechShip MU201 interface board which provides a high quality, but very small USB to M.2 interface to directly address the modem.

We explored many 5G modem products but, thus far, the Telit FN980m has the best support for our private network, as many of the other modems did not support our experimental PLMN 999:40 network. The Telit can log all the parameters, such as power, quality, and signal-to-noise ratio that we are most wanting to capture. A Raspberry Pi camera was used as the primary camera. These components were integrated into a small custom-made aluminum box and attached to the bottom of the drone. The box also includes a mount for a mission camera gimbal to be installed later.

To best support the modem without having to do much configuration ourselves, we discovered that Ubuntu 22 supports the Telit FN980m. That is, simply plugging in the modem with a valid Subscriber Identity Module (SIM) card will cause the wireless network to automatically connect and provide network access to the computer. ModemManager and NetworkManager work together with the Qualcomm Mobile Station Modem Interface (QMI) Library to configure the modem transparently.

Directly using the QMI Library is probably the best way to communicate with any Qualcomm-based modem, but the Telit firmware also provides an AT-command interface to query and configure the modem. In the interest of time, we developed a simple program called "read_telit" to both configure the modem on boot and query the modem once per second with eight AT commands that provided the data elements required. The program parses the output of the AT queries and presents the output in a comma separated value format for export. In the interest of simplicity, the program sends the output to standard out where the traditional UNIX "netcat" command reads the stream and sends the stream on to our Azure server over UDP.

To connect the Mavlink packets between the drone and the Ground Control Station (GCS), we originally set up a Virtual Private Network (VPN), which did work; however, there were two undesirable side effects. First, the latency of VPN is a known issue that was going to eventually affect the fidelity of our connectivity. Second, more pressing was the VPN we could set up via Azure involved dynamic IP addressing. Whenever there was an interruption in connectivity, the VPN IP address could change. This made direct connections between the drone and GCS unreliable and forced a manual process of determining which device had which IP address to configure the connection. The solution was to use the Azure server with a fixed IP as a MavLink packet router. The drone and the GCS now both connect to the Azure server, and the packets are forwarded amongst all endpoints. This feature allows for an arbitrary number of GCS to connect and monitor the flight remotely. Security is a concern and is currently handled by specifically only allowing the public static IP address of our private 5G network to connect to the service (whitelist). Future work will consider a more scalable security framework to allow for a more flexible network short of re-inventing VPN. In the future, this router service will be moved to a local server co-located with the 5G Core to minimized latency for more advanced use cases.

- Video was our primary mission data payload. The software package libcamera provides the basic interface to the camera to read the raw output stream to either the GCS or Azure server. Converse to various formats was usually handled with GStreamer, but FFmpeg and the VLC media player were used as needed for the application. We also configured the drone to live stream direct to YouTube, which incurred some delay but gave us the combination of sharing, recording, and live monitoring we are looking for with our video services. We are currently exploring Free Software options to allow for similar functionality in a private server solution to minimize latency.

Performance metrics of interest are discussed in the next section. Latency and throughput are included in our set. Means to capture latency and throughput-related performance metrics during our testing are as follows:

- Latency: measured with scripts using ping. The "-D" option is used to timestamp the results.
- Throughput: the raw number of bytes transferred through the network device is continually captured by logging the Linux kernel virtual file "/proc/net/dev" with a time stamp.
- Speed capacity testing: IPerf3 is run manually periodically to test the maximum transfer speed in both directions.

The output of the read_telit, ping, and /proc/net/dev logs were live streamed to the Azure server, which also hosted a custom-made dashboard using Python and StreamLit that could display real-time plots of key performance metrics. More details on the dashboard are provided in Section 2.6.4.

The 5G-integrated Aurelia Drone is shown in Figure 4.

FIGURE 4: 5G-INTEGRATED DRONE

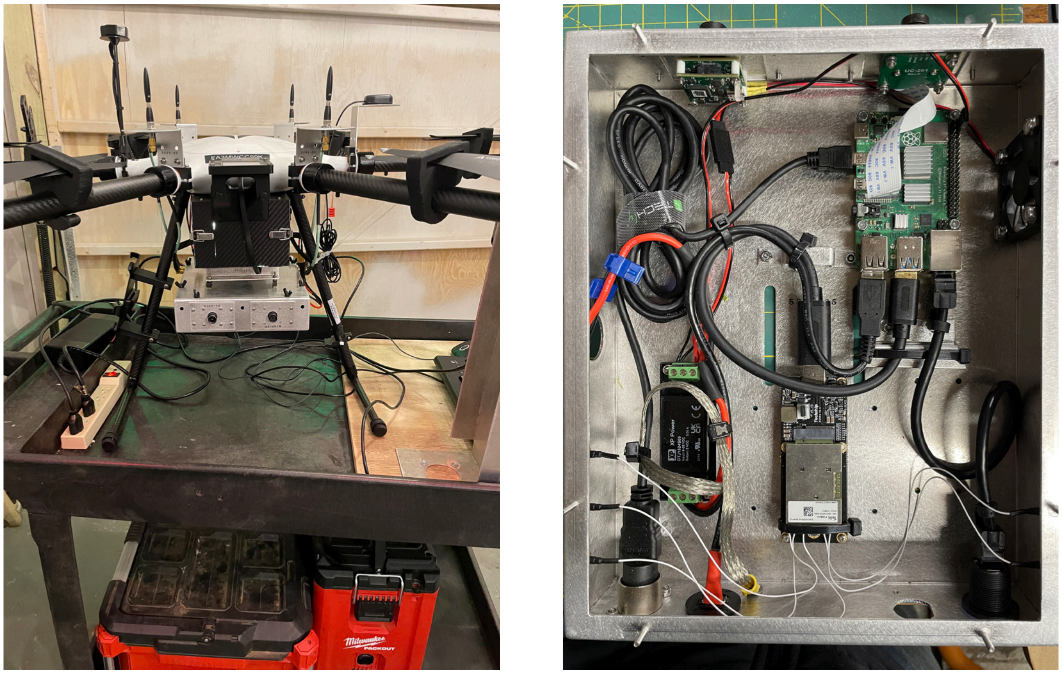


FIGURE 5: 5G-INTEGRATED DRONE WITH CUSTOM PAYLOAD, FRONT, AND INTERIOR VIEWS

2.4 Performance Metrics of Interest

5G NR link metrics of interest include:

- Synchronization Signal – Reference Signal Received Power (SS-RSRP)
- Synchronization Signal – Reference Signal Received Quality (SS-RSRQ)
- Synchronization Signal – Signal to Interference and Noise Ratio (SS-SINR)
- Received Signal Strength Indicator (RSSI)
- Throughput on the downlink (DL)
- Throughput on the uplink (UL)
- Latency
- UL transmit power (i.e., the power transmitted from the drone's 5G NR UE to maintain connectivity and to transmit telemetry and payload data from the sUA to the ground)
- Modulation and Coding Scheme (MCS) on the DL
- MCS on the UL

SS-RSRP, SS-RSRQ, SS-SINR, and RSSI are indicators of the performance of the 5G NR link that is used to transmit C2 commands from the ground to the sUA (i.e., the [DL]). SS-RSRP measurements are used by the network for multiple purposes such as cell selection, cell reselection, power control calculations, and mobility procedures. SS-RSRQ may also be used to support cell selection, cell reselection, and mobility procedures. To determine SS-RSRQ, the RSSI metric needs to be obtained. SS-SINR is an optional UE capability, and it can be used for connected mode mobility procedures.

DL throughput over the 5G NR link at any given time is impacted by the actual MCS on the DL transmission at that time. Similarly, UL throughput is impacted by the actual MCS on the UL.

Data collection and analysis will enable us to assess how the 5G NR link performance varies with sUA altitude for various altitudes and flight paths at the NUAIR testbed.

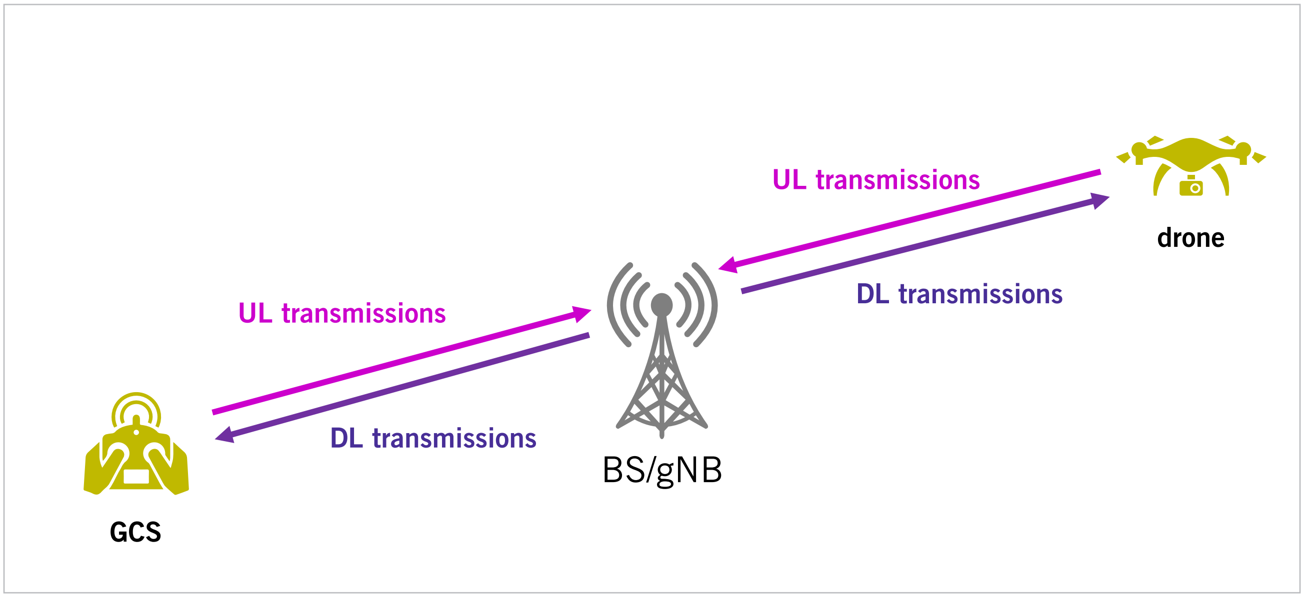


FIGURE 6: 5G NR DL AND UL TERMS IN A DRONE AND GCS CONTEXT

Further analysis of the data collected during field measurements for such metrics will inform upcoming experiments at NUAIR for use cases identified by the MITRE Engenuity Open Generation Use Cases Working Group.

The diagram in Figure 6 illustrates uplink and downlink transmissions for scenarios in which both the GCS and the sUA are users in the same 5G NR network, which for the deployment described in this report is the private 5G SA network at the NUAIR testbed.

2.5 System Predictions

Signal level and signal quality predictions shown in this section have been obtained using the Atoll RF network design and optimization tool. Predictions assumed that all three radio sites described in Section 2.1 are active. These predictions use 10-meter digital terrain data and land use/clutter data. All predictions shown in this section refer to the n66 band.

The figures also show a sample envisioned sUA flight path between Griffiss and Oriskany to be utilized during experiments.

2.5.1 Signal Level (SS-RSRP) Predictions

Figure 7 shows a set of average SS-RSRP predictions for sUA flying at different altitudes AGL. The assumed sUA altitude is 30 ft AGL for the results shown in a), 100 ft AGL for those in b) and 300 ft AGL for the results in c). Results indicate that as the sUA altitude increases from 30 ft to 300 ft AGL, the SS-RSRP improved, as the impact of terrain and/or clutter is reduced.

Terrain and/or clutter impacts are most noticeable for sUA at the lower altitudes. As the sUA altitude increases to 100 ft AGL, the terrain impact decreases. No terrain or clutter impact is seen in the SS-RSRP prediction for sUA at 300 ft AGL.

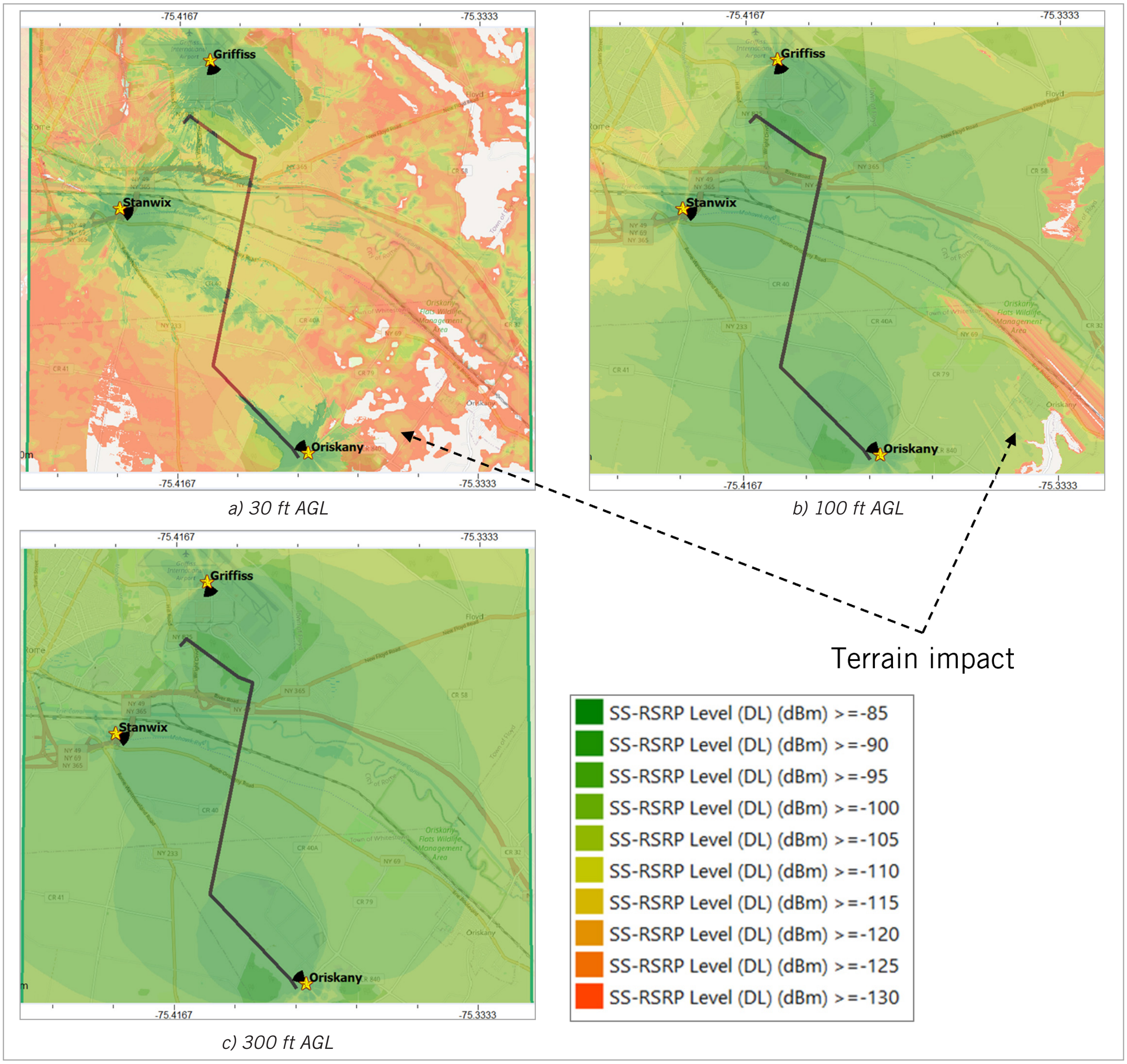


FIGURE 7: 5G NR DL AND UL TERMS IN A DRONE AND GCS CONTEXT

2.5.2 Signal Quality (SS-RSRQ and SS-SINR) Predictions

In Figure 8, we present a sample set of average SS-RSRQ predictions. The assumed sUA altitude is 30 ft AGL for the results shown in a), 100 ft AGL for those in b) and 300 ft AGL for those presented in c). As with the SS-RSRP results described in the previous section, terrain, and/or clutter impacts are most noticeable for the sUA at the lower altitudes (e.g., 30 ft).

Comparing the SS-RSRQ results at 100 ft and 300 ft AGL, it can be observed that, in areas not impacted by terrain, SS-RSRQ decreased as the drone altitude increased. This is shown as a

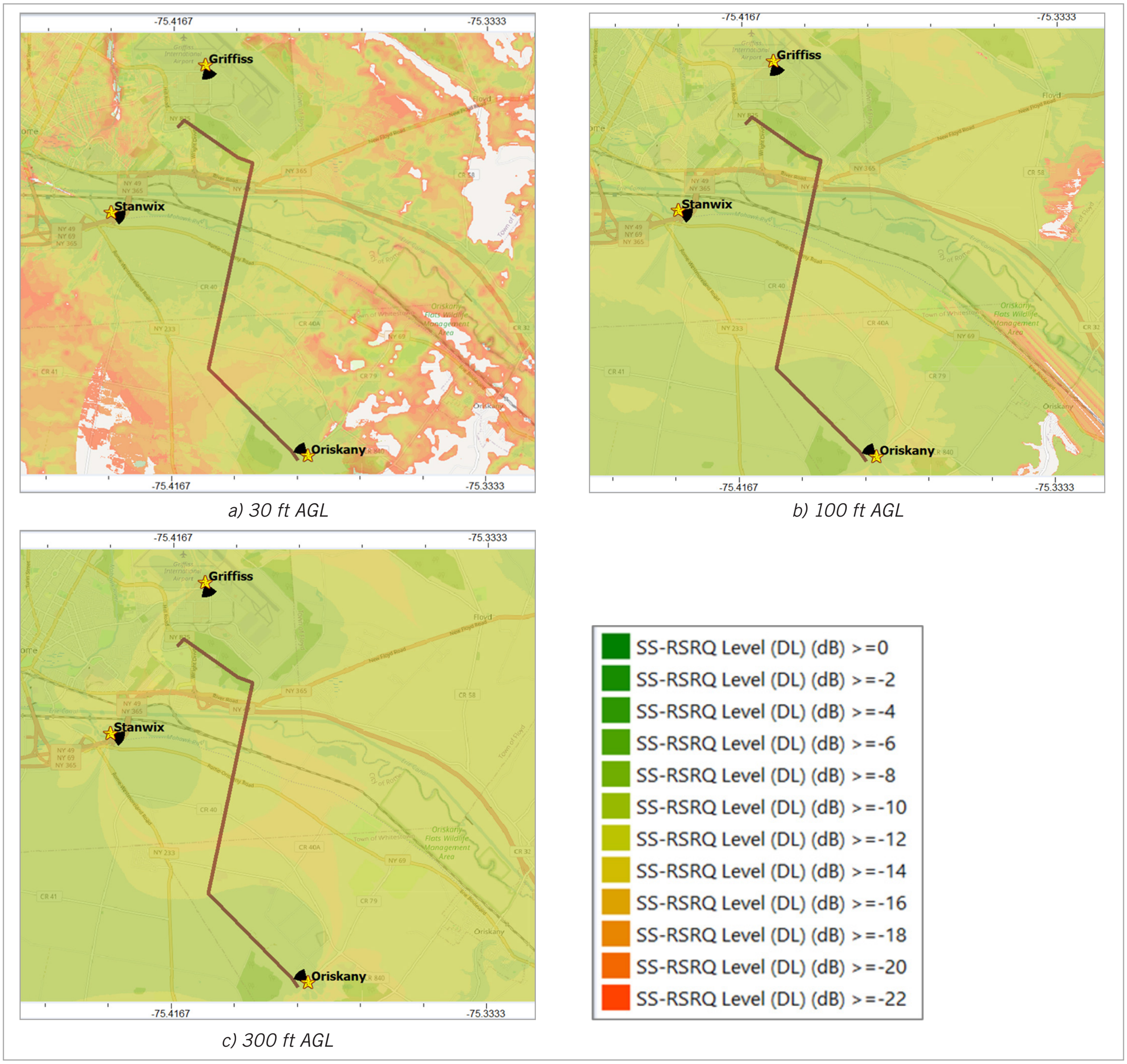
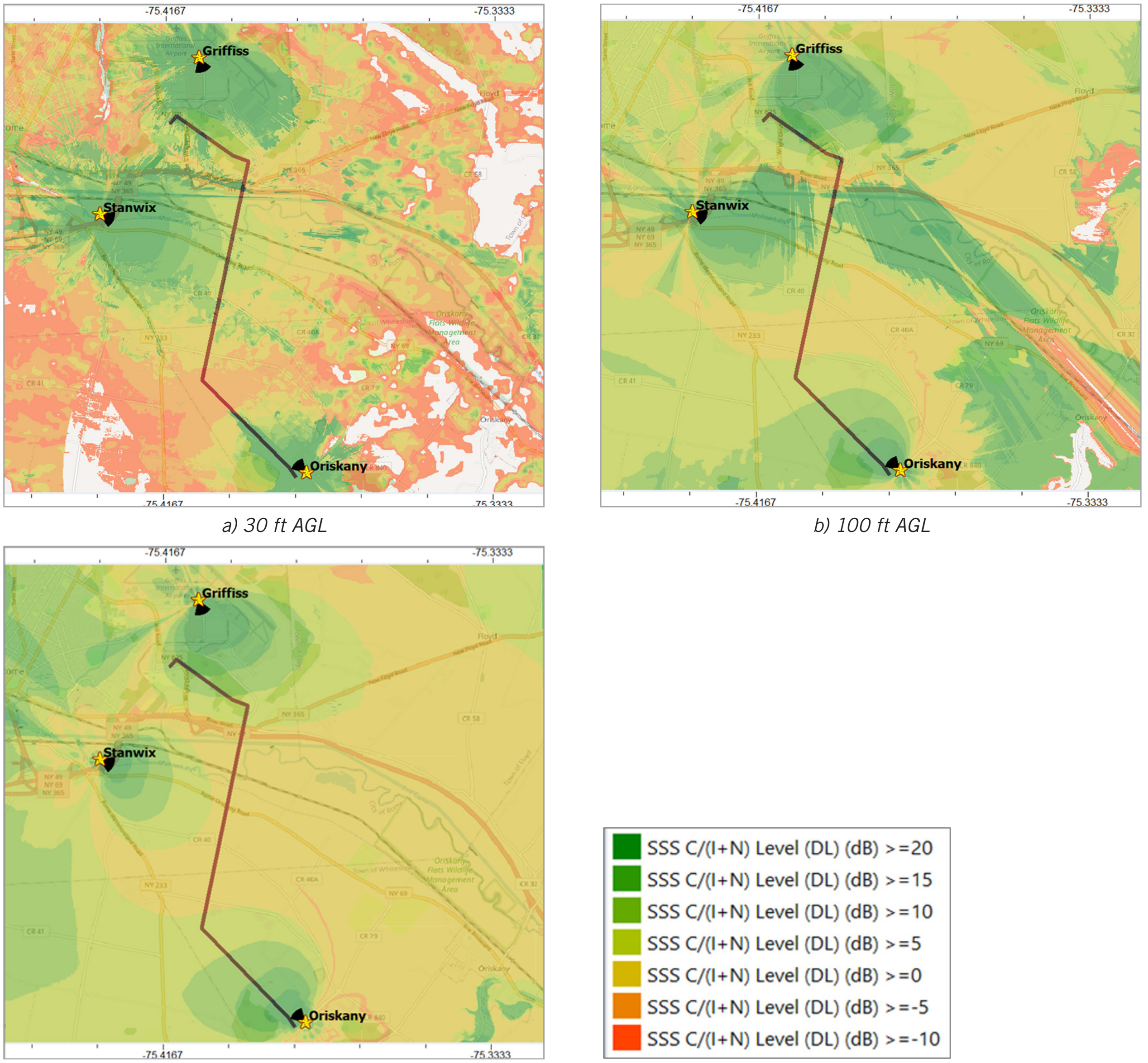


FIGURE 8: PREDICTIONS OF AVERAGE SS-RSRQ FOR SUA AT 30, 100, AND 300 FT AGL

decrease in green areas in c) compared to b), and it is due to intra-system interference effects that would be experienced by sUA at altitude once all three radio sites are active.

Average SS-SINR predictions for sUA flying at different altitudes are shown next. As with the SS-RSRQ predictions, results are shown for sUA altitudes of 30 ft, 100 ft, and 300 ft AGL. SS-SINR results also show that terrain impacts are most noticeable for the sUA at the 30 ft altitude.

Comparing the SS-SINR results at 100 ft and 300 ft AGL, it can be observed that in the areas not impacted by terrain, SS-SINR decreases as the drone altitude increases. Smaller areas in green are



a) 30 ft AGL

b) 100 ft AGL

c) 300 ft AGL

FIGURE 9: PREDICTIONS OF AVERAGE SS-SINR FOR SUA AT 30, 100, AND 300 FT AGL

seen in c) for a sUA altitude of 300 ft AGL than are shown in b) for a sUA altitude of 100 ft AGL. SS-SINR is expected to decrease as the sUA altitude increases from 100 ft to 300 ft AGL. This trend is similar to the one observed for SS-RSRQ.

The signal quality predictions (i.e., SS-RSRQ and SS-SINR) shown in this section illustrate the impact of intra-system interference effects from within our private 5G network that would be experienced by sUA at altitude once all three radio sites are active.

In Section 4.3, we present measurement results that include SS-RSRQ and SS-SINR. Those results capture intra-network interference effects from the radio sites active within our network at the time of the measurements, and interference effects from external sources in the environment.

2.6 Performance Data Collection

2.6.1 Field Data Collection Setup

To meet the present and future demands that are necessary to work in the field, MITRE Engenuity designed and built a mobile laboratory over a custom 20-foot V-Nose heavy duty trailer, as illustrated in Figure 10 below. The interior was designed to be reconfigurable to meet evolving needs. The trailer is equipped with interior heat, air conditioning, AC outlets, and a Honda EU7500 generator.

To measure raw RF power, we used a Keysight N9914B Fieldfox Analyzer in spectrum analyzer mode with an omni directional antenna. To capture 5G network metrics, we used a Rhode and Schwartz tool called QualiPoc further described in Section 2.6.3. We also designed and fabricated a ground-based mobile modem equivalent to what was used in the drones used for drive testing, as shown in Figure 11. These devices are illustrated below.

FIGURE 10: MITRE ENGENUITY MOBILE LABORATORY

FIGURE 11: DATA COLLECTION DEVICES

We also performed static point measurements using a BlueSky mast system. We mounted both a Ridged Waveguide Horn and the QualiPoc, as illustrated in Figure 12.

FIGURE 12: SETUP FOR STATIC POINT MEASUREMENTS

2.6.2 5G Network Operation

The Nokia DAC 5G solution includes a self-service portal that was primarily used for basic monitoring and operations of the private 5G network. It provides a quick view of the overall network status and allows for simple network management actions such as network monitoring, configuration management, fault management, and user account management. The key features of self-service portal are:

- Real-time health of overall network and active and historical alarms, inventory management, basic troubleshooting tool with quick links to documentation and helpdesk portal.
- Status and view basic configuration of radio, baseband unit, and 5GC network.
- Display real-time status of connected devices, network statistics for data transfer.
- Provisioning and de-provisioning of SIM cards, static or dynamic IP allocation of user devices.
- QoS profile management for prioritizing critical and non-critical communication.
- Data Network Name configuration.
- Radio Management – allows to quickly lock, unlock, and reboot cell.

The Network Management Application Programming Interface (API) provides detailed network performance and can be integrated to any Network Management System (NMS) (e.g., Open NMS) or external database using Operation Support Systems mediator and mediator plugin.

2.6.3 Rohde and Schwarz (R&S) 5G Test and Measurement Tools

As part of the 5G network deployment, the following commercially available R&S tools were used for:

- drive and flight test to validate 5G network coverage at different locations on ground and in air

- 5G user equipment registration and PDU session procedures with 5GC in test PLMN configuration
- running various throughput and latency tests
- collecting radio performance KPIs.

R&S® QualiPoc Android – A handheld troubleshooting device from R&S that runs on a smartphone (Samsung Galaxy S22) was used for RF optimization and network quality assessment, as shown in Figure 13. It provides a rich set of service quality tests for data and video, advanced optimization features such as 5G technology, PLMN, channel and cell locking.

R&S® Smart Monitor – is a real-time service quality monitoring tool that provides latest results from probes such as QualiPoc in real time.

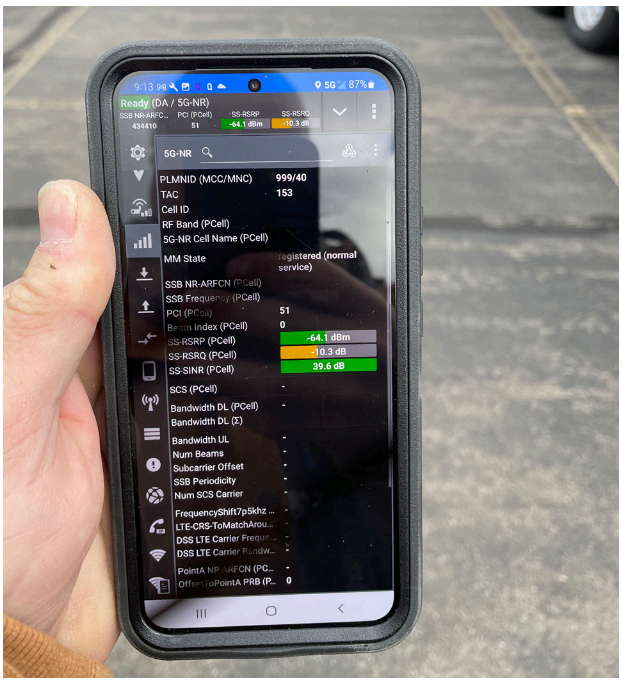


FIGURE 13: SAMPLE MEASUREMENTS CAPTURED BY THE QUALIPOC

2.6.4 MITRE Engenuity Developed Custom Dashboard

In addition to the radio performance KPIs described above, the MITRE Engenuity team developed a custom-built dashboard for enabling visualization of KPIs reported from the Telit modem and of data obtained from the custom program described in Section 2.3.

The dashboard uses Python and Streamlit, and it provides key features to allow for:

- Data visualization in both real-time and post-processing modes.
- Geographic visualization of signal strength, signal quality, and other KPIs over OpenStreetMap.
- Comparison between predicted RF coverage and the measured RF coverage.
- Time series and statistical analyses.
- Examination of relationships in data (e.g., data rate versus height).

Network deployment and early testing activities benefited from the Live-View feature in the dashboard, as captured in Figure 14. The Live-View feature allowed our team to see real-time data being captured in the field. Sample results from post-processing measured data using the custom-built dashboard are shown in Section 4.2.

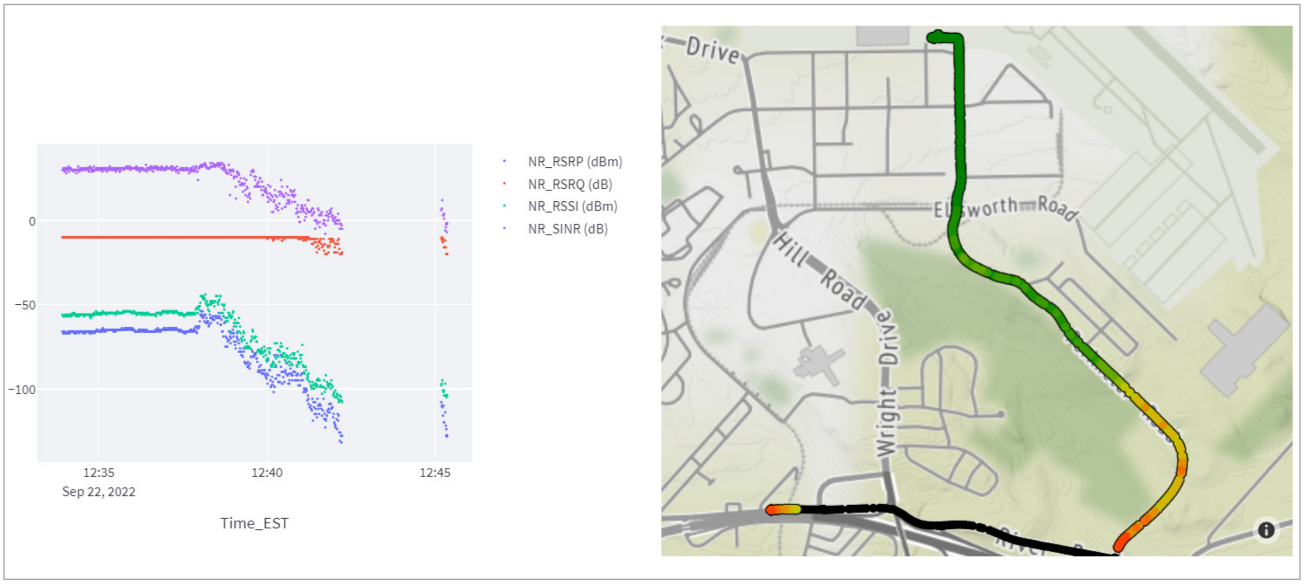


FIGURE 14: TELIT KPI MONITORING WITH LIVE VIEW OPTION OF CUSTOM-BUILT DASHBOARD

3 Deploying the Network

In addition to the metrics-related findings from our preliminary operation, the Open Generation team has identified some **insights and recommendations related to deploying and operating a private 5G experimental network**, which we consider worth highlighting in this section.

We also mention some specific challenges that we have faced throughout the process of deploying and starting operation of the network, to help share the experience with readers who may happen to face similar challenges.

3.1 Private Network Deployment

As the Open Generation team moved on with the intent to deploy the consortium's first 5G private network, several key pre-deployment steps were identified. These steps are illustrated below and described in the next paragraphs.

1. **Define network requirements:** Through the work of defining the target use cases and experiments envisioned for the network, key performance requirements need to be well understood. Those include expected coverage for targeted areas of operation, whether those areas are indoors or outdoors, along with specific propagation characteristics (e.g., speed, altitude supported). It also includes expected throughput and latency levels for downlink and uplink, network reliability, ability to perform processing at the edge, and other key expected capabilities. Based on the performance requirements, several aspects related to the potential alternatives for technology solutions can be narrowed down.
2. **Spectrum band decision:** The decision on what band to be utilized needs to happen early on, as it affects the path forward on multiple decisions for the network. This decision depends on multiple factors, such as:
   - Understanding spectrum available and regulations related to its use.
   - Choice of a band that is not restricted for aerial use by spectrum regulations.

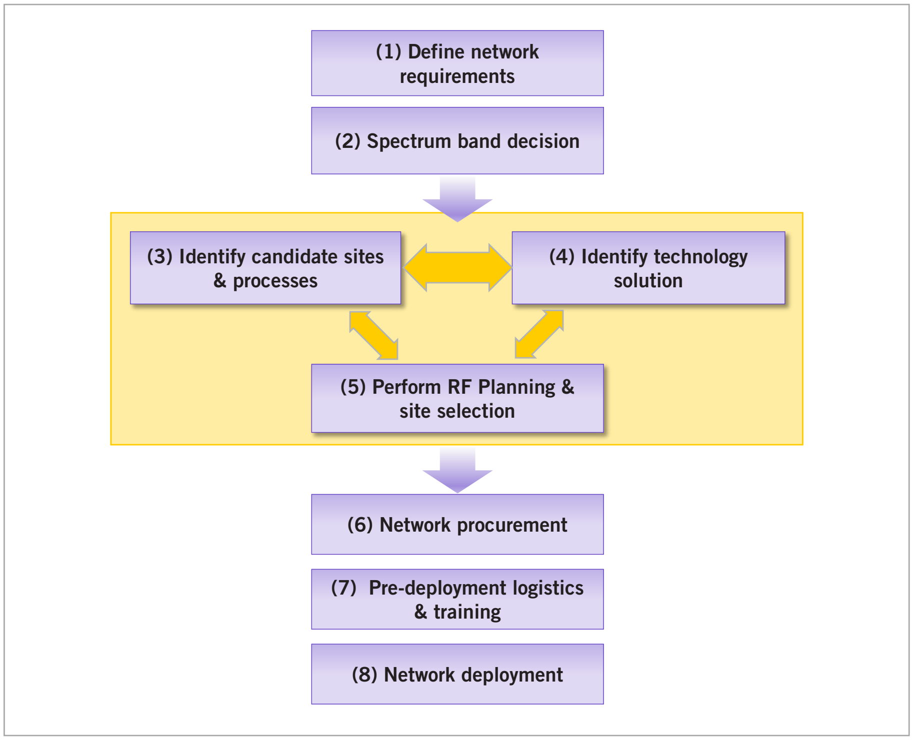


FIGURE 15: SUMMARY OF KEY STEPS TOWARD NETWORK DEPLOYMENT

- Ability to request experimental use of a band if not currently licensed, or to address restrictions in its use.
- Ability to leverage a commercial band if an agreement with the current licensee can be reached and target geographic area is acceptable.

Depending on the band selection, appropriate documentation needs to be generated, both with respect to legal agreements with a band licensee (e.g., lease agreement) and with appropriate documentation required for Federal Communications Commission approvals, before transmission can start. These steps take time, and it is important that they be started early on.

3. **Identify candidate sites and processes:** Once a general area of operation is defined, early site survey is a key step to start identifying potential candidate sites and existing infrastructure that may serve as base stations and locations to host core equipment and servers. As part of this step, it is important to identify all the legal steps and protocols needed for enabling each location as a potential site. Those may include:
   - Understanding each site's ownership, rules of operation, processes, and constraints related to utilizing existing or deploying new infrastructure at the location.
   - Know the people with whom you will work (contractors, approvers, property-owners, and so on).
   - Understand all steps required for site deployments, documentation and permits needed, as well as timing involved in these steps. Do not underestimate the time needed by authorities to perform due diligence before approving construction and operation, and the extent of documentation needed to support those approvals.

- Understand dependence on contractors for installation and expected time allocations.
- Understand post-deployment challenges that may exist with respect to access to each site if/when maintenance and changes are needed.
- Understand risks, worst-case scenarios. Account for the unexpected (for instance, an environmentally protected bird nest in one of our selected towers caused a delay for access to install at one of our selected locations, for a full spring/summer season).

4. **Identify technology solution:** This phase consists of identifying the specifics of the network solution to be deployed to fully inform the upcoming procurement process. It includes detailed solution specification informed by the requirements identified in step (1) in this list. Through multiple discussions with equipment vendors, a key step is to fully understand commercially available and open-source alternative solutions, identify which releases of 3GPP standard are supported, what specific capabilities from each release are implemented, and a timeline for release of new capabilities. This step will inform several next steps, including technology specifics to be used as input/assumptions for link budget and RF planning, and for procurement moving forward.
5. **Perform RF planning & site selection:** This step is key to understand coverage and capacity achievable in the planned network, and to assess the potential candidate sites, validating locations and coverage for a given solution before moving forward with site selection. As part of this step, assessing feasibility of candidate sites in terms of RF coverage, logistics, and challenges specific to each site to be considered before a final site selection decision is made. As expected, findings in this step may lead to the need to identify additional candidate sites and revisit the solution specification. Therefore, steps (3), (4), and (5), will likely be performed in an iterative manner.
6. **Network procurement:** This step refers to the actual procurement of the network. Good practices for procurement should be in place, including careful planning of time allocations related to shipping, delivery, and installation, understanding of training needs, and requirements for operation, maintenance, updates, and so on.
7. **Pre-deployment logistics:** Prior to moving to actual installation, several logistics need to be addressed, including working with appropriate contractors and providing inputs and documentation necessary to plan installation and submit all appropriate requests for permits.
    - Leasing a place on existing cellular towers involves many complex tasks such as filing application with tower company, providing detailed installation drawings and overall design, RF study showing no interference to other operators, and town/county approval.
    - Some steps in this process are lengthy, and not all outcomes are predictable. Keep flexibility to plan timeline and logistics, and to adapt when plans are affected.
    - Pre-deployment phase is also a good opportunity to receive training to acquire skills that will be necessary to operate the network.
8. **Network deployment:** Deploying outdoor 5G needs is quite a challenge, especially if you are not a mobile operator or have no experience deploying or operating wireless networks. Support from the vendor and contractors are key in this phase.
    - Field installation is also affected by weather and time of year plays. For example, due to concerns with frozen ground, and since two of the three sites required new fiber circuits for connectivity to the data center, we opted to have baseband unit at radio edge sites instead of consolidated in the data center.

3.2 Integrating User Equipment and Capture of KPIs From the Network

When investigating applications of the leading edge of technology, there are limited solutions available. While 5G phones have been in the market for a few years, when we first started this work the number of 5G devices supporting 5G SA and Private networks was extremely limited. Since Open Generation is not a mobile operator with a registered PLMN, we were forced to use a test PLMN. In general, commercially available 5G devices do not work with test PLMNs and do not support all 5G bands, as profiles are locked to major mobile operator networks. Since test PLMN are not in those profiles, many phones will not function on a test network. As of this writing, we have not found an off-the-shelf, consumer-grade cell phone that supports the combination of band n66, a PLMN of 999:40, and 5G SA.

Specialized licensed solutions are relatively expensive (compared to consumer-level phones) and require specific companion-adapted hardware. As such, while some of these specialty solutions may meet our configuration needs (particularly appropriate for network performance assessment on ground and air, with collection of a multitude of KPIs), due to the cost, these are not the solutions best suited to be the primary UE for a drone.

As more 5G modems became available during the project, we identified the Telit FN980m as meeting most of our requirements. As early users of the modem, some troubleshooting was required, and on several occasions we worked with Telit to address needs or issues found, which they worked to resolve.

As discussed previously, libqmi provides an API that provides access via the QMI protocol and is the preferred method to access a Qualcomm device. However, given the limited time, it was determined to implement an AT-command based program to query the modem at once per second to obtain UE measurement on-board the drone. The AT commands and responses change slightly with each version of the modem firmware which presented an additional challenge to keep in synchronicity with the particular firmware used.

We also obtained various measurements of the system from different levels of the architecture. In other words, some measurements were made by the modem, others were made by the drone mission computer, and others by the GCS. To synchronize these data elements during post-processing, every data measurement was required to contain an accurate time-tag of when it was measured.

While the resulting combination of hardware and software is a bit complex, the development was based on building up on simple component parts. The modem software could be developed by simply plugging in the modem into the USB port of a development computer. Then, once it was working well, it could be moved to the mission computer. Each type of data log was developed and independently before being run together. We were also able to test each of the components using commercial cellular networks both on the ground and in limited flight tests close to our normal working location. The challenge of finding a UE that worked with SA on band 66 and our PLMN of 999:40 was accomplished using a MITRE 5G cellular lab where we could evaluate many devices in our home office before traveling out to the field.

A key element to a successful field deployment was knowing what to expect before the team arrived in the field. Very early in the deployment, we experienced some challenges with the network configuration and suspected that the RSRP was much lower than expected; however, simulation and modeling were essential to knowing what type of values we expected to see versus what we were measuring in the field. Using a variety of devices was also helpful. While two different UE showed a low RSRP, a spectrum analyzer clearly showed a strong signal. This information combined allowed us to isolate the issue to a 5G network setting and not an issue with the antenna or amplifier.

3.3 Integrating for End-to-End Operations

Recommended early steps towards integrating for end-to-end operations include:

- Use an iterative approach by "building and testing" as the solution evolves, including for the drone integration solution.
- Perform testing and dry runs to reproduce to the extent possible the conditions that will be encountered in the field.
- Perform RF predictions and network simulations using key performance metrics that will be captured in the field. Results from such RF analyses will form a baseline for comparison with actual performance once the network deployment starts. These analyses need to be performed both at ground level and for different drone altitudes.
    - Predictions at ground level will enable comparisons with data collected during drive tests.
    - Predictions at different flight altitudes and in multiple locations, to enable comparisons with data collected during flight tests. Predictions at altitude should use propagation channel models for aircraft (sUA at low altitudes in our case).

When moving to the actual field environment, one key recommendation is to know what to expect and verify while in the field. With that purpose, some steps are recommended, including:

- Ability to double check installations (e.g., antenna azimuths, transmit powers).
- Ability to assess performance in real time while in the field and compare with baseline predictions.
- Ability to quickly process data from multiple sources and assess network performance. This will continue to be needed for network monitoring during typical operations.
- Have a focused office-based team to analyze data from the field and provide alternative next steps to the team in the field.
- Ability to troubleshoot the network as much as possible. Existing predictions will provide a baseline for comparison with actual network performance, as the network is deployed. Having different ways to gather information (e.g., different metrics from different measurement devices) will provide insights that no single device can give.

As the deployment matures, and the network is validated, further measurement campaigns will continue to provide valuable data to further enhance propagation models for users at altitude. To enable such enhancements, being able to both incorporate field measurements into the RF network planning tool and to perform propagation model calibration are necessary.

In summary, knowing what to expect before arriving in the field and being able to react quickly are essential to an effective deployment.

3.4 Field Operations

The development of a research platform mobile laboratory (trailer) was a key enabler of this work. The trailer allowed the team to bring sufficient spare parts, measurement equipment, and other support facilities to avoid lost time during key deployment activities. This mobile lab was carefully configured and exercised in our home areas, so items to be included in the lab could be identified and installed prior to field deployment.

Field deployment also has the challenges of weather delays and access approval. Sufficient extra days in the field must be assumed as inclement weather (e.g., strong winds, precipitation) can impede drone flights. The chance of weather delays was included in deployment plans and each was usually forecast to take an entire week with a wide range of possible outcomes of the trip, depending on the success of each experimental flight. In addition, pre-coordination with external parties should be performed as early as possible to identify schedule conflicts and other issues. Specifically, a field deployment typically involves some use of other parties' equipment and real estate. It may also require a safety review of the operation and the equipment. These agreements need to be in place well in advance of arrival on location.

Bring as many spare parts as you can. We cannot underestimate the importance of bringing to the field an organized setup for operations, including spare parts for drones, measurement devices, and other equipment and materials that may be needed.

3.5 Data Processing (Real Time and Post-Processing)

While still a work in progress, we are developing live graphical dashboard tools so we can quickly assess the state of our measurements while in the field. This was often performed by observation of the raw text data being recorded, but it is far easier to see subtle trends in graphical presentation. Having this information available live when the team has limited time on location can make for a more productive trip.

Open Generation built several drone platforms from commercial off-the-shelf components. One lesson learned is the significant time and effort to build, validate, and safety assure each of these platforms. For the measurements in this paper, a commercial prebuilt, configured, and tested drone was used. This greatly accelerated data gathering for our experiments. While many commercial drones use proprietary systems that are not appropriate for an experimental platform, there are commercial drones available that use open systems that give an excellent starting point for this type of research. If there were production 5G drones available that met the mission need, this research would likely be of a different nature. However, the value of this leading-edge research is precisely because of the lack of availability of fully integrated platforms.

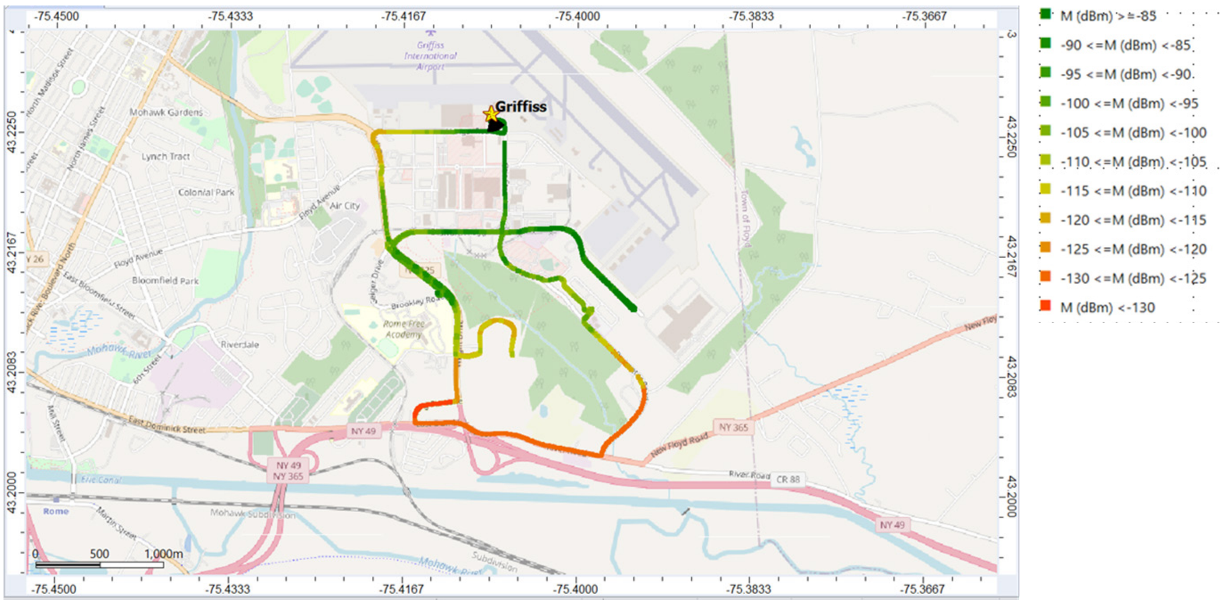
4 Early Performance Assessment Results

The findings presented in this section are preliminary results from limited data collection performed so far, following the recent launch of the experimental private network. All metrics presented in this chapter refer to the signals from our private network operating in band n66.

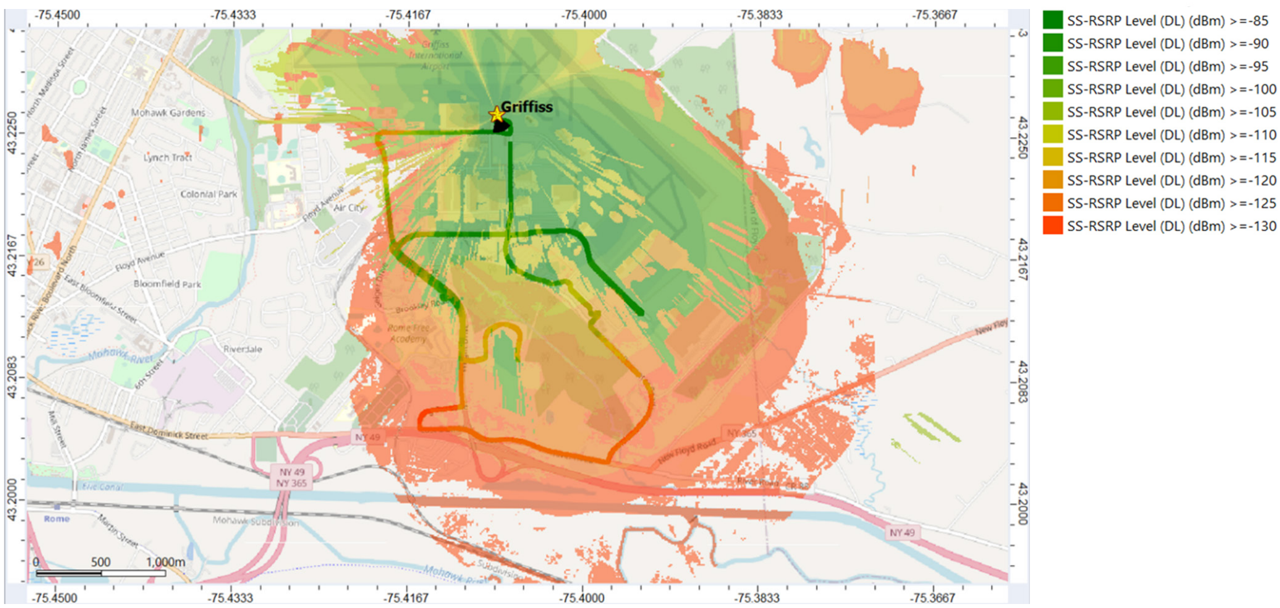
4.1 Drive Test Results Near Griffiss Radio Site

Once the network was operational, we performed multiple drive tests near the base stations to assess signal strength and compare with expected levels (from predictions) as a way to validate coverage.

As an example, Figure 16 a) illustrates SS-RSRP measured data near the Griffiss radio site during drive testing using the QualiPoc tool. Figure 16 b) illustrates the same SS-RSRP measured data overlayed with average SS-RSRP predictions. It should be noted that a minimum SS-RSRP of -130 dBm is used as a threshold to visualize predictions. For the comparison with measurements, measured SS-RSRP values below -130 dBm are shown in red in a). Overall, good agreement is observed between the average predictions and actual measurements.



a) SS-RSRP Measurements During Drive Test Near Griffiss



b) SS-RSRP Measured Data Overlay with Average Predictions

FIGURE 16: SS-RSRP DATA FROM DRIVE TESTS NEAR GRIFFISS AND OVERLAY WITH AVERAGE PREDICTIONS

4.2 Flight Test Results Near Griffiss Radio Site

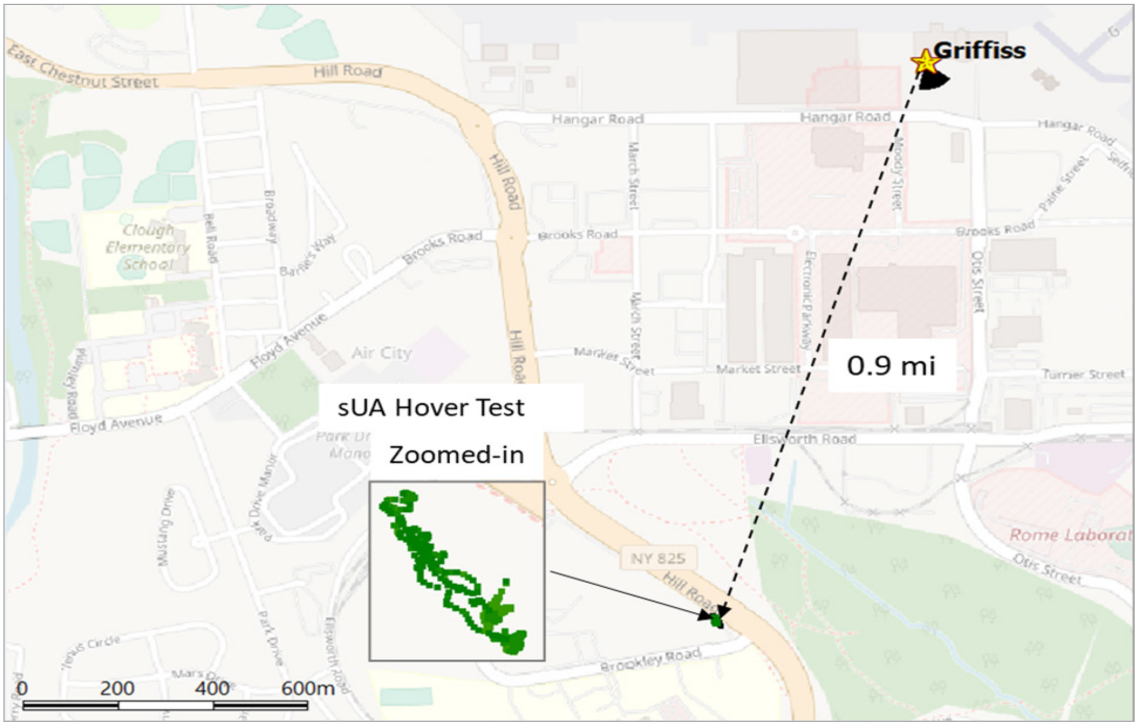
Multiple sUA flight tests took place near the Griffiss Radio site during September 20–22, 2022. Our Griffiss and the Oriskany radio sites were active during these tests.

Sample Hover Test Results

Several sets of measurements were captured during a hovering flight test (up to a maximum altitude of 400 ft AGL) using the Telit modem. Figure 17 shows a sample of those measurements within a zoomed-in area of 30 m by 25 m. The geographical area for the test and the altitude profile are shown in the subplots identified as a) and d). The dependence of altitude for SS-RSRP, SS-RSRQ, and SS-SINR are captured in the subplots denoted as b) and c). The corresponding sUA altitude is shown in subplot d). Subplot d) illustrates the altitude as reported by the drone, which is expressed as above mean sea level, the terrain elevation in the hover test area, and the resulting sUA AGL altitude also shown in feet.

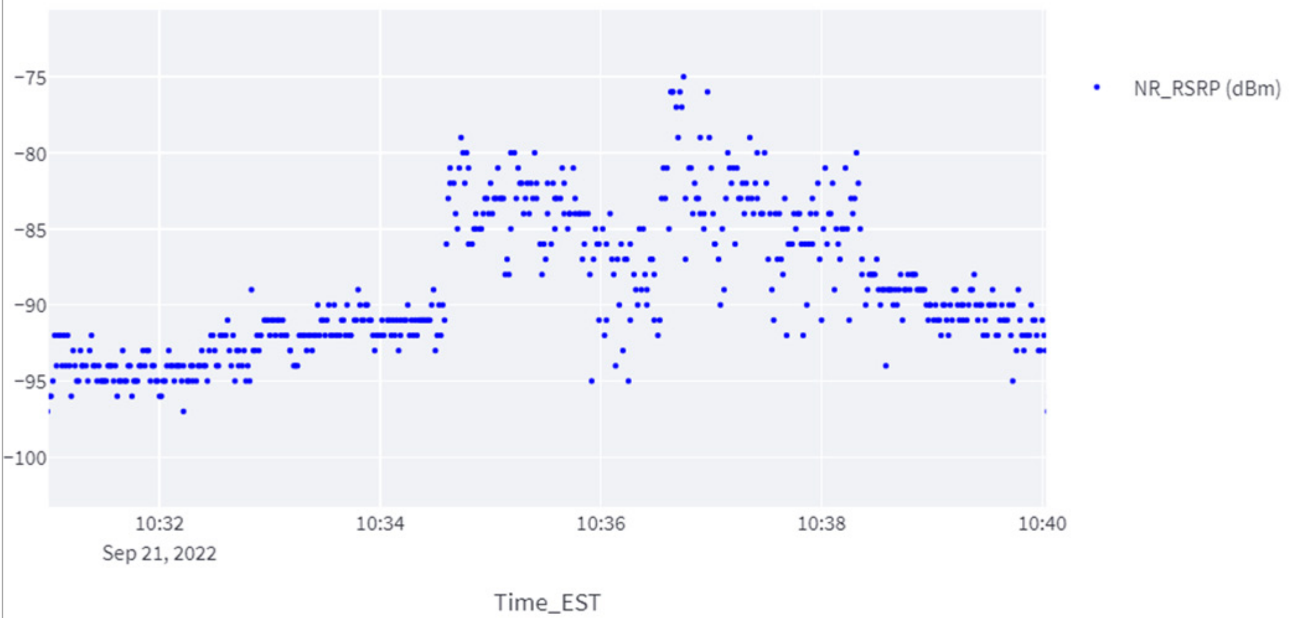
Overall, the measurement results captured during this test show SS-RSRP values above -100 dBm. It can also be observed that the SS-RSRP measurements increase as the sUA altitude increases and the drone starts flying above the clutter. In terms of signal quality, both the SS-RSRQ and SS-SINR metrics decrease as the sUA altitude increases. As the drone flies above clutter, its signal level improves as losses due to clutter are minimized. At the same time, the drone captures signals from our other active radio site and any other signals from the environment. Those are seen as interference; therefore, a decrease in signal quality is observed at the drone as its altitude increases.

These results are consistent with altitude-dependence trends observed for average predictions as described in Section 2.5.



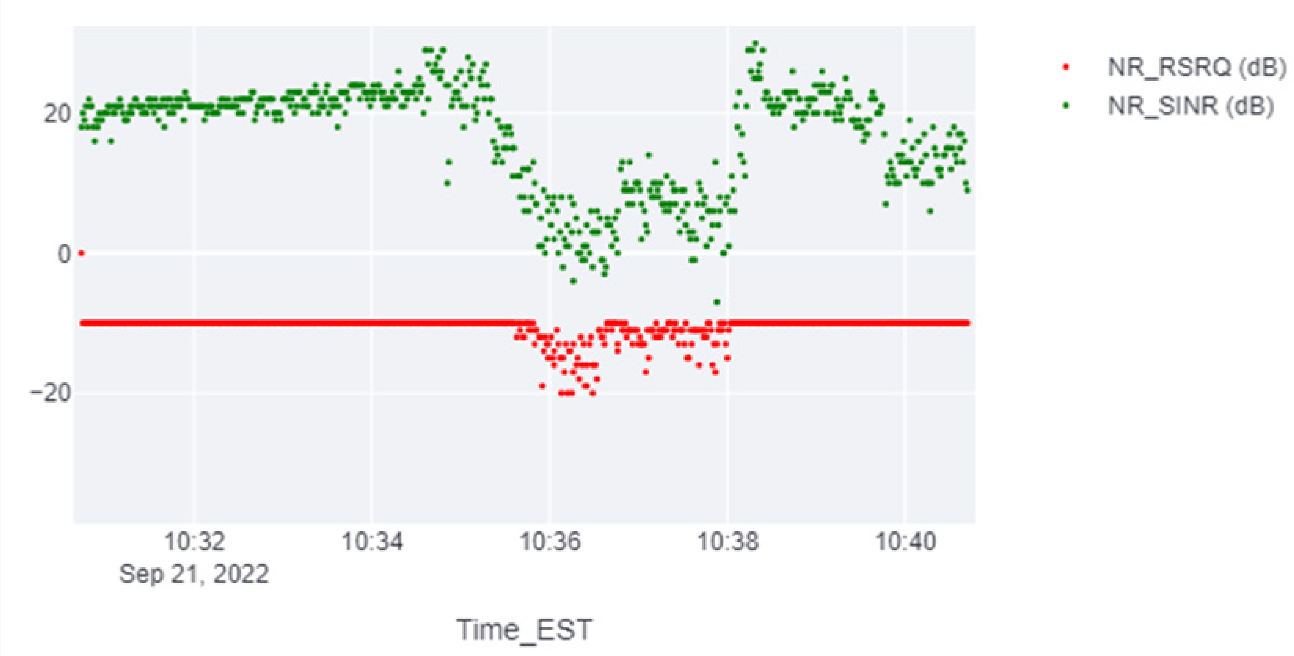
a) Sample Flight Hover Test Shown on Map

FIGURE 17A: SAMPLE DATA FROM FLIGHT HOVER TEST NEAR GRIFFISS



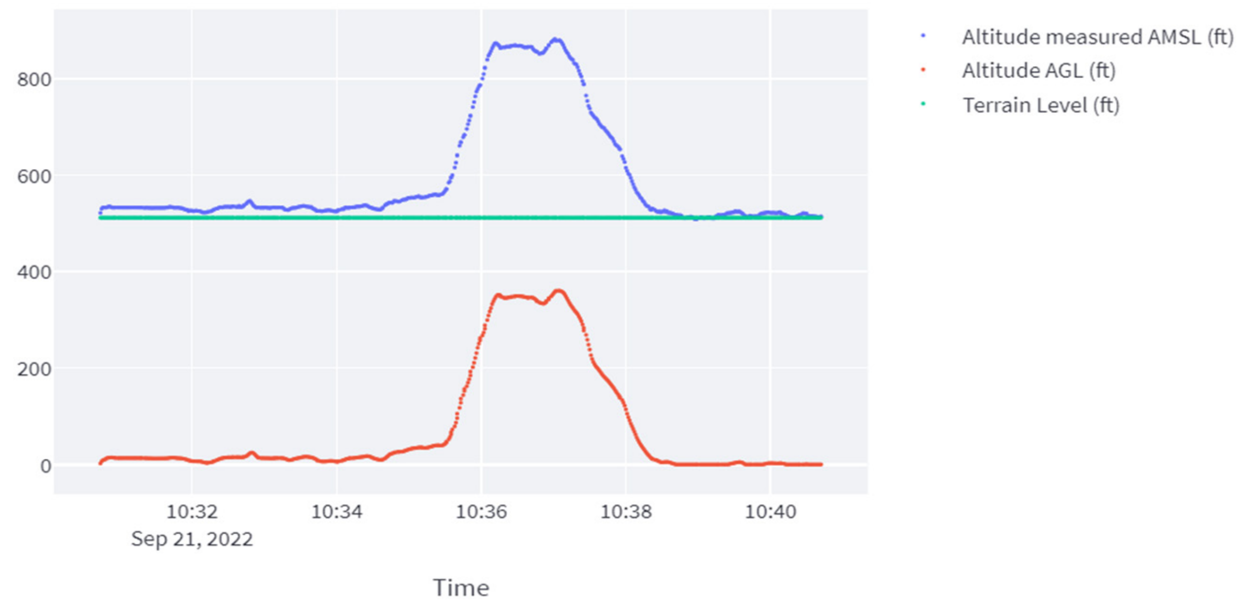
b) Sample SS-RSRP Data

FIGURE 17B: SAMPLE DATA FROM FLIGHT HOVER TEST NEAR GRIFFISS



C) Sample SS-RSRQ and SS-SINR Data

FIGURE 17C: SAMPLE DATA FROM FLIGHT HOVER TEST NEAR GRIFFISS



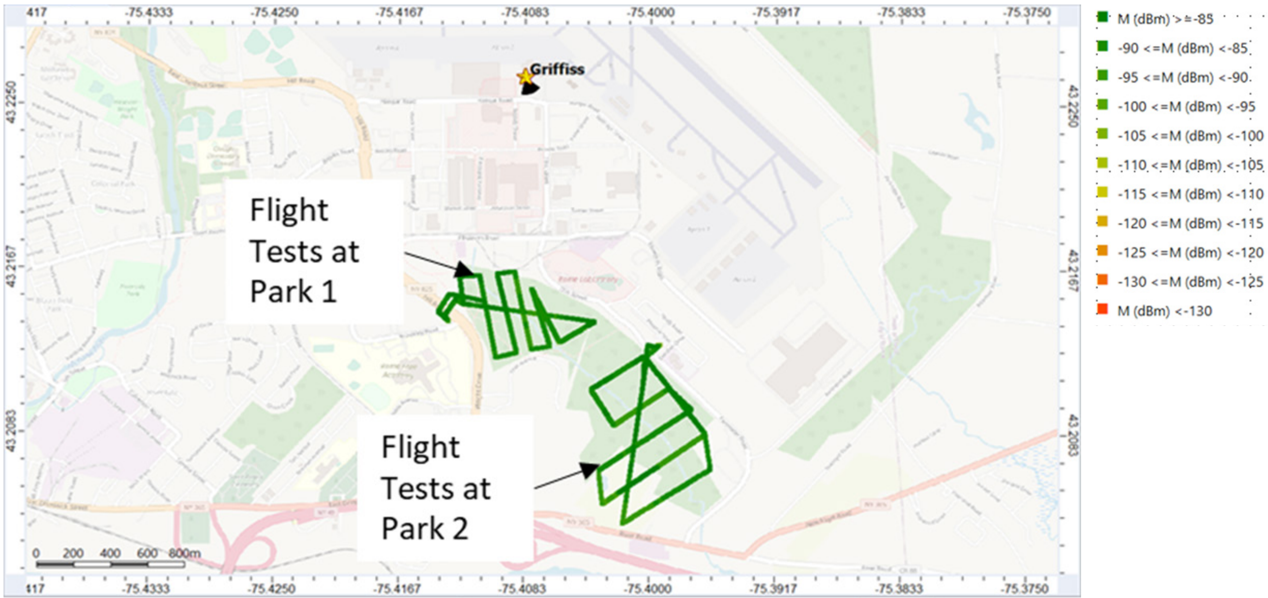
d) Corresponding sUA Altitude for the Sample Data

FIGURE 17D: SAMPLE DATA FROM FLIGHT HOVER TEST NEAR GRIFFISS

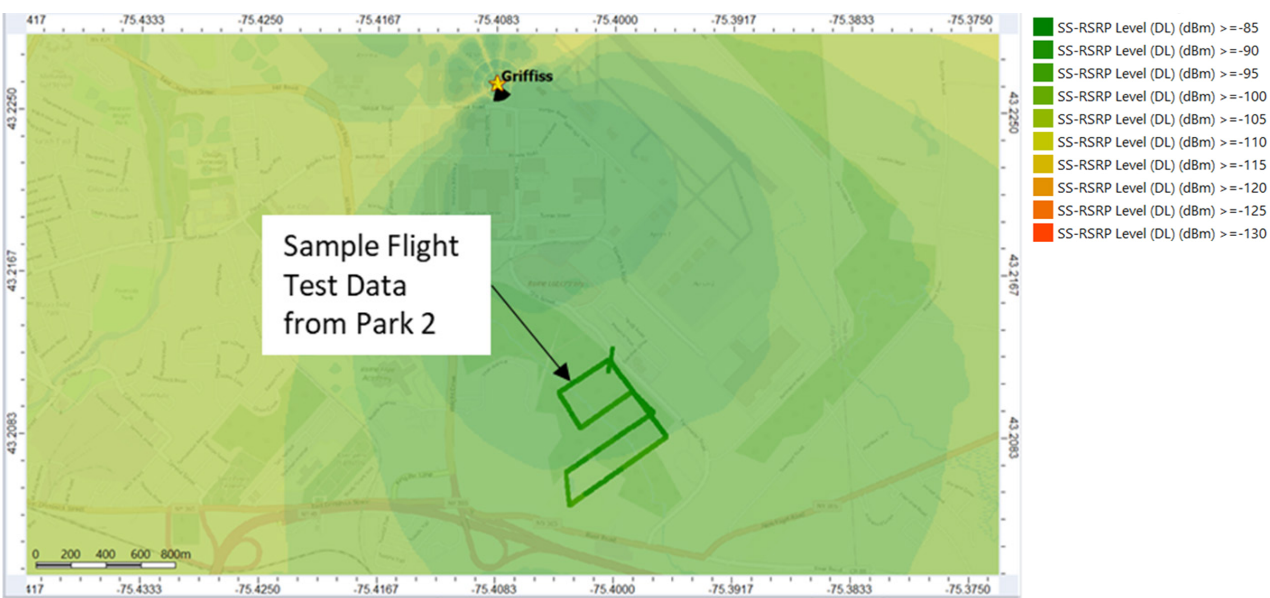
Results from Flight Tests

Flight tests in an area about 1 mile away from the Griffiss radio site took place on September 20–22, 2022, and are described next. They were performed at two locations denoted as Park 1 and Park 2 in Figure 18. Subplot a) shows SS-RSRP for an aggregate of the flight tracks for all altitudes. Subplot b) shows SS-RSRP from measurements for sUA between 250 and 350 ft AGL and overlayed with the average SS-RSRP prediction for 300 ft AGL.

Further flight tests took place on November 8, 2022, near the Griffiss Radio site. Our Griffiss radio site was active during these tests. The tests were performed using both the QualiPoc tool and the Telit modem. The focus continued to be on 5G NR link quality parameters captured during the drone flights. Additional scripts were also active during these tests on November 8, as described in Section 2.3, to enable latency assessments, and data rates calculations during typical operations, and maximum throughput (using iPerf3). During these tests, telemetry and video were transmitted from the drone to the ground.



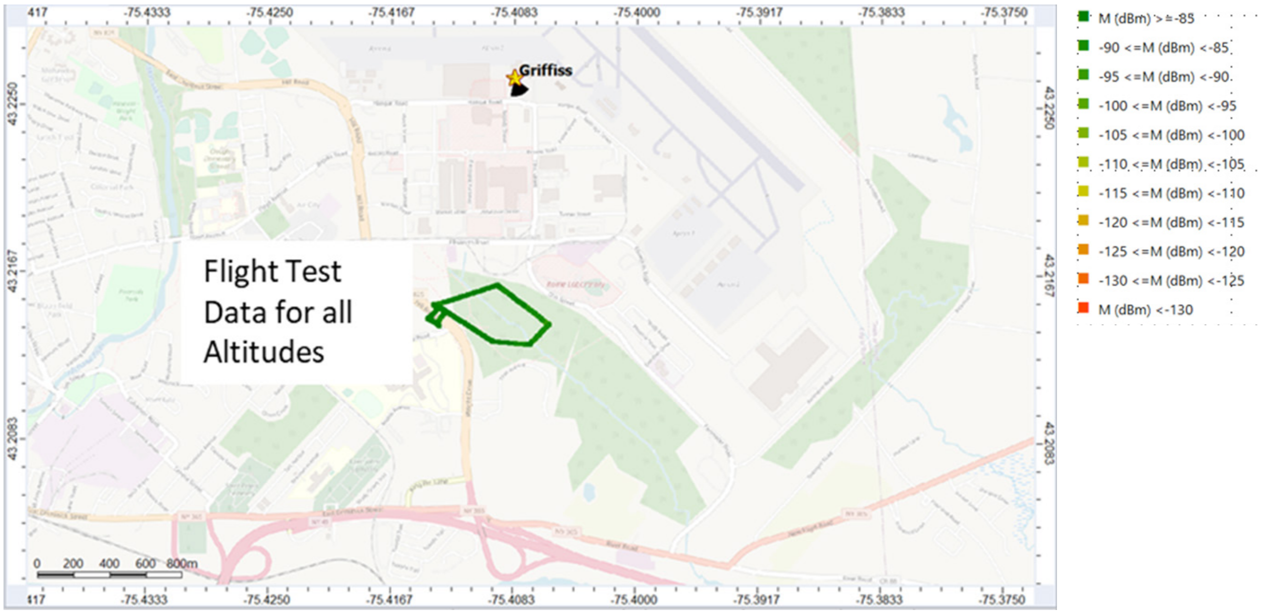
a) Flight Tests SS-RSRP Data at Park 1 and Park 2 for All Altitudes



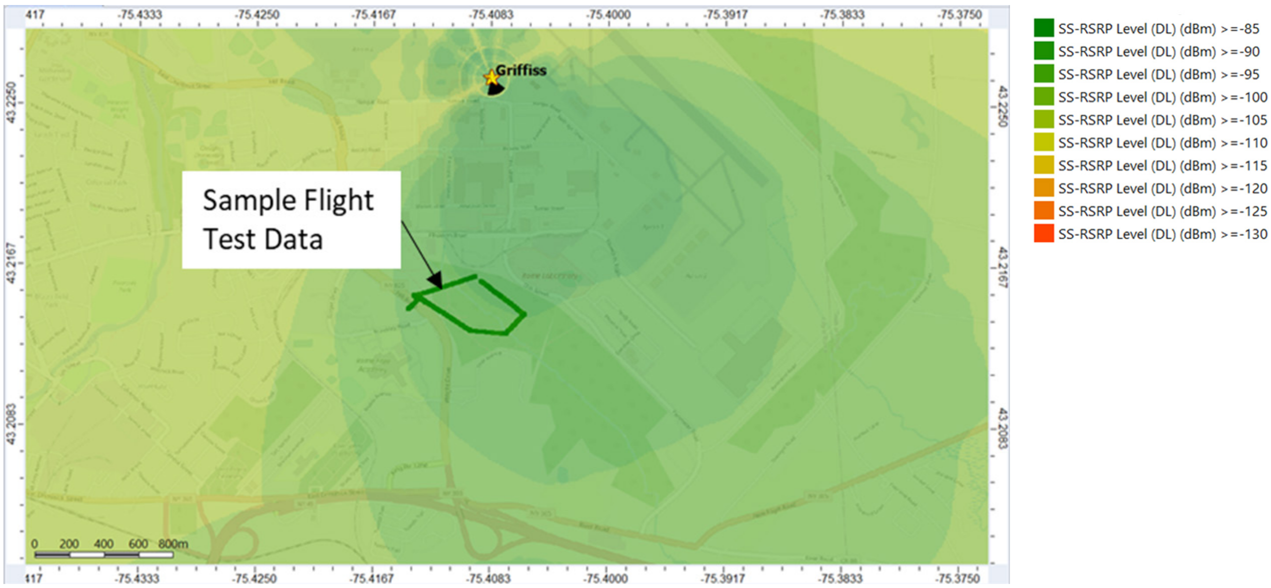
b) Sample Subset of SS-RSRP Data at Park 2 Within 250 and 350 ft AGL and Overlay With Average Predictions

FIGURE 18: SAMPLE SS-RSRP DATA FROM FLIGHT TESTS AND OVERLAY WITH AVERAGE PREDICTIONS AT 300 FT AGL

A sample set of flight test data captured using QualiPoc is shown in Figure 19. Subplot a) shows flight tracks with altitudes between 300 and 400 ft AGL. Subplot b) shows SS-RSRP from measurements at these altitudes overlayed with the average SS-RSRP prediction for 350 ft AGL.



a) *Flight Test Data for All Altitudes*



b) *Sample Subset of SS-RSRP Data and Overlay with Average Predictions*

FIGURE 19: SAMPLE SS-RSRP DATA FROM FLIGHT TESTS AND OVERLAY WITH AVERAGE PREDICTIONS AT 350 FT AGL

Similar results indicating good signal level in terms of SS-RSRP were also obtained from measurements using the Telit modem integrated on the drone.

Latency values were obtained using ping scripts, as described in Section 2.3. Data was captured during multiple flight tests. Video was also streaming from the drone at an average rate of 4 Mbps, and with additional live streams of recorded data; the resulting average data rate was around 5 Mbps.

A sample of that data is illustrated in Figure 20 below (in a logarithmic scale). The latency as measured is the time to send an ICMP (ping) packet from the drone to our Azure server on the internet. This not only includes any latency in our 5G private network, but also the local network, internet service provider, and the internet route to the Microsoft virtual server.

As shown in Figure 20, most latency values are in the 30 to 60 ms range, some are up to 100 ms, and a much smaller subset consists of values above 100 ms and below 600 ms.

Figure 21 shows drone data rate results obtained from flight test data during which video streaming was active.

Early Assessment of Altitude Dependence

Additional analysis was performed to assess the altitude dependence of measured data, and results are presented next. It is important to note that the amount of the data collected from the network so far is very limited, so all insights highlighted in this section are still preliminary and to be confirmed as more data is analyzed.

For the flight tests performed within about 1 mile from the Griffiss radio tower, SS-RSRP did not show a strong variability with altitude, as seen in Figure 22. A strong signal is typically observed at this distance from the tower. There is a little reduction of received power while the drone is on the ground.

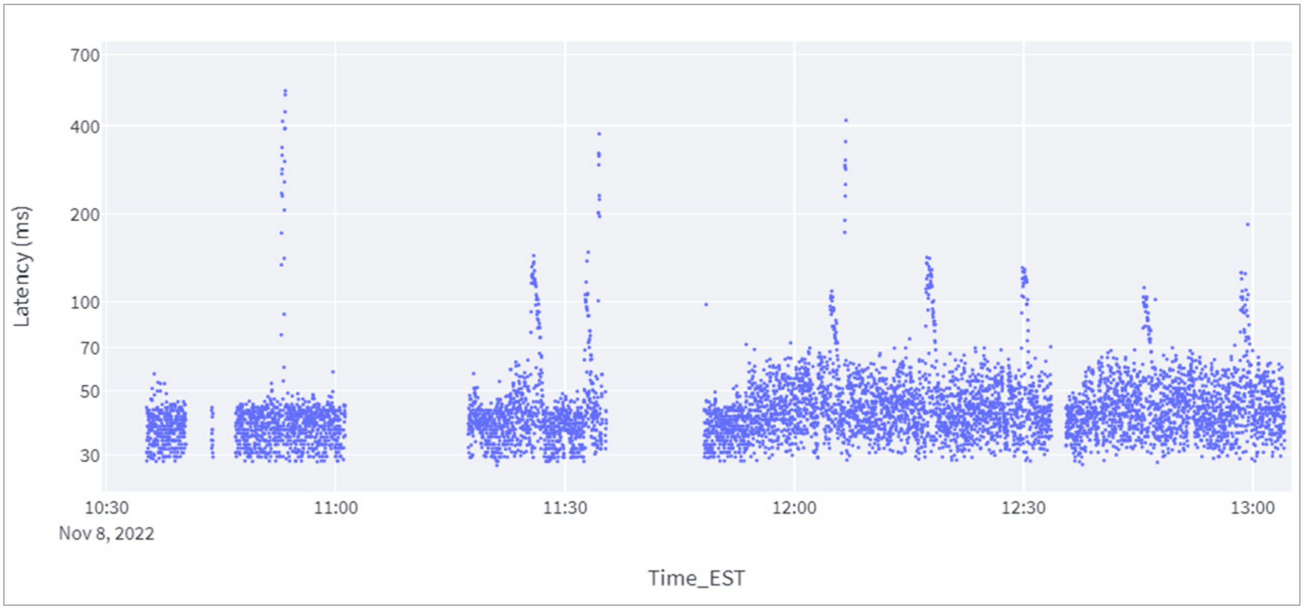


FIGURE 20: LATENCY RESULTS FROM FLIGHT TESTS

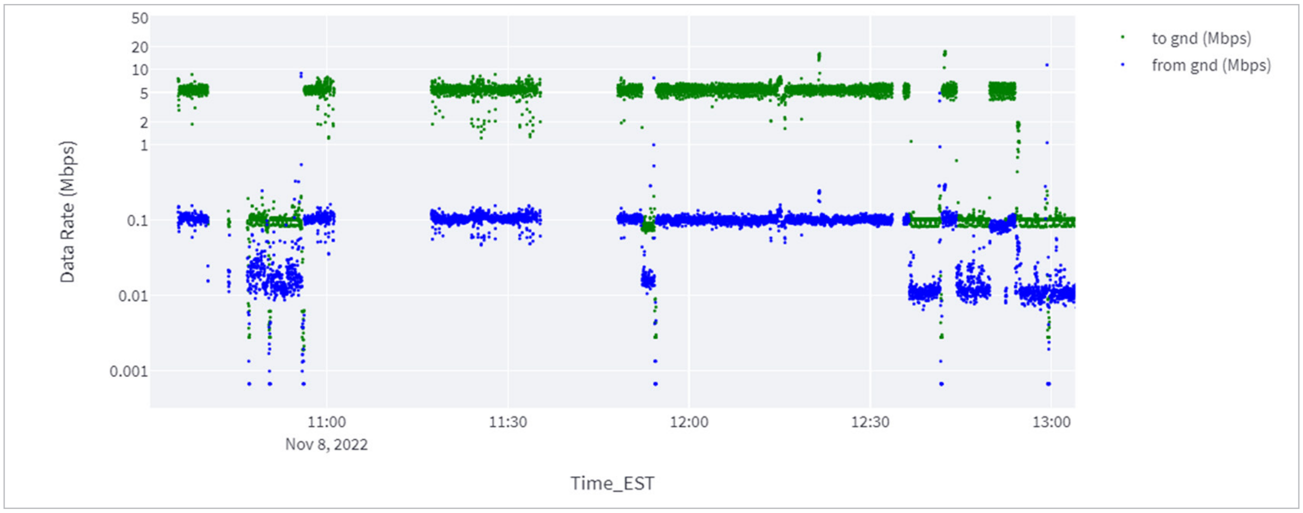


FIGURE 21: DRONE DATA RATE RESULTS FROM FLIGHT TESTS

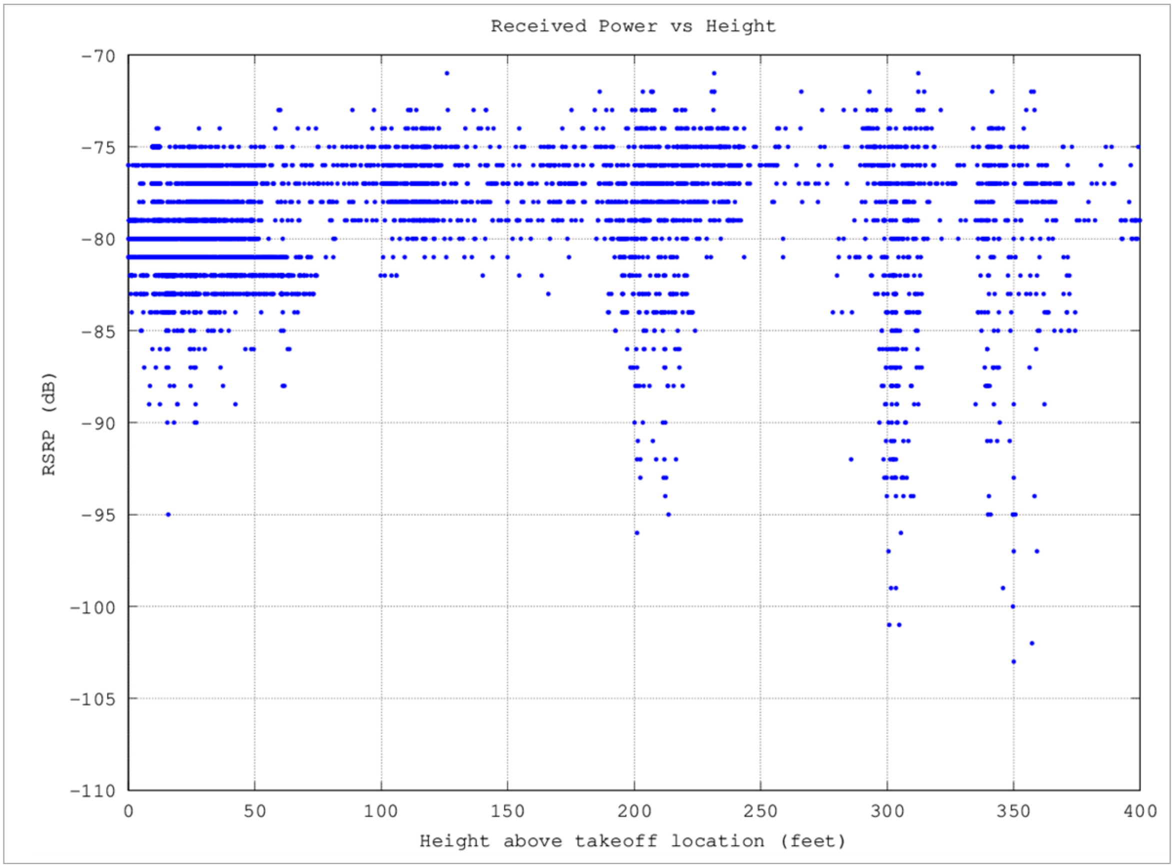


FIGURE 22: SS-RSRP RECEIVED ON DRONE AS A FUNCTION OF HEIGHT ABOVE TAKEOFF LOCATION

The SS-SINR in Figure 23 shows a significant variation with altitude for the lower flight heights where tree and other obstructions block the signal from other towers. Once the drone is a little over 200 ft above takeoff location, the SS-SINR appears to not vary much with additional height, as other nearby towers (potential interference) are likely fully visible to the drone above that height.

We also looked at how latency varies with altitude. A plot of latency for different heights above takeoff location is illustrated in Figure 24. The vast majority of values are between 30 and 60 ms. There were no perceived trends in latency varying with height in this data sample. Some higher latency values were observed when the drone was on the ground. Those high latency periods were likely due to software services being restarted prior to flight.

As previously mentioned, video was streaming from the drone at an average rate of 4 Mbps, and with additional live streams of recorded data, the resulting average data rate was around 5 Mbps. Significantly less data was sent back on average from the GCS to the drone for these experiments; this is likely just the TCP acknowledgement messages. The plot in Figure 25 shows no variation in the data rate with altitude showing a good connection independent flight height. The observed data rates are consistent with the demand placed on the network during the flight tests.

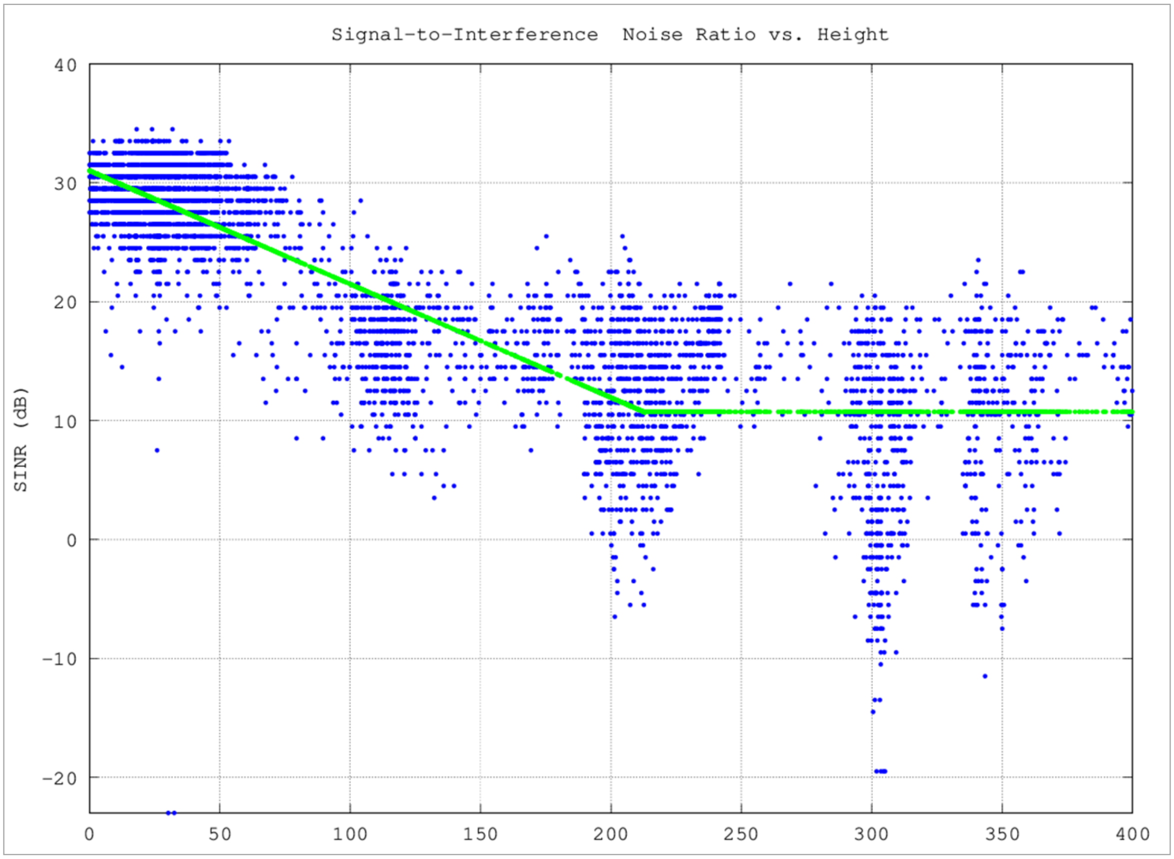


FIGURE 23: SS-SINR RECEIVED ON DRONE AS A FUNCTION OF HEIGHT ABOVE TAKEOFF LOCATION

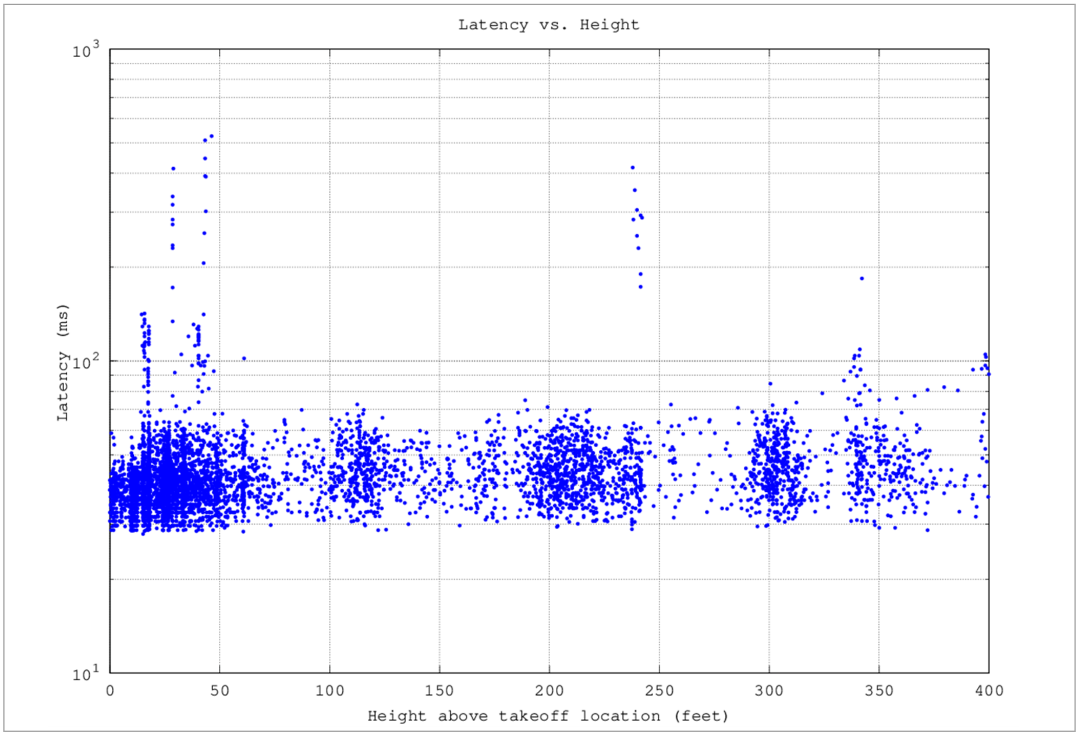


FIGURE 24: LATENCY AS A FUNCTION OF HEIGHT ABOVE TAKEOFF LOCATION

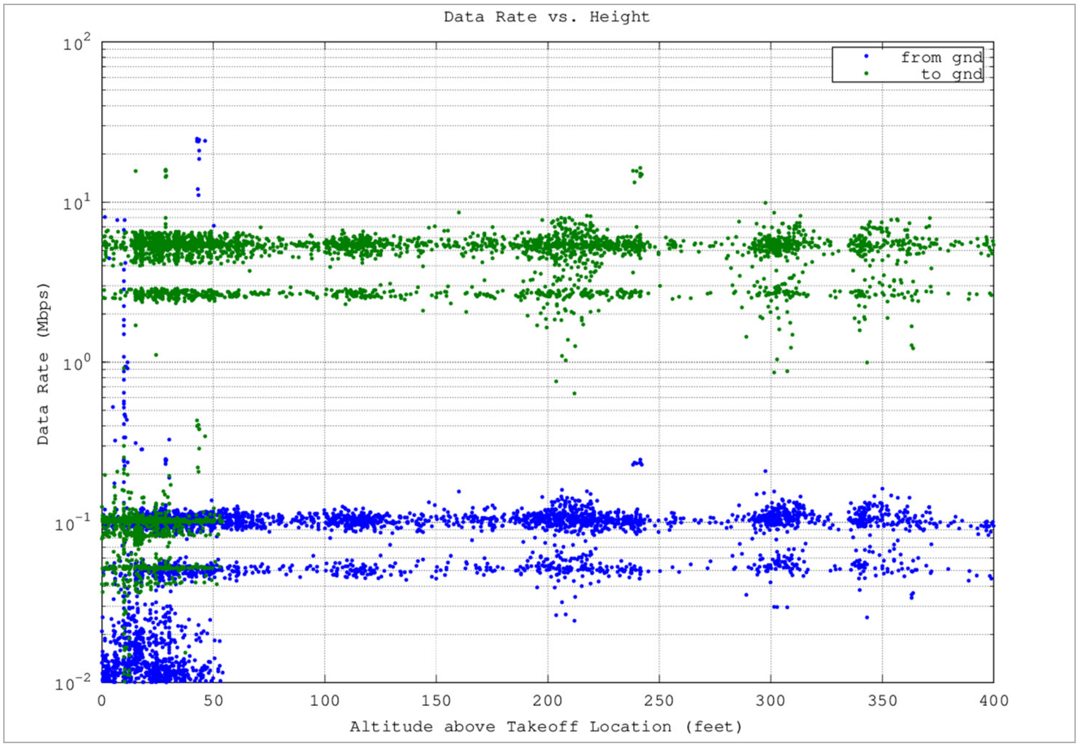


FIGURE 25: DATA RATE AS A FUNCTION OF HEIGHT ABOVE TAKEOFF LOCATION

5 Next Steps

The successful deployment of our 5G SA private network, as well as the early sUAS testing results at the NUAIR Test Site, are already informing our plans for upcoming activities and experiments. Upcoming activities include the activation and coverage validation of the third radio site at Stanwix, as well as hardware changes to support edge computing research.

Now that the network is operational, next steps include additional data collection for further network validation and to establish a complete baseline of performance for our 5G network, followed by executing our currently planned experimental activities on selected use cases.

Those experiments are focused on enabling use cases identified for this testbed environment, utilizing the 5G NR capabilities at the testbed and 5G-enabled drone connectivity. The key use cases identified for experimentation at the NUAIR test range at this time include:

- **Emergency Response – Hazmat Incident:** Simulate a situation of an accident with hazardous substances and perform drone response, including capture of high-quality visual and sensor data, computer vision to detect and identify symbols for substances involved, and support to multiple drones being used concurrently.
- **Package Delivery:** Simulate short distance local deliveries, including scenarios of vertiports serving as hubs or warehouses where multiple drones are close together.
- **UAM/AAM:** Experiment with scenarios that utilize drones as proxy for UAM vehicles, reproducing context for DAA functions, UAS Traffic Management (UTM) coordination, and connectivity assessment, among other variables.

From a connectivity perspective, areas of focus include assessing 5G NR link performance to enable C2, payload, and DAA/state information exchanges in BVLOS operations of increasing complexity. Evaluating the 5G NR link performance variability with the sUA altitude will continue throughout the upcoming experiments at the testbed.

Experimentation at the testbed will assess key performance metrics relevant to drone operation, such as coverage reliability, throughput, and latency at different aerial scenarios. We will assess network-based metrics from the private network to be able to characterize that performance in both directions (downlink and uplink), and experiment with customizing the network for drone and for hybrid (drone plus terrestrial) improved performance.

We also plan to enable research on artificial intelligence/machine learning algorithms to better support emergency response use cases. As the testbed continues to evolve, the use of 5G millimeter wave capabilities will also be explored.

6 Definitions and Abbreviations

6.1 Abbreviations

Acronym	Description
3GPP	3rd Generation Partnership Project
5GC	5G Core Network
AAM	Advanced Air Mobility
AC	Alternating Current
ADS-B	Automatic Dependent Surveillance Broadcast
AGL	Above Ground Level
AMF	Access and Mobility Function
API	Application Programming Interface
AT	Hayes command set command language used to control modems
BBU	Baseband Unit
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CPRI	Common Public Radio Interface
DAA	Detect and Avoid
DC	Direct Current
DL	Downlink
FAA	Federal Aviation Administration
gNB	gNodeB is the term used to describe a 5G base station
GCS	Ground Control Station
GPS	Global Positioning System
ICMP	Internet Control Message Protocol
IP	Internet Protocol
KRME	International Civil Aviation Organization airport code for Griffiss International Airport in Rome, New York
MCS	Modulation and Coding Scheme
NM	Nautical Miles
NMS	Network Management System
NR	New Radio
PDU	Protocol Data Unit
PLMN	Public Land Mobile Network
QMI	Qualcomm Mobile Station Modem Interface
QoS	Quality of Service
R&S	Rohde and Schwarz
RAN	Radio Access Network

Acronym	Description
Remote ID	Remote Identification
RF	Radio Frequency
RRH	Remote Radio Head
RSSI	Received Signal Strength Indicator
SA	Stand Alone
SIM	Subscriber Identity Module
SS-RSRP	Synchronization Signal – Reference Signal Received Power
SS-RSRQ	Synchronization Signal – Reference Signal Received Quality
SS-SINR	Synchronization Signal – Signal to Interference and Noise Ratio
TCP	Transmission Control Protocol
UA	Uncrewed Aircraft
UAM	Urban Air Mobility
UAS	Uncrewed Aircraft System (formerly a.k.a. Unmanned Aerial System)
UAV	Uncrewed Aerial Vehicle (formerly a.k.a. Unmanned Aerial Vehicle)
UDP	User Datagram Protocol
UDM	Unified Data Management
UE	User Equipment
UL	Uplink
UPF	User Plane Function
USS	UAS Service Supplier
UTM	UAS Traffic Management
VPN	Virtual Private Network

6.2 Definitions

Term	Definition
Remote ID of UAS	The ability of a UAS in flight to provide identification and tracking information that can be received by other parties to facilitate advanced operations for the UAS (such as beyond visual line of sight operations as well as operations over people) and to assist regulatory agencies, air traffic management agencies, law enforcement, and security agencies when a UAS appears to be flying in an unsafe manner or where the UAS is not allowed to fly. The Remote ID information payload may include the Serial Number or Session ID assigned to the UA, location of the ground-station controller, emergency status indication, and so on.
UAS	Composed of UA and related functionality, including C2 links between the UA and the controller, the UA, and the network, and for Remote ID. A UAS is composed of a UA and a UA controller.
UA Controller	Enables a drone pilot to control a UA. A UA Controller is also denoted as Ground Control Station in this document.
Uncrewed	An aircraft operated without the possibility of direct human intervention from within or on the aircraft. (14 CFR §1.1 changed “unmanned” to “uncrewed”).
USS	An entity that provides services to support the safe and efficient use of airspace by providing services to the operator/pilot of a UAS in meeting UTM operational requirements. A USS can provide any subset of functionality to meet the provider's business objectives (e.g., UTM, Remote ID).
UTM	A set of functions and services for managing a range of autonomous vehicle operations.
Visual Observer	A person who is designated by the remote pilot in command to assist the remote pilot in command and the person manipulating the flight controls of the small UAS to see and avoid other air traffic or objects aloft or on the ground.

As MITRE's tech foundation for public good, MITRE Engenuity collaborates with the private sector on challenges that demand public interest solutions, to include cybersecurity, infrastructure resilience, healthcare effectiveness, microelectronics, quantum sensing, and next-generation communications.