Aerial Connectivity Joint Activity – Work Task #2:

Reference Method for assessing Cellular C2 Link Performance and RF Environment Characterization for UAS

October 2022

Contents

1. Introduction

1.1.1. Overview

In order to investigate and characterize the performance of cellular links for Beyond Visual Line of Sight (BVLOS) drone operations at scale, appropriate measurements of drone application-level Command and Control (C2) and radio frequency (RF) parameters have to be conducted via flight testing. This helps to answer questions such as "what is a representative environment for drones?" For example, such environments may be defined for specific drone use cases (linear infrastructures inspection, parcel delivery, …), or areal characteristics (flat, hilly, mountainous, …), etc. And another key questions such as "how well does cellular connectivity infrastructure support C2 in such representative environments"? With this information, complex BVLOS operations using cellular may be better assessed by drone developers, operators, regulators, and other stakeholders.

Method harmonization is needed in order to compare and interpret results from different projects correctly, i.e. to compare apples with apples, and to provide objective information about feasible technical capabilities to authorities, depending on the considered environment, and standardization bodies for defining safety-related cellular link performance standards and technical-operational requirements and recommendations. Practically, this means that a Reference Method includes: 1) the aerial and ground measurement of the cellular RF environment 2) measurement of the C2 link performance between a particular drone type and its control station (CS) 3) process and procedures for conducting flight measurement operations in a standardized fashion.

Establishment of this Reference Method may have implications for the likely end-to-end (aircraft-to-control station) measurement and logging capabilities of a drone system using cellular for C2. Drone developers, operators, and regulators may also benefit from having a reference method for assessing the performance of a particular drone type's cellular C2 link across varying operational environments throughout the lifespan of the drone system. Drone and cellular equipment OEMs could support this Reference Method by providing enhanced parameter logging where needed.

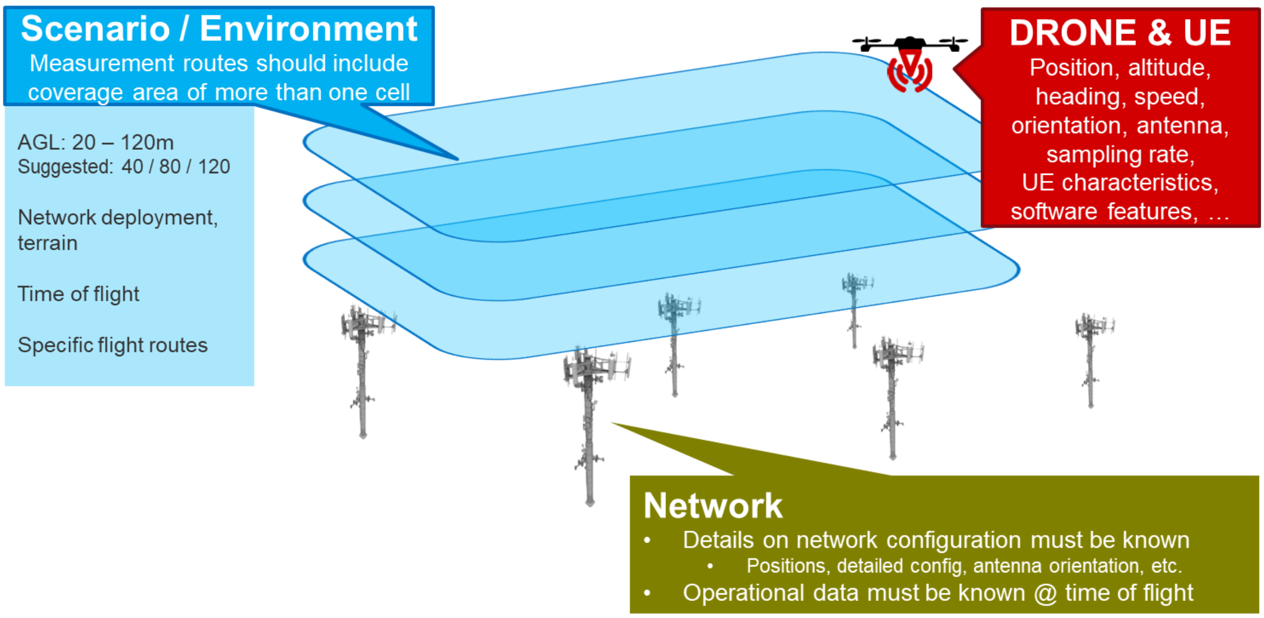

Figure 1 - Operational environment for cellular RF characterization for drones

For a holistic description of the C2 link performance and RF environment applicable to BVLOS drone operations, aspects in different key areas have to be taken into account (note: some of the information is publicly available, some is proprietary information from mobile network operators):

- ***Operational Scenario and Environment***

  This includes information about which "typical and characteristic areas" should be investigated, such as rural, urban or sub-urban environments. Considerations about the terrain and the population density have to be considered, as this has a direct impact on the cell and inter-site density of the cellular networks. Furthermore, land usage classes, 3D topology and other environmental considerations are to be taken into account.

  In the setup for a harmonized approach, flight and measurement altitudes should be defined. To support the applicability of specific use cases, typical time of flight (morning, mid-day, evening, weekday, weekend, …) or density of drones simultaneously flying, as well as specific flight routes, e.g. along highways, railroads, etc., need to be considered.

- ***Drone, UE and Measurements***

  This includes information about the aircraft itself (physical and performance-related information), such as cellular modem information, underlaying chipset used (e.g. SINR is not standardized by 3GPP), antenna characterization at the drone, logging capabilities, measurement frequency (sampling rate), band locking information (i.e. connected to a dedicated frequency band or not – e.g. subject to the allowance of frequencies for aviation use), parameters to be measured, packet sizes for the comparison of retransmissions, latency and packet loss ratios, flight heading, speed, telemetry data, etc.

- ***Radio Access Network Data***

  Some of the network parameters are important to be able to compare the RF characteristics of different networks. This includes frequency bands (e.g. 900MHz), access technology (e.g. LTE), and so on. Furthermore, for detailed characterization and deeper understanding, additional network data and details may be needed. This includes information about the actual site configuration, antenna orientation, operational parameters such as transmit power settings, as well as performance data such as cell loading at the time of the flight/measurement for interference assessment and many more.

1.2. Notional Stakeholders and their needs

For the purposes of this paper, we assume that the Reference Method presented here is of relevance to the below listed key stakeholders. While the respective stakeholders may have different needs individually, collectively they all want to have a minimum set of rules and methods allowing them to

- set up, support and conduct measurements and measurement campaigns in the airspace so that the results can be compared with results from other projects,
- demonstrate minimum conformance with required thresholds
- demonstrate capabilities of equipment, network, components, services based on harmonized procedures, rules and methods
- benchmark connectivity in the airspace for C2 and other services

- warrant minimum performance for safety critical performance
- Etc.

Stakeholder that this may apply to include examples such as

- Drone Operators
- Drone and Control Station OEMs & Integrators
- Cellular UE OEMs
- Aviation and spectrum regulators
- Mobile Network Operators
- Aviation and Cellular Standards Bodies, rule makers.
- Etc.

1.3. Goals

There are a number of goals defined that this paper aims to achieve:

1. A goal is to define a representative setup to measure and compare the applicability and capability of cellular C2 link performance and RF connectivity for BVLOS drone operations. (Payload connectivity assessment may be conducted using similar approaches to C2 performance methods described in this document)

2. A goal is to identify a variety of measurement and analysis setups representative for different business models and application cases that can be used for initial qualification and in-service assessment of drone cellular C2 link performance

3. A goal is to provide recommendations for the minimum number of flight routes needed for drone measurements so that the C2 link performance and RF environment for the lower airspace can be characterized.

4. A goal is to identify the minimum number of key parameters that have to be measured for C2 link performance and RF characterization.

5. A goal is to agree on the required data (and data format, reference format) coming from the drone, drone operations, measurements and the associated log-format.

6. A goal is to organize those needs that require standards input from ASTM, 3GPP or other standards developing organizations (SDOs). This helps close the gap between standards organizations. For example, flight plans may come from ASTM but Key Performance Indicator (KPI) analysis methods may come from 3GPP, EUROCAE and RTCA.

7. A goal is to understand and define end-points for measurement procedures and to define rules and assumptions for elements not involved in the end-to-end measurement procedure. For example, assumptions being made about the Aviation Data Network, rather than including it in the measurements.

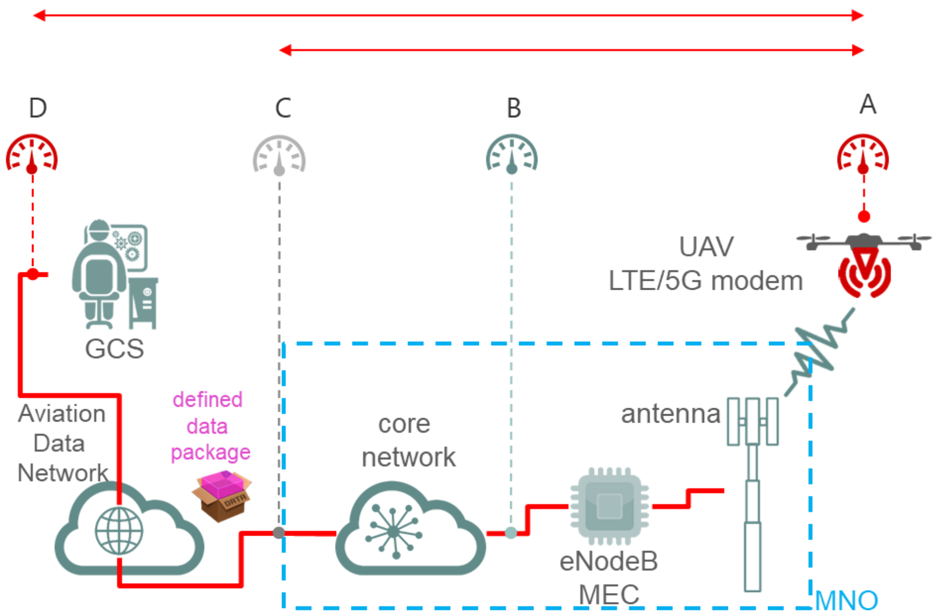

Figure 2 – End-to-end latency measurement options

8. A goal is to understand what real time metrics, non-real time and aggregated data can come from the MNO, such as, but not limited to RF measurement reports for individual RF transceivers on a drone which could be useful for measuring and characterizing the airspace connectivity.

The overall objective is to provide a "Reference Method", comprising of a minimum set of descriptions to standardize the way that C2 link performance and RF measurements are to be conducted for the characterization of the connectivity in the airspace. The Reference Method does not limit any entity, by any means, to deploy or implement other measurement procedures instead of, or in addition to the defined methods.

This document is not anticipated to be a complete set of functions and definitions required for a holistic C2 link performance measurement and RF characterization of the airspace.

This Reference Method is intended to be read by service architects, system engineers and operational people in charge of designing and developing measurement campaigns.

2. Reference Method for Assessing Cellular C2 Link Performance for UAS

2.1. Method Introduction

This chapter summarizes a method for measuring, assessing, and documenting C2 link performance and RF characterization of a particular type of drone system (UAS) utilizing a 4G/LTE connection from an MNO. With some changes to some parameters, this general approach may be adapted for other 3GPP communications technologies as well.

In a previous implementation of this method, fixed-wing uncrewed aircraft were flown. There is nothing in method that prevents other types of aircraft – crewed or uncrewed – from using a similar approach. Future implementers may need to make adjustments accordingly.

In this chapter, we assume that all aerial cellular RF parameters are being ***measured from the UE connected to the aircraft's autopilot*** as part of the performance assessment of the cellular C2 Link. Auxiliary instrumentation – standalone UEs not connected to the aircraft's autopilot – are covered in more details in Chapter 3. The operational flight test approach described here can generally be used for either purpose.

2.1.1. Background

The scope of this Reference Method was developed during the development and execution of an actual flight test program with having in mind the following high-level motivating questions:

- "How well does a 4G/LTE network generally support small drone C2 links today?"
- "How does aerial cellular C2 performance vary under different conditions?"
- "What technical capabilities should a drone and a pilot have when they are using cellular for C2?"
- "How can a drone operator assess cellular performance in an area?"
- "What are the trainings, procedures, policies, and operational considerations for cellular C2 drone operations?"

Addressing the above questions benefits the following stakeholders:

- **Aviation regulators** – in evaluating complex drone operational requests utilizing cellular links.
- **Standards bodies** – developing cellular C2 specific standards.
- **Drone & cellular equipment manufacturers** – in providing equipment with the needed KPI measurement capabilities and cellular relevant features and functions.
- **Drone operators and pilots** – in the development and utilization of relevant procedures, processes, and training material.
- **Mobile Network Operators** – in promoting adoption of cellular networks as a viable communications method for BVLOS drone operations.

2.1.2. Purpose

This Reference Method seeks to quantify the degree to which 4G/LTE connections can support typical drone C2 links broadly using the framework of Required Link Performance [1]. While this Method includes the recording of typical cellular RF KPIs[1], the primary objective is to understand ***interruptions in the link*** that prevent C2 message transactions[2] from occurring for a ***particular*** drone type. Specific link requirements may vary widely, from one drone to another, depending on the operational environment, regulator expectations, and level of drone automation.

It is expected that the Reference Method supports two key future outcomes:

1. **Identify the relevant network and UAS conditions under which interruptions are likely to occur.**
2. **Quantify the frequency, duration, and distribution of interruptions for representative use cases, operating environments, airspace classes and network conditions.**

Both of these outcomes provided by a drone operator could be used by an aviation regulator for evaluating complex operational requests.

At a high level, message transaction interruptions can either be operationally insignificant or significant to a drone mission, depending upon a wide range of factors, including airspace-safety regulatory requirements. Understanding causes of link interruptions is of importance to key drone ecosystem stakeholders. For example, during a flight a particular drone may encounter an *unpredicted and unknown* 2 seconds interruption in the link to its control station without the drone invoking any pre-planned behavior (this is an insignificant interruption). An interruption of 5 seconds or more may cause its onboard autopilot to automatically invoke a Return to Launch (RTL) condition, where the drone flies back to its launch point, or other designated location (this is a significant interruption). The pilot or drone autopilot could override this RTL behavior and resume the mission if the C2 link is reestablished and flight rules permit this course of action.

Using either the 2 seconds (insignificant) or 5 seconds (significant) example scenario, some questions are raised regarding contributing factors to the interruption such as:

- Did the interruption correspond to substantial changes in the cellular RF environment?
- Did the interruption correspond to a cellular handover - of any type - and what was the duration of the cellular handover?
- Was the aircraft flying straight and level, or was it banking or maneuvering in other ways?
- Was the pilot intervening with the pre-programmed automatic flight route?
- Did the control station or autopilot experience a fault, temporary loss of power etc?

The diagram below illustrates the overall scope of the Reference Method. Information is collected from both the MNO and the drone domains in order to identify contributing factors to link interruptions. Information from both domains is of different categories and from different sources, as it will be discussed in the next section.

[1] RF KPI examples include RSRP, RSRQ, SINR and others

[2] C2 KPI examples include cyclical heartbeat messages, pilot-initiated commands, telemetry messages

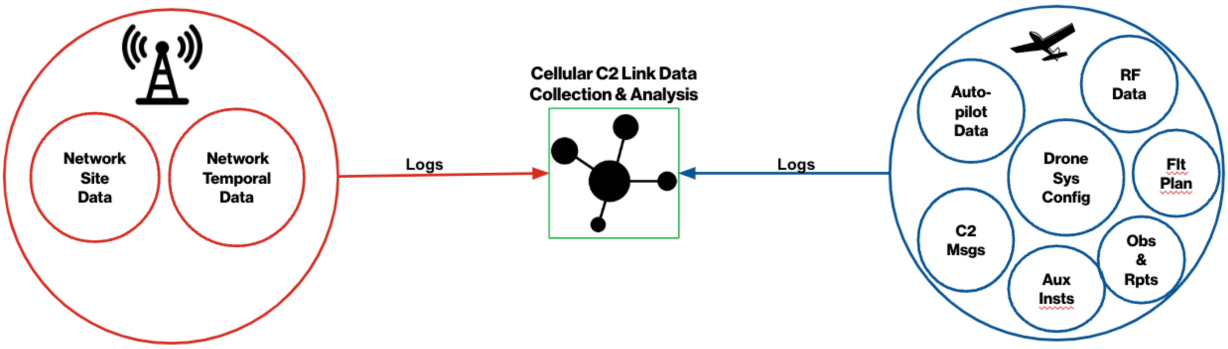

Figure 3: Merging of Cellular and Drone Domains

Using this approach allows us to investigate a hypothetical scenario which guided the development of this method:

A drone at 350 ft, banks left 10 degrees, thereby changing the serving cell, which causes a long handover and link interruption, to a new serving cell after which the drone measures cellular KPIs of…

The Reference Method seeks to capture and assess the above scenario using an end-to-end, control station-to-aircraft approach.

2.1.3. Categories of Information

As illustrated in Figure 2, interruption analysis involves the end-to-end assessment of the drone system, from aircraft to MNO to cloud service (if applicable) to control station (CS). Information is collected from these technical systems and from flight test program stakeholders, such as flight test program managers and drone pilots. There are 3 general categories of information used in this Reference Method:

- **Configuration Data:** Information regarding the state and settings of all operational elements at the time of a flight, such as drone make & model, autopilot settings, drone antenna types, MNO cell tower details, etc.
- **Logs:** Technical-system generated information collected during the execution of a flight, such as C2 and RF KPIs recorded by the aircraft, control station, and MNO. From the aircraft are also collected: position, orientation, and velocity information. If the CS is mobile, positional information is also recorded.
- **Observations and Reports:** Reports are generated by flight test program managers and drone pilots both before and after the flight. This includes information about contextual scenario conditions, such as urban/suburban/rural characteristics, weather and local air traffic, anomalies encountered, and other observations. Reports may also be submitted by MNO teams on a case-by-case basis, including any observations regarding network interference.

2.1.4. Information Sources

<u>**Configuration and Log**</u> data are collected from the following technical sources:

- ***Drone / Uncrewed Aircraft (UA)***

    - Autopilot: for collecting C2 KPIs and other aircraft information such as the position of the aircraft
    - UA UE: for collecting RF KPIs
- ***Control Station (CS)***
    - C2 software: for collecting C2 KPIs and other CS information
    - CS UE, if applicable: for collecting RF KPIs
        - If the control station is connected to a MNO via a cellular link
- ***MNO***
    - Network configuration: for aerial coverage modeling and simulation
    - Network logs: for identifying network utilization and other issues
- ***Cloud & networking providers***
    - If the drone system network architecture includes cloud and external networks
- ***Auxiliary Instrumentation, if applicable***
    - This could include handsets like Qualipoc [2], Nemo [3] or other similar devices. These are not used in the C2 link, but can provide additional information about the RF environment.

Observations and Reports are collected from the following sources:

- ***Program managers and analysts***
- ***Pilot and flight support staff***
- ***MNO staff, such as a regional performance team, if applicable***
- ***Airspace regulator, if applicable.***

2.1.5. Future Applicability to C2CSPs

Though beyond the scope of this paper, the method described here may help inform the general approach, required data, and high-level interfaces between various drone system elements and a future C2 Communications Service Provider (C2CSP). A C2CSP may provide drones future “Link Services” such as:

- Predicted communications coverage and performance
- In-flight quality monitoring and status notifications
- Dynamic in-flight communication policy changes
- Post-flight performance assessment
- Reporting to regulators

Providing these services may require the sharing – between drone system elements and the C2CSP - of data similar to what is described in this method, both logged and in real-time. To provide these services, a C2CSP may need to utilize and provide an aerial coverage and modeling simulation tool that automatically ingests much of the data described in this Reference Method. Such a modeling and simulation tool could be used during 1) initial qualification of a new drone system 2) future cellular drone operational requests and approvals. A C2CSP’s role in a future drone landscape is depicted in the figure below.

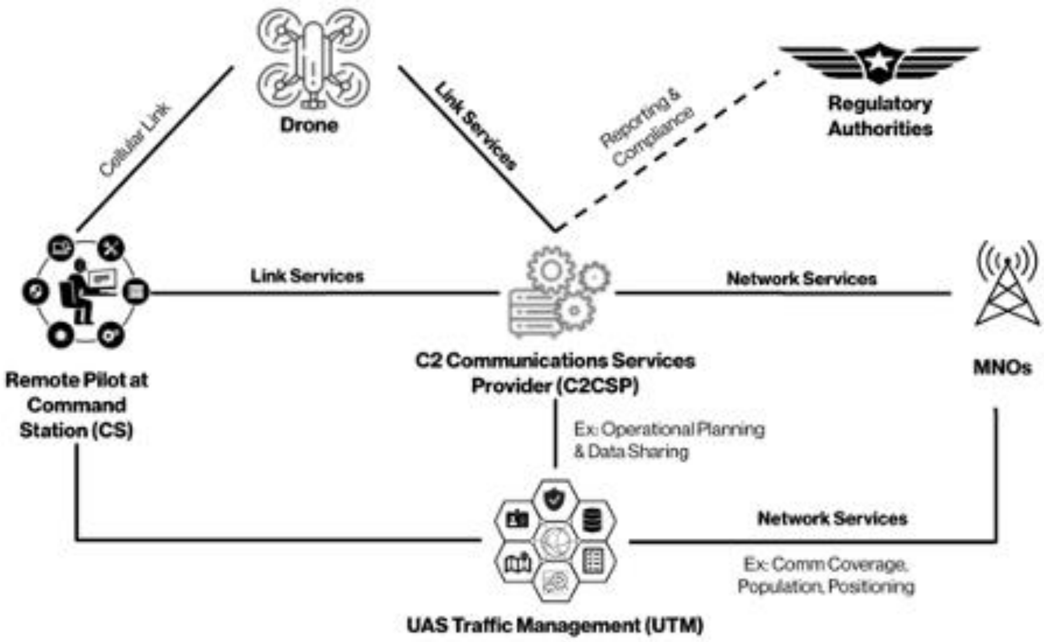

Figure 4: Future Drone Cellular Landscape

2.1.6. Known Challenges and Limitations

There are a variety of known challenges that may affect the implementation of this Reference Method. Such challenges may require implementers to generalize and normalize certain parameters in flight test programs utilizing more than one type of aircraft. Implementers may find it helpful to create a data dictionary for each aircraft type along with a data normalization document when combining data from multiple aircraft. Based on prior experience, some challenges include:

- The expense - time and budget - of logging and customizing UAS to collect measurements in the way described in this method.
- Differences from one drone autopilot ecosystem to another regarding the measurement, logging, and definition of key C2 parameters, such as heartbeat messages, command transactions, flight modes, and altitude reporting.
- Differences in UE OEM exposure of RF and other KPIs and available measurement rates. This includes measurement readings in floats vs integers, non-3GPP standardized reporting of SINR and heterogeneous sampling rates.
- Differences in types of drones such as a fixed wing aircraft vs a multirotor. For example, multirotor drones can orient with respect to the velocity vector in ways that fixed wing aircraft cannot and ascend & descend differently. The drone inclination may lead to different cell associations and handovers, depending on the direction of its motion.
- Differences in Control Station software implementations as they are related to exposed features and functions. RTL timers can be easily user configurable in some software applications but not in others. Displays, such as link quality indicators, may have been designed for direct link radios, may possibly not be accurate and/or useful for cellular links.

- Measuring and recording of Control Station RF KPIs, depending upon type of device used for the CS and its ecosystem.
- National and carrier specific differences affecting permitted aerial cellular bands and possible data rate restrictions, especially in the vicinity of airports, military zones, radio astronomy or meteorological stations.
- National restrictions may affect permitted spaces for RF measurements collection. Flights may be authorized only for experimental purposes, over secure areas (typically airports), often with particular cellular infrastructure settings. Waivers may be still hard to obtain, especially over urban environments. Results obtained from measurement campaigns are in this case only representative of such type of environment.
- Due to the expense of flight operations, the information and data collection approach defaults to collect as many likely relevant parameters as possible, even if the interruption analysis doesn't immediately require it.
- If applicable, the management of multiple flight service providers and oversight of the correct implementation of this method by their staff.
- Access and use of proprietary network data for use in aerial coverage modeling tools and rate at which changes are made to the local network configuration.
- Collecting information on the geographical position of base stations may be a real challenge, it may not be public or be associated with different identifiers.

2.2. Technical Pre-Conditions

This section summarizes the recommended technical capabilities, tools, and information needed by users of this Reference Method. This Reference Method assumes that those implementing this method have access to the items in the list below. Items with an asterisk (*) are explained in more details within this section.

1. **Network Data:** A mobile network operator's proprietary network planning tool with configuration and log data that is imported into a 3D or 4D aerial coverage modeling tool. This data includes parameters on the physical locations and RF characteristics of the MNO's cells and their temporal utilization within the vicinity of flight operations. Such data may be accessible through the network repository, configuration management platforms, radio network data bases or planning tools used by the respective MNO. Proprietary solutions as well as commercially available planning tools and data repository solutions such as ASSET [4], Atoll [5], or Planet [6] are examples.

2. **Aerial Coverage Modeling Tool**: A 3D or 4D aerial cellular coverage modeling tool that can generate propagation and link performance predictions in a general flight operations area or a long a specific flight route. Such a tool can help identify ***predicted areas of link interruptions***. This type of tool can be used to assess whether a candidate area is of interest and assess the performance of the link after a flight. A tool that compares actual measurement data with pre-flight predictions can assist implementers by reducing flight hours in areas of predictable performance. AirborneRF [7] is an example of such a tool.

3. **File Storage Service:** One or more file storage services that contain all the files to be collected using this Reference Method. Google Drive is an example of such a service. In a previous implementation of this Reference Method, multiple separate storage services were established: 1x for each third-party Flight Service Provider (FSP) and 1x for archiving proprietary network data. In this way, proprietary network data can be separated from UAS-collected data and one FSP does not have access to data collected from another.

   A sample nested folder-organization schema is shown below for the *non-MNO provided data only*. Selected files are also listed under some of the folders. Network data files are stored in a separate location, for the data-protection reasons previously discussed.

   a. **[Folder] Log File Schema Version (example - "V1.0")**
   b. **[Folder] Campaign Unique Identifier (w/ Canonical Name)**
      i. [File] Campaign Definition File
      ii. **[Folder] Operation Unique Identifier (w/ Canonical Name)**
         1. [File] Post-Flight Report Questionnaire answers (1 file for all flights in an Operation)
         2. [File] Flight Waypoint File Name File with Planned Flight Hours
         3. **[Folder]** Aircraft Registration Number
            a. [File] UAS Configuration File
            b. **[Folder] Flight Date**
               i. **[Folder] Flight Number of the Day**
                  1. [File] Combined Log File
                  2. [File] other original files from the UA and CS

   Implementers of this method may choose to automate the transferring of these data files from the storage service to the aerial coverage modeling tool and the data analytics platform (discussed below).

4. **Aerial Data Plans & Devices (if applicable):** If an MNO offers an aerial-specific machine-to-machine data plans, these plans should be utilized by the UE on the UA. Some MNO's restrict aircraft-to-cellular network data rates in an attempt to mitigate interference generated from aerial devices. Alternatively, some countries prohibit specific cellular frequencies from being used by aerial devices. It is critical to evaluate if any aerial restrictions apply prior to starting flight data collection. If not, results derived from flight testing could be invalid.

5. **Aircraft-to-Control Station Networks:** Implementers of this method should consider and evaluate the networking approaches used to communicate between UA and CS. In general, the purpose of this Reference Method is to evaluate how well cellular networks support C2 link performance. Networks external to the MNO can be characterized without flight testing using other well-known methods. When reporting results using this Reference Method, particularly latency metrics, it is important to qualify results with a description of the network used by the UAS.

There are a variety of potential solutions to connect UA to CS. In some cases, a UAS OEM may already have a commercially available solution. In other cases, the UA-to-CS network will need to be developed by implementers of this Reference Method. In a previous implementation of this method, a Private Mobile Network with one fixed-location physical switch was established for the aircraft and control stations. Data routing occurred only within the MNO and no external network was used. The UEs had no access to the internet. This resulted in a deterministic network path for all flights occurring under the program.

6. **Data Analytics Platform:** In order to automate the processing, analysis and reporting of the various files collected in this Reference Method, it is recommended to utilize a data analytics platform. Alteryx [22] is an example of such a platform. This can aid in quantifying link performance at the individual flight, operation level, campaign level and program levels of abstraction. At the individual flight level, such a platform can greatly aid in identifying possible contributing factors to link interruptions.

7. **Optional: Auxiliary Instrumentation Equipment:** In some cases, implementers of this method may desire to record lower-level RF information than what is provided by the aircraft's UE. In such cases, a handset like a Qualipoc [2] can be carried as a payload if the aircraft permits it. While not a part of the C2 link, such a tool can help understand network behaviors at altitude - keep in mind chipset and device type differences between handsets and M2M devices. Auxiliary instrumentation is discussed in more details in Chapter 3.

8. **UAS with a Known Configuration and Enhanced Logging:** The next two sub-sections, "UAS Configuration File" and "UAS Data Logging" document 1) what information is required to understand the UAS to be operated at 2) the logging capabilities of the UAS used in this method. Currently, such configuration data and logging capabilities are not widely available in off-the-shelf UAS. As such, direct coordination with UAS OEMs is likely needed.

2.2.1. UAS Configuration File

The UAS Configuration File is a set of information to be captured prior to the start of a flight data collection program about the aircraft and control station to be operated. It contains information on the characteristics, capabilities, and configurations of the aircraft and control station. Ideally, the UAS Configuration File is completed by a drone OEM, though it is also possible for a flight service provider to provide some of this information. The UAS Configuration File should be updated if any relevant changes to the aircraft or control station occur during the execution of the program. A UAS Configuration File should exist for every individual airframe. Not all parameters captured in the UAS Configuration File are currently used in the Reference Method, but should be captured for future analysis opportunities.

Uncrewed Aircraft Physical Parameters

1. Aircraft Registration Number from CAA
2. Unique Configuration Specifier (optional)
3. Make
4. Model
5. Serial Number
6. Manufacturing Year
7. Airframe Type

8. Primary Mission Types
9. Airframe Materials
10. Takeoff Type
11. Landing Type
12. Wingspan (m)
13. Nose-to-Tail Length (m)
14. Max Takeoff Weight (kg)
15. Propulsion Type
16. Max Flight Duration (min)
17. Max Payload Weight (kg)
18. Max Airspeed (kph)
19. Cruise Airspeed (kph)
20. Stall Airspeed (kph)
21. Max Groundspeed (kph)
22. Max Ascent Rate (m/s)
23. Max Descent Rate (m/s)
24. Max Kinetic Energy (J)
25. Turn Radius at Max Airspeed (m)
26. Turn Radius at Cruise Airspeed (m)
27. Wind Resistance: Continuous (kph)
28. Wind Resistance: Gust (kph)
29. Max Flight Ceiling (m)
30. Minimum Operating Temperature (degC)
31. Maximum Operating Temperature (degC)
32. If eVTOL, max hover duration at configuration weight (min)

Uncrewed Aircraft Avionics

1. High-Level Description of Avionics
2. High-Level Avionics Block Diagram
3. High-Level Networking Architecture Diagram (UA to CS)
4. General Description of the Uses of Cellular Link: example - “C2”, “payload”
5. Planned communications protocol: example - “UDP”
6. Trigger Settings Causing Cellular Lost Link Declared
7. Record Planned Latency Threshold For Cellular Lost Link Declared
8. Trigger Settings Causing Switchover from Cellular to Other C2 Link
9. Typical Pre-Programmed Aircraft Behavior after Loss of All C2 Links
10. *Autopilot*
    - 10.1. Make
    - 10.2. Model
    - 10.3. Serial Number
    - 10.4. Operating Software Type
    - 10.5. Software Version
    - 10.6. Available Flight Control Inputs
    - 10.7. Available Flight Control Modes
    - 10.8. Level of Automation
11. *Companion or Onboard Computer*
    - 11.1. Make
    - 11.2. Model
    - 11.3. Serial Number

11.4. Operating Software
11.5. Software Version

12. Cellular Modem (UE) (repeat as needed)

12.1. *Make*
12.2. Model
12.3. Serial Number
12.4. Operating Software
12.5. Software Version
12.6. RF Chipset Make & Model
12.7. RF Parameter Interface: example - "AT commands"
12.8. Number of SIM Cards
12.9. Carrier certifications
12.10. Operating Frequency Bands

13. SIM Cards and Communications (repeat as needed)

13.1. MNO
13.2. ICCID
13.3. MDN
13.4. Data Plan Description: *If using an airborne-specific data plan, record permitted frequency bands, data rate restrictions, and other relevant constraints.*
13.5. Forward Link Data Rate (UA received)
13.6. Return Link Data Rate (UA transmitted)

14. UA Cellular Modem Antennas (repeat as needed)

14.1. Make
14.2. Model
14.3. Part Number
14.4. Serial Number
14.5. Manufacturing Year
14.6. Number of Antennas
14.7. Mounting Location
14.8. Mounting Orientation
14.9. Polarization
14.10. Min Frequency (MHz)
14.11. Max Frequency (MHz)
14.12. Center Frequency (MHz)
14.13. Applied Voltage (V)
14.14. Ground Plane (Y/N)
14.15. Antenna Gains by Band (dB)
14.16. Photo of antenna location

15. As needed, list and describe other transmitters and receivers onboard the aircraft

Control Station

1. High-Level Description of GCS
2. High-Level GCS Block Diagram
3. *Compute Device*

3.1. Make
3.2. Model
3.3. Serial Number
3.4. Operating Software Type
3.5. Software Version

4. *CS Cellular Modem (UE) (repeat as needed)*
    4.1. Make
    4.2. Model
    4.3. Serial Number
    4.4. Operating Software
    4.5. Software Version
    4.6. RF Chipset Make & Model
    4.7. RF Parameter Interface: example - "AT commands"
    4.8. Number of SIM Cards
    4.9. Carrier certifications
    4.10. Operating Frequency Bands
5. *SIM Cards and Communications (repeat as needed)*
    5.1. MNO
    5.2. ICCID
    5.3. MDN
    5.4. Data Plan Description: *record frequency bands, data rate restrictions, and other relevant constraints.*
    5.5. Forward Link Data Rate (CS transmitted)
    5.6. Return Link Data Rate (CS received)
6. *CS Cellular Modem Antennas (repeat as needed)*
    6.1. Make
    6.2. Model
    6.3. Part Number
    6.4. Serial Number
    6.5. Manufacturing Year
    6.6. Number of Antennas
    6.7. Mounting Location
    6.8. Mounting Orientation
    6.9. Polarization
    6.10. Min Frequency (MHz)
    6.11. Max Frequency (MHz)
    6.12. Center Frequency (MHz)
    6.13. Applied Voltage (V)
    6.14. Ground Plane (Y/N)
    6.15. Antenna Gains by Band (dB)
    6.16. Photo of antenna location
7. *As needed, list and describe other transmitters and receivers associated with the control station.*

2.2.2. UAS Data Logging: Drone/UA & CS

UAS Data Logging refers to all relevant measurements collected by an aircraft and its control station during the execution of a flight. To assist with C2 interruption analysis, RF characterization, and future modeling and simulation objectives, an approach is to record as much data as possible from UAS 4G/LTE modem, UA autopilot, CS C2 software, and GNSS equipment on both the UA and CS.

For each flight, there are typically multiple log files generated from both the UA and CS. In a prior implementation of this Reference Method, measured parameters are separately logged by the UA and CS then merged into a single, unified file, using a file merging program. This file merging program that creates an "**UAS Combined Log File"** can be developed either by the UAS OEM or by the flight operations team. Implementation may depend on whether the drone uses open source or proprietary technology.

A Combined Log File:

- Has the **advantage** of facilitating the analysis process by creating a single file where measurements of all UAS data sources can be compared easily. This is particularly useful if the Combined Log File is used in an aerial coverage modeling and simulation program.
- Has the **disadvantage** of adding an additional process step under this Reference Method and in some cases, cannot be directly compared from one OEM to another without abstraction.

Based on the asynchronous measurement of various UAS parameters, time interpolation is required. Moreover, some data sources provide parameters at higher rates than others – often the 4G/LTE modems are the slowest data sources and may have bounded, though unpredictable response times to parameter requests. Recording frequency in a UAS highly depends on OEM or chosen ecosystem. Furthermore, recording frequency between UA and CS may differ.

In a previous implementation of this Reference Method, the measurements and timestamps from the UA's UE were used as the target to synchronize the other measurements with it. For example, in a merged logged file, measurements from the UA autopilot and CS software are interpolated to the RF parameters from the UA UE. In the Combined Log File, higher rate measurements, such as from the autopilot, are discarded as they do not correspond to UA UE RF measurements.

However, for each flight, all *original logs* from the UA and CS are archived so that higher-rate data is available for in-depth analysis. For example, if a flight experiences an interruption and it is suspected that the UA is quickly maneuvering, the autopilot logs may be examined for additional detail.

As mentioned in the section "*Known Challenges and Limitations,* the avionics and logging implementations vary between drone and cellular OEMs. Similarly, UE interfaces and polling response times differ. For some types of parameters, particularly for C2 message transactions, it is difficult if not impossible to directly correlate one OEM's logs to another. For example, aircraft flight mode status definitions and heartbeat implementations vary from one drone ecosystem to another.

The technical parameters in the table below represent the type of UAS data that is essential to assessing aerial 4G/LTE C2 link performance of a drone system - both C2 link interruptions and characterizing the RF environment.

As a reminder, other information sources – logs, observations, and reports – may be used in conjunction with the contents of this UAS Combined Log File in performing the interruption analysis.

Table 1: UAS Combined Log File contents

#	Parameter	Meaning	Comments
1	Active Link	Active link used for communication. Cellular, Wifi etc…	
2	UA PS log header	PS = positioning system (NMEA string GNSS, GPGGA, etc…), blank if not reported	
3	CS PS log header	PS = positioning system (NMEA string GNSS, GPGGA, etc…), blank if not reported	
4	UA-PS UTC (hhmmss)	Time reported by the UA positioning system, expected to have this format (hhmmss)	If there are multiple sources of the same data, use the primary one. Time and date reported in UTC should all match from various sources
5	UA-PS Date (ddmmyy)	Date reported by the UA positioning system, expected to have this format.	If there are multiple sources of the same data, use the primary one. Time and date reported in UTC should all match from various sources
6	CS-PS UTC (hhmmss)	Time reported by the CS positioning system, expected to have this format	If there are multiple sources of the same data, use the primary one. Time and date reported in UTC should all match from various sources
7	CS-PS Date (ddmmyy)	Date reported by the CS positioning system, expected to have this format.	If there are multiple sources of the same data, use the primary one. Time and date reported in UTC should all match from various sources
8	UA-PS Lat (Deg)	Lattitude. Decimal degrees value.	Convert as needed
9	UA-PS Lon (Deg)	Longitude. Decimal degrees value.	Convert as needed

10	CS-PS Lat (Deg)	Decimal degrees value.	Convert as needed
11	CS-PS Lon (Deg)	Decimal degrees value.	Convert as needed
12	Range btn CS_UA (Slant in m)	Calculated or auto generated slant based on lat, long and alt.	For line-of-sight alternate (non-cellular) link analysis.
13	CS-Cmd msg timeout ind (0/1)	Command message timeout. If there is timeout of a command message, represent it by "1", otherwise "0"	Implementation differs based on OEM.
14	UA-Heartbeat loss (0/1)	Heartbeat loss is recorded by "1" in case of loss of heartbeat, otherwise "0"	Implementation differs based on OEM.
15	CS-Heartbeat loss (0/1)	Heartbeat loss is recorded by "1" in case of loss of heartbeat, otherwise "0"	Implementation differs based on OEM.
16	Loss of C2 link (0/1)	Command and Control (C2) link is lost.	Implementation differs based on OEM, including data source.
17	UA-Ctrl Mode	Control Mode (Auto, Manual, Semi-Auto)	Mode differs based on OEM. Refer to manual. Generalize where possible.
18	UA-DwnVel (m/s)	Aircraft Downward Velocity	
19	UA-Heading (deg)	Aircraft true heading	

20	UA-Air Speed (m/s)	Aircraft Air Speed	Some OEMs record ground speed.
21	UA-Baro Alt (m)	Aircraft Barometric Altitude	Understand calibration and reporting by OEM.
22	UA-Latency (ms)	Round trip time (RTT)	Understand/Define how this is measured between UA and CS.
23	UA-Srv Cell Type	Aircraft Serving Cell type	String value indicating whether it's serving cell or not.
24	UA-Srv PCID (dec)	Aircraft Serving physical cell identifier (PCI)	
25	UA-Srv EARFCN (dec)	Aircraft Serving EARFCN	
26	UA-Srv Freq. Band ID	Aircraft Serving Frequency Band Identification	
27	UA-Srv RSRP (dBm)	Aircraft Serving RSRP	
28	UA-Srv RSRQ (dB)	Aircraft Serving RSRQ	
29	UA-Srv RSSI (dBm)	Aircraft Serving RSSI	
30	UA-Srv SINR (dB)	Aircraft Serving SINR	Some OEM measure SINR, others measure SNR.

31	CS-Srv Cell Type	Ground Control Station Serving Cell type	
32	CS-Srv PCID (dec)	Ground Control Station Serving physical cell identifier (PCI)	
33	CS-Srv EARFCN (dec)	Ground Control Station Serving EARFCN	
34	CS-Srv Freq. Band ID	Ground Control Station Serving Frequency Band Identification	
35	CS-Srv RSRP (dBm)	Ground Control Station Serving RSRP	
36	CS-Srv RSRQ (dB)	Ground Control Station Serving RSRQ	
37	CS-Srv RSSI (dBm)	Ground Control Station Serving RSSI	
38	CS-Srv SINR (dB)	Ground Control Station Serving SINR	
39	UA-Roll (deg)	Aircraft Roll	
40	UA-Pitch (deg)	Aircraft Pitch	
41	UA-Yaw (deg)	Aircraft Yaw	

42	UA-NorthVelocity (m/s)	Aircraft North Velocity	
43	UA-EastVelocity (m/s)	Aircraft East Velocity	
44	UA-Srv State	Aircraft Serving State (RRC connected, RRC Idle etc…)	
45	UA-Srv. RAT	Aircraft Serving Radio Access Technology	LTE/5G/…
46	UA-Srv FDDorTDD	Aircraft Serving FDD or TDD technology	FDD/TDD
47	UA-Srv MCC (dec)	Aircraft Serving Mobile Country Code	
48	UA-Srv MNC (dec)	Aircraft Serving Mobile Network Code	
49	UA-Srv CellID (ECI)	Aircraft Serving Cell ID (ECI)	
50	UA-Srv TAC (dec)	Aircraft Serving Tracking Area Code	
51	CS-Srv State	Ground Control Station Serving State (RRC connected, RRC Idle etc…)	
52	CS-Srv RAT	Ground Control Station Serving Radio Access Technology	

53	CS-Srv FDDorTDD	Ground Control Station Serving FDD or TDD technology	
54	CS-Srv MCC (dec)	Ground Control Station Serving Mobile Country Code	
55	CS-Srv MNC (dec)	Ground Control Station Serving Mobile Network Code	
56	CS-Srv cellID(ECI)	Ground Control Station Serving Cell ID (ECI)	
57	CS-Srv TAC (dec)	Ground Control Station Serving Tracking Area Code	
58	UA-Nbr# Cell Type	Aircraft Neighbor # Cell type	Record multiple neighbors
59	UA-Nbr# RAT	Aircraft Neighbor # RAT	Record multiple neighbors
60	UA-Nbr# EARFCN	Aircraft Neighbor # EARFCN	Record multiple neighbors
61	UA-Nbr# PCID	Aircraft Neighbor # PCID	Record multiple neighbors
62	UA-Nbr# RSRP	Aircraft Neighbor # RSRP	Record multiple neighbors
63	UA-Nbr# RSRQ	Aircraft Neighbor # RSRQ	Record multiple neighbors

64	UA-Nbr# RSSI	Aircraft Neighbor # RSSI	Record multiple neighbors
65	CS-Nbr# Cell Type	Ground Control Station Neighbor # Cell type	Record multiple neighbors
66	CS-Nbr# RAT	Ground Control Station Neighbor # RAT	Record multiple neighbors
67	CS-Nbr# EARFCN	Ground Control Station Neighbor # EARFCN	Record multiple neighbors
68	CS-Nbr# PCID	Ground Control Station Neighbor # PCID	Record multiple neighbors
69	CS-Nbr# RSRP	Ground Control Station Neighbor # RSRP	Record multiple neighbors
70	CS-Nbr# RSRQ	Ground Control Station Neighbor # RSRQ	Record multiple neighbors
71	CS-Nbr# RSSI	Ground Control Station Neighbor # RSSI	Record multiple neighbors

2.3. Campaign & Operations Planning

This section summarizes practices developed during a previous implementation of this method on how candidate flight areas are identified, evaluated, and selected. In general:

- a ***Campaign*** area is a large geographic region which *may* correspond to a mobile network operator performance team's area of responsibility.
- Multiple ***Operations*** may be conducted in that Campaign area with one or more specific UAS at specific times and under specific conditions.

It is assumed that every data collection and analysis program will be different. The implementation experience described below is offered as a ***reference only.***

2.3.1. Campaign Definition File

Before a series of flights are specified under an Operation, a Campaign area is evaluated for its applicability to the overall cellular data collection and analysis program. The parameters below are used by the program management team in order to evaluate various candidate areas. For example, some areas may permit flights up to a maximum legal altitude limit, for example 400 ft AGL, in areas of low population density, while another area may provide a high-population density but restrict flights to a lower altitude limit in controlled airspace, for example 200 ft AGL. It is up to the management team to make tradeoffs in candidate Campaign areas, using some of the following parameters. It is recommended to create a spreadsheet with these parameters to evaluate and disposition candidate Campaign areas.

1. Campaign Area Unique Identifier
2. Location Canonical Name: example - “Houston Metro”
3. Types of Use Case Operations Planned: example – “baseline”, “long linear”, “area survey”
4. Planned flight hours
5. Aircraft make(s)
6. Aircraft model(s)
7. Aircraft type(s): example - “multirotor”, “VTOL Fixed Wing”, “Fixed Wing”
8. Aircraft UE make(s) and model(s)
9. UA-to-CS networking summary: example - “private mobile network”
10. Availability of an auxiliary instrumentation payload: example – Qualipoc [2]
11. Max permitted flight altitude, above ground level
12. Day and/or night flights permitted
13. Operating airspace(s): example – “Class G”
14. Airspace authorization required: example – LAANC
15. General population density
16. Type of terrain
17. Cellular network operator’s region description
18. Base station supplier in region: example - “Nokia”
19. Cellular network operator’s topology definitions

2.3.2. Operation Area Assessment

After initially characterizing potential Campaign areas, more in-depth flight operations planning can be conducted at the Operations level. This generally includes the following:

1. **Assess Candidate Operations Areas:** Using public or private network coverage tools, identify one or more candidate flight operations areas within the Campaign area. Ideally use a tool that assesses 4D coverage which uses both network cell location and network utilization data, such as AirborneRF [7]. If supported by the tool, hypothetical flight routes can be generated to evaluate predictions of the RF environment, like areas of interruptions, number of neighbor cells, and other performance parameters. Aspects to evaluate include, but are not limited to, estimated RF conditions, cell density, number of expected handovers, geographic features, overflight of people and airspace restrictions. A few different candidate flight operation areas should be identified.

   - Any areas of ***Predicted or Known C2 Link Interruption*** should be identified and communicated to the pilots for planning purposes. To facilitate understanding of lost link contribution conditions, it is very useful to fly into areas interruptions. *At all times, operational safety should take precedence over data collection objectives.*

2. **Network Performance Team Coordination:** If applicable, discuss candidate flight operations areas with the network operator's local performance team. Identify time windows for any planned maintenance activities or other location-specific concerns, including areas of non-dominant cells.

3. **Operation Area Selection:** Using information from the Campaign Definition File, assessment of candidate Operations areas, and consultation with the network planning team, specific flight operations areas can be proposed to the pilot and flight operations team. The flight operations team can evaluate these candidate areas for any air and ground risk safety concerns and the need for additional operational approvals, such as airspace authorizations or local air traffic.

Route Test Objectives

Route Test Objectives is an approach for conducting methodical flight data collection within an operations area. The approach also facilitates consistency between operations in different operating areas. Route Test Objectives are defined by the following parameters:

- Unique Route Test Objective Identifier: example - "1000.2"
- Objective Description: example - "Level altitude baseline"
- Target Altitude (m): example - "80 m"
- Minimum Altitude (m): example - "70 m"
- Maximum Altitude (m): example - "90 m"
- Orientation (if a rotorcraft): example - "keep nose towards velocity vector"
- Flight Route Pattern - example - "Lawnmower over horizontal plane"
- RTL Timer Trigger (s): example - "10 seconds"
    - If the time to trigger RTL setting is pilot configurable, it may be useful to vary timer settings to further investigate interruptions particularly in aircraft with relatively low-rate parameter recording. Flight safety should always have priority over the data collection objectives.

Route Test Objectives can be further defined using .kml files in Google Earth and reviewed with the pilot. With knowledge of the locations and characteristics of cell sites from proprietary network sources, more detailed flight objectives can be specified. For example, it may be of interest to fly towards, across, and at various altitudes with respect to a particular cell. Flight patterns can be flown both clockwise and counter-clockwise. When pilots design waypoint missions, they should reference specific Route Test Objectives. Desired flight hours can be assigned to each Route Test Objective and briefed during the Collection Readiness Review. ***For data analysis and reporting purposes, flights through predicted and known areas of interruption should be assigned different Route Test Objective IDs.***

2.3.3. Operation Preparation

After selection of the Operations area, but before the start of flights, the following items should be completed:

1. Update Operations checklists, as needed

2. Update the UAS Configuration File if any relevant changes to the UAS have occurred
3. Verify any airspace authorization requests are granted
4. Create Campaign and Operation-specific log file storage locations
5. If relevant to the UAS, create drone waypoint files that satisfy individual Route Test Objectives. Note: not every time a drone may support the ability to accomplish the Route Test Objectives in an automated fashion. If so, semi-manual piloting is required.
6. Update and review results from the 4D prediction tool, if required
    6.1. Clearly document if flying through areas of expected interruptions is a test objective.
7. Perform readiness checks on the UAS and any auxiliary instrumentation
8. Perform prerequisite logistics necessary for drone operations.

2.4. Flight Execution

This section summarizes practices developed during a previous implementation of this method. It is assumed that every data collection and analysis program will be different. The information below is offered as a ***reference only.***

2.4.1. Collection Readiness Review

A Collection Readiness Review is a formal meeting with program managers, analysts, pilots, and other stakeholders to review the immediate flight operations to be conducted. This review should ideally be conducted at least 1 day prior to the first flight of the Operation. Items to review include:

1. ***Operation objectives***
    1.1. Campaign and Operation Unique Identifiers
    1.2. Flight locations
    1.3. Flight Route Test Objectives and corresponding waypoint flies
    1.4. Specific aircraft make, model, and registration numbers to be flown
        1.4.1. In some cases, multiple aircraft can be simultaneously flown
    1.5. Quantity of flight hours required
    1.6. Specified days of the week
    1.7. Specified times of day
    1.8. Pre-flight ground tests, if required
    1.9. Photo/imagery objectives, if applicable
2. ***Operation-specific flight rules, constraints, and limitations***
    2.1. Airspace regulatory approvals, waivers, etc
    2.2. Altitude restrictions
    2.3. Geographic restrictions
    2.4. Flight proximity to cell towers
    2.5. Lost-link Return-to-Launch settings
    2.6. Expected backup link utilization rules, including failover settings
    2.7. Instructions to the pilot regarding repeatedly flying through known interruption areas.
    2.8. Contingency procedures and mishap notification expectations
    2.9. Weather forecast
    2.10. Use of Auxiliary Instrumentation, such as a measurement handset like Qualipoc [2]
3. ***Personnel and coordination***
    3.1. Drone operator entity or flight service provider name
    3.2. Specific pilot assignments
    3.3. Personnel points of contact

3.4. Coordination tools and expectations
3.5. Post-flight data log storage location and guidelines

4. Operation Risk Assessment

4.1. Outstanding or unusual safety or air and ground risk concerns. *Note: it is advised that a consistent operational risk assessment tool is used to evaluate risk prior to the start of an operation.*

After completion of the Collection Readiness Review, any additional stakeholders should be informed of the Go/No-Go decision to proceed.

2.4.2. Flight Day(s)

Flight execution should primarily follow previously established plans. Additional flight day coordination may be required due to the following types of events:

1. Weather changes
2. Equipment problems or failures
3. Excessive local airspace traffic
4. Pilot recommendations to change established aircraft settings, such as the lost link timer setting.
5. Changes to any parameter listed in the UAS Configuration File or Waypoint Route Files
6. Mishaps

2.4.3. Post-Flight Reports

A Post-Flight Report (PFR) is used by the pilot and flight execution team to record additional information after a flight is completed. In a prior implementation of this Reference Method, the following types of information were included in the PFR and submitted for every flight. Reports were submitted in an electronic form, via Google Forms, and compiled in a spreadsheet within the Operations folder. The questions were nested so that the pilot only fills in lower levels of detail if higher-level questions are relevant.

1. Date and time the report was submitted: example - "12/14/2021 8:29:50"
2. Pilot's last name
3. Pilot's drone license number
4. Report submitter's last name
5. The date of the flight: example - "12/14/2021"
6. The sequential flight number of the day (qty): example - "2" for the 2nd flight of the day
7. The Unique Operation ID the flight was conducted under. Generated from a drone aviation management software platform.
8. The Route Test Objective ID of the flight flown, if applicable to the UAS
9. The aircraft registration number assigned by an aviation regulator
10. Aircraft turn-on time
11. Aircraft takeoff time
12. Aircraft landing time
13. Total flight time in minutes (min)
14. What is the configured lost link trigger timer setting for this flight? (s)
15. What is the configured, autopilot-invoked, automatic behavior of the UA after cellular C2 link is declared? example - "RTL" or "continue flight"
16. Were there any cellular C2 lost link events?
    16.1. How many cellular C2 lost link events were declared? (qty)

16.2. Did the UA / CS perform the planned lost link behavior after cellular C2 lost link was declared? (Y/N)
 16.2.1. If yes, what behavior was executed?
 16.2.2. If no, what happened?
17. Is the root cause of the cellular C2 lost link known? (Y/N)
 17.1. If yes, what was the root cause?
 17.2. If no, what are suspected causes?
18. Were cellular C2 lost link occurrences temporary or permanent or both?
19. Were there any instances of C2 link switchover from cellular to another the backup link because of loss of the cellular link? (Y/N)
 19.1. Was the switchover performed manually by the pilot or was it automatically by the UAS?
 19.1.1. If it was a manual switchover, why did the pilot initiate it?
20. Were any commands or telemetry messages misdirected to the incorrect UA or GCS?
 20.1. Explain if Yes
21. Did any commands from the GCS result in unintended UA system behavior?
 21.1. Explain if Yes
22. At any point in the flight were there any GCS software or hardware failures?
 22.1. Explain if Yes
23. At any point in the flight were there any comm-related UA software or hardware failures?
 23.1. Explain if Yes
24. At any point in the flight was there any use of contingency or emergency procedures by the pilot?
 24.1. Explain if Yes
25. Was the flight aborted while the UA was in flight?
 25.1. Explain if Yes
26. Was the UA in an uncontrolled flight into terrain or controlled flight into terrain?
 26.1. Explain if Yes
27. Did the UA suffer a loss of aerodynamic control?
 27.1. Explain if Yes
28. At any point in the flight did the UA fly beyond the flight area?
 28.1. Explain if Yes
29. Weather Information
 29.1. Percentage of Cloud Layer Coverage (%)
 29.2. Cloud Height
 29.3. Relative Visibility
 29.4. Air Temperature
 29.5. Continuous Wind Speed
 29.6. Gust Wind Speed
 29.7. Precipitation
 29.8. Additional weather events
30. Any additional relevant information pertaining to the flight

On or immediately after every flight day, the data analyst should review the file storage locations to assess the completeness and accuracy of the upload logs, reports, and their location.

2.5. Operation Analysis

Operation analysis can be performed during the course of flights executed under the operation, or after all flights have been completed. The purpose of this analysis is to assess and understand the high-level performance of the link and the RF environment.

If performed mid-way through an operation, analysis can guide changes in the overall operations plan. For example, it may be desired to fly though known areas of poor link performance more than in areas where a solid, uninterrupted link is maintained. Similarly, it is less useful for all flights to connect to a single or very few cells. Detecting these conditions early allows flight operations team to adjust the operational location or time of day.

From a prior implementation of this Reference Method, data analysts should consider some of the following topics:

- **Filtering:** It is important to filter measurements from the aircraft when it is on or near ground level. Previously, a 5-meter filter was used. Otherwise, results will be biased.

- **Flight Hour Tracking:** Using the above altitude filter, a Qualified Flight Hour metric can be defined. This is defined as actual aircraft flight time only when program-mandated logs and reports are provided by the drone pilots. For instance, if a flight occurs, but no Post-Flight Report is generated, the flight time is not counted towards Qualified Flight Hours.

- **Known and Predicted C2 Link Interruption Areas:** During the course of flying, it is likely that areas of repeatable ***Known C2 Link Interruptions*** will be encountered by the aircraft within an operational area. These can be treated in a similar manner to Predicted C2 Link Interruptions identified by an aerial coverage model tool. In many ways, these are the most useful types of areas to operate near and through. Flying through these areas using different flight routes and on different days and times can provide very valuable information on the causes of link interruption. All subsequent flights after the initial interruption area detection should recorded as "intentionally flying into a known or Predicted interruption area." Assigning unique Route Test Objective IDs to these types of flights can later assist in the analysis and reporting activities.

- **Full Connectivity:** In order to accurately represent the impact of the RF environment and cellular connection availability on the performance of the C2 link, the concept of full connectivity is separated into two metrics: C2 link connection and cellular network RF environment. A degradation of the cellular network RF environment is expected to cause a degradation in the C2 link connectivity statistics.
  - **Full C2 Link Connection:** Percentage of time with a "full C2 link connection" is defined as the amount of time that the UA is connected to the cellular network for command and control as represented by successful heartbeat messages logged at the same frequency as modem parameters, divided by the total amount of time that the UA is in flight and using cellular for the C2 link.
  - **Full RF Connection:** Percentage of time with a "full cellular network RF environment" is defined as the amount of time that the onboard UE reports sufficient RF parameters such as RSRP and RSRQ divided by the total amount of the time that the onboard UE reports RF parameters. "Sufficient" should be defined by the implementers of this method.

2.5.1. Individual and Aggregate Flight Analysis

C2 link performance analysis begins at the individual flight level. Using a flight's Combined Log File, pilot-submitted Post-Flight Report, and reports from the MNO's local RF engineers, all detected interruptions (predicted, known, unknown) can be investigated, regardless if they are insignificant or significant. Subject to interpretation, a significant interruption could result in an aircraft invoking an automatic Return to Launch behavior, whereas an insignificant interruption could have no impact on the execution of a planned flight operation.

If coordinating with an MNO, it is important to consult the local RF engineering team's perspective when an event is being analyzed. The local RF team can provide additional insight based on their localized knowledge of network and possible network changes.

Individual Flight RTL Events

A high-level metric is obtained by assessing the end-to-end link performance between UA and CS is the ***quantity, duration, and distribution*** of unpredicted interruptions resulting in Return to Launch events. Again, this is where the aircraft experiences a lost link for more than a set amount of time and initiates an automatic fail-safe return to its launch location. After a flight, any invocation of a fail-safe process, including RTLs, should be analyzed and its root cause should be identified, if possible. The exact triggers, guard conditions, and effects may differ between aircraft of different avionics ecosystems.

One caveat to the above: If the aircraft invokes an RTL, but subsequently the link is reestablished, the pilot may choose to override the RTL action and resume the flight. ***Measuring the duration of the interruption – from loss of link to its re–establishment – is a critical parameter that should be measured and reported if possible.***

Individual Flight RF Measurements at Aircraft and Control Station

It is important to assess the measurements from both the aircraft and control station when analyzing interruptions and anomalies. It is recommended that analysts understand general RF KPI trends (RSRP, RSRQ, throughput, interference, etc…) in both UA and CS even when there are no C2 interruptions causing RTLs. When there are interruptions of any type, analysts should investigate the link state of both aircraft and control station. This is especially applicable to cellular-connected control stations and even more relevant for ground-mobile control stations. For example, a control station serving cell change may cause an interruption, even if it is stationary.

After individual flight analysis, it is recommended that analysts understand how the operation area performed as a whole. This further enables the in-depth analysis of a single flight compared to all the others within an operation. Some topics to investigate include:

1. What percentage of time did all UAS have connectivity in the operating area?
2. How did the RF signal levels vary between various flight routes?
3. How did the RF signal levels vary between various aircraft of different configurations?
    a. Differences may suggest how hardware selection and hardware placement impact these KPIs. For example, this could include different chipsets or different antennas.
4. How did a mobile GCS vs stationary GCS impact link performance?
5. How did a particular flight of interest compare to all other flights in the operation?

Flight Predictions vs Actual Performance Comparison

If using an aerial coverage modeling tool, comparison of predicted vs actual interruption performance should be made for all applicable Route Test Objectives. This enables better understanding of how varying conditions affects tool performance. Specific questions include:

- Were there any areas of unknown interruption the tool did not predict?
- Were there any areas of predicted interruption that were not encountered?
- What were differences in predicted vs actual interruption duration along a particular flight segment?
- Are existing network data sources sufficient?

Iteratively improving confidence in prediction performance is essential to reduce the overhead of this Reference Method and lays the foundation for future C2CSPs.

2.6. Reporting

This section summarizes the reporting of the performance of the cellular C2 link to external stakeholders, such as an aviation regulator. The analytical report is a document encompassing the analysis of field data, network data, prediction data and root cause analysis of aircraft mishaps and C2 link failures. The section should be modified as needed, based on specific informational requests and stakeholder needs. Figure 5 depicts a high-level workflow of a previous implementation of this method.

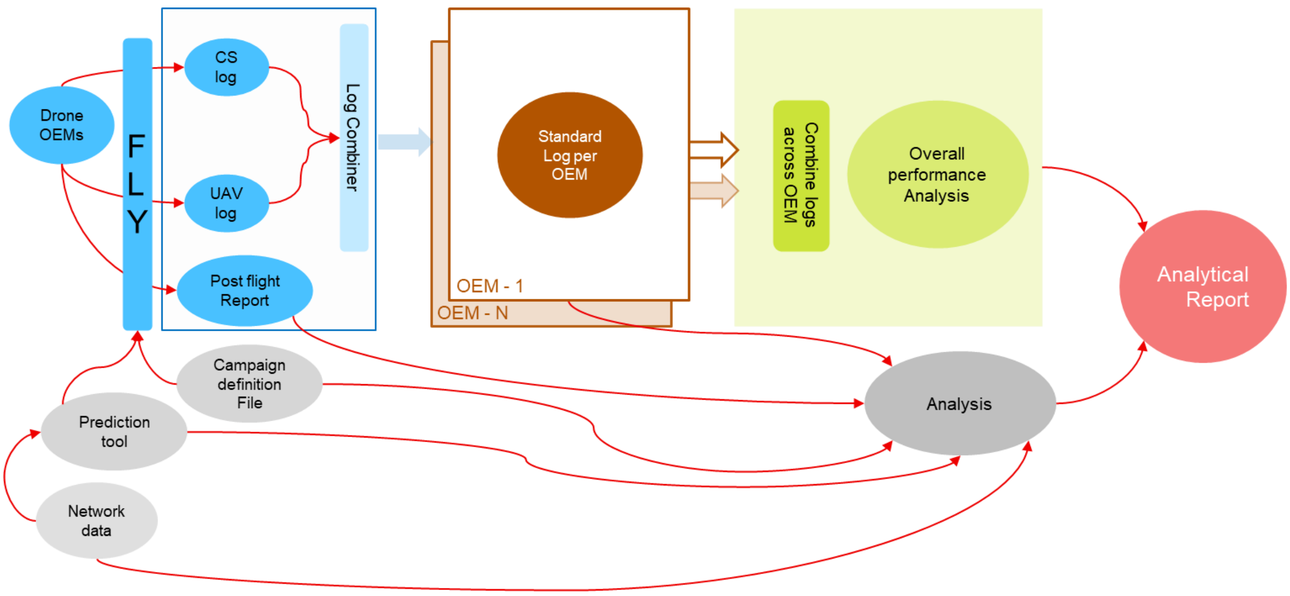

Figure 5: Future Drone Cellular Landscape

In a prior implementation of this Reference Method, reports were provided to stakeholders approximately every 2 months, roughly corresponding to completion of 1 or more Operations of 20 – 80 flight hours. Sufficient time must be given between completion of an Operation's data collection and required analysis and reporting activities.

1. **Overview of Flight Campaigns:** This includes all operations conducted during the reporting period. For example, there could be multiple operations being conducted in multiple geographic areas, but multiple types of drones.
   a. Start and end dates
   b. Total quantity of flight hours

c. Total quantity of flights
d. Percentage of time with Full C2 Link Connection
e. Percentage of time with Full Cellular Network RF Environment
f. ***Unknown and Known*** C2 link interruptions encountered
    i. Quantity of interruptions.
    ii. Frequency of interruptions.
    iii. Statistics on the duration of interruptions, from initial loss to re-establishment of the link.
g. Drone OEM makes and models flown

2. Overview of Analysis Method
a. Altitude filter
b. Full connectivity definitions
c. Known Interruption Areas

3. Operational Area and Environment
a. Unique Operation Identifier
b. Operation Area Name
c. Flight Objective: example – area baselining, long-linear survey, search and rescue pattern
d. Type of Environment: example: urban, suburban, rural. This can be based off of either population characteristics in the flight area vicinity, or based off of network topology
e. Total Quantity of Flight Hours
f. Total Quantity of Flights
g. Average Altitude
h. Maximum Altitude
i. Operational Risk Assessment (ORA) determination: example – low, moderate, high

4. **UAS Configuration and Architectures:** The below fields are duplicated from each UAS's Configuration File for ease of review:
a. Reporting and Polling Frequency: the rate at which parameters are recorded by each drone in the UAS Processed Log File.
b. C2 Network Architecture: the full routing path between UA and CS, important for RTT latency reporting
c. Typical UA Cruise Speed

5. Cellular & Aircraft Metrics
a. Cellular Carrier Band Utilization:
    i. Bands, Names, Bandwidth, Mode, Downlink Frequencies connected to the UAs connected to
    ii. Percent time on each band
    iii. Number of Carriers utilized if the UA has multiple SIM capabilities
    iv. C2 Method Utilization: percent time on cellular vs backup link method, such as point-to-point radios
b. Altitude Analysis
    i. Altitude reporting source: specify whether altitude measurements are from a barometric altimeter or GNSS receiver
    ii. Distribution of altitude levels
c. Distance between UA and CS: Though not relevant for cellular communications, this measurement is useful for complying with relevant line-of-sight regulations or for performance analysis of a backup point-to-point radio link.

d. Autopilot Control Mode: The control modes of an autopilot vary by drone OEM and ecosystem. Analyzing control modes is a useful way of determining whether an aircraft has lost link and is invoking an RTL behavior or if the pilot has manually intervened in the flight. In general, modes can be categorized as "Automatic", "Semi-Manual", or "Manual". For some drones, pilot intervention during takeoff and landing is the norm and could be excluded in the analysis. Autopilot Control Mode should be defined for each particular type of UA used.
e. Latency: This can be reported using distribution graphs and reporting of select percentiles and maximum values. The networking path should be specified and any location-specific influences, such as a network gateway. Additionally, the Lost Link Trigger timer for each UA may be repeated to compare latency times to UA settings. Latency should be examined in detail when loss of heartbeat and link interruptions are encountered.
f. Signal Parameters: The parameters below can be reported in various charts, such as a whisker plot, distribution curves, and comparisons with altitude. They can also be reported in tables with select percentiles and minimum and maximum values. These cellular parameters should be examined in detail when loss of heartbeat and link interruptions are encountered. When examining link interruptions, it is helpful to map the aircraft's flight with color-coded waypoints of the signal parameters. In this way, some understanding may be gained of the correlation between aircraft maneuvering (roll, pitch, yaw) and these parameters.
    i. RSRP
    ii. RSRQ
    iii. SINR: While RSRP and RSRQ are 3GPP standardized parameters, SINR is not. SINR values may thus vary from one UE to another given identical conditions. It is important to understand SINR measurements for a particular UE in various operational environments.
g. Cellular Network Handovers: When examining link interruptions, it is helpful to map the aircraft's flight with color-coded waypoints of handover event times, such as those listed below. A UE may not be able to record instances of handover failures due to limitations of logging capabilities. When examining link interruptions, it is helpful to map the aircraft's flight with color-coded waypoints of handovers events. In this way, some understanding may be gained of the correlation between aircraft maneuvering (roll, pitch, yaw) and handovers.
    i. Quantity of Intra-Frequency Handovers
    ii. Quantity of Inter-Frequency Handovers
    iii. Quantity of Inter-RAT Handovers, if applicable
h. Interference Analysis: Anomalies and indications of interference caused by the flight tests could be incorporated into reports to stakeholders.

6. **Anomalies and Interruptions** A variety of off-nominal events and significant interruptions could be encountered during flight testing that point to issues in the C2 link, UAS equipment, or procedural issues. Information collected in the Post-Flight Report may assist in identifying these issues. When reporting these events, a variety of tables, graphs, and maps could be generated along with a timeline of events. It is particularly important to correlate information such as altitude, aircraft maneuvering, cellular parameters, and key events. If known at the time of the report, root causes of the anomalies and accidents should be explained. As an example, below are some types of issues that could be encountered:

   a. **Unintended Flight Operations Area Excursions**: Number of times a UA unintentionally exceeded the bounds of the flight operations area. This is a general flight safety concern.
   b. Return to Launch Events: Number of times the UA automatically returned home due to any number of causes, including loss of C2 link
   c. Other Fail-Safe Events: Depends on specific UAS capabilities and automatic behaviors.
   d. Automatic Backup Link Failovers: Number of times the UAS switched from the cellular C2 link to a backup link, if available.
   e. Interruption Events: For any significant loss of C2 link, it is important to quantify the duration of the interruption and whether the link was restored prior to the aircraft invoking an automatic behavior, such as RTL.
7. **Lessons Learned:** In addition to the reporting of KPIs, implementers should also consider capturing and reporting knowledge acquired during the course of flight test programs. Some likely areas of new knowledge include:
   a. Ways in which existing networks treat aerial UEs differently than terrestrial US. Also, any identified methods for potentially improving service to aerial UE performance.
   b. Ways in which cellular network performance can dynamically vary - specific to aerial UEs and drone operational considerations.
   c. Assessment of existing aerial UEs, and potentially new features and functions that UE OEMs, base station vendors, and mobile network operators could implement for aviation users.
   d. Improvements of this Reference Method for the purpose of informing how drone operators can determine the suitability of connectivity within an operational area of interest.

3. Flight Measurements for RF Environment Characterization using Auxiliary Instrumentation

3.1. Best Practices and FAQ – General, Setup, Parameters, Tools

The following table provides an overview of collected FAQ and best practices from practical experience and implementation projects.

With the answers to these questions, it is expected that a measurement campaign for characterizing the airspace connectivity can be set up and implemented successfully. As the focus is on the Characterization of the aerial RF Environment rather the operational C2 performance, auxiliary tools are deemed sufficient.

Measurement Design, Environment, Flight Route, Network & General Considerations	
In which areas should the measurements be conducted?	Areas where application cases are most likely and where permissions are easy to get. Typically: it is recommended to start with the sub-urban & rural areas.
How many different environments should be considered?	It is recommended to consider at least two different environments. Such environments could be defined for specific drone use cases (linear infrastructures inspection, parcel delivery, …), areal characteristics (flat, hilly, mountainous, …), rural and sub-urban scenarios (such as for rescue services), etc. Flight areas with few cells and few likely handovers are less useful. More are always welcome and subject to the targeted application cases
How many different scenarios per environment should be done?	Based on project experience, it is recommended to conduct eight flights (scenarios) per flight route, and per environment, e.g. a flight route repeated at different altitudes
Is it enough to have VLOS flights?	To get started – yes (easy to get permission). For more complex investigations also in terms of an application POC, longer flights (typically BVLOS) are required. However, the MNO-side wireless communication characteristics (eNodeB-UAV link) are independent of this fact.
How long (time & distance) should one flight route be?	As long as possible. For a multirotor drone, typically, one battery can record around 15 minutes of flight time. This is considered long enough to also include inter-cell handovers along a flight path. Small fixed-wing drones can fly on the order of an hour or more.

At which altitudes should the measurements be carried out?	Five (5) distinct layers are recommended, e.g. 10, 30, 60, 90, 120[m] AGL. The layer at 10[m] is interesting to have a near-ground reference layer. If 5 layers are deemed too many (or outside the budget), a minimum of 3 levels is suggested, e.g. at 30m, 70m, 110m.
Should the measurements be done along a specific flight route?	As a first step, a typical flight route would be of rectangular shape, repeated at different altitudes levels (see above). Typically, easy to realize under VLOS-constraints and also in terms of flight planning. The rectangle should be as large as possible, equal to a circle of 500m in diameter under VLOS constraints. Additional flights routes within the outer most rectangle should be conducted. The altitude and direction of flight should vary. (See discussion on Test Route Objectives in Chapter 2)
What time of day should the flights be done?	It doesn't really matter as long as information about the “cell load” of the mobile network is available so that the measurements can be correlated for the correct interpretation of the interference.
Should the measurements be done with a particular frequency band – lock, e.g. 800MHz?	The advantage of a band lock is that more data will be collected for this frequency band, which is of interest if only a very limited number of flights can be realized. Other factors are also removed for the analysis of a specific frequency band performance. The disadvantage is that phenomena that are specific for UAV scenarios - such as handover to atypical frequency bands in comparison to the ground user scenario - are excluded by this setup. This means that inter-frequency handovers are eliminated. Hence, the recommendation is to avoid band locking – except for specific cases where there is interest in the analysis of a specific band. Please note: in some jurisdictions the aerial use of specific frequency bands is not allowed. Please check with your authorities. In such cases, band locking is one of the possibilities to comply with the legal obligations
How many measurement samples should be taken per second?	A minimum of about two samples per second (five would be appreciated) is recommended, which is achieved by typical measurement software. For a minimum set of measurements using quadcopters, it is recommended to not exceed a flight speed of 10 m/s. For faster drones (fixed wing) it is recommended to clearly report the flight speed and the number of samples taken per second (the higher the better for analysis purposes).
How to define the setup for characterizing the C2 traffic?	For C2 evaluation the adjustable settings proposed from 3GPP can be used. Packet size, packet inter-arrival interval, and transport model define the traffic model.

	By default, for C2 evaluation the traffic model and inputs proposed by 3GPP [8] can be used.
Which network configuration data need to be considered?	In order to correctly correlate and interpret measurement data from the drone, network configuration information at the time of the measurement flight should be considered and processed. Automated correlation mechanisms that include both network configuration data and drone measurement data, are provided by available toolsets, such as AirborneRF [7]
Which network performance data need to be considered?	Network performance data, such as cell load information is important to interpret and understand interference at altitude. Hence, cell load data should be available for the time of the measurement flight to enable root cause analysis and optimization.
Parameters to measure	
General measurements	• Timestamp • Longitude (WGS 84) • Latitude (WGS 84) • Altitude (meters above either WGS 84 ellipsoid or above EGM 96 geoid ("mean sea level".) • Altitude reference (WGS84 or EGM96) • Height (meters above ground) - optional Longitude, latitude and altitude is what GPS receivers commonly return.
Aircraft parameters	• Roll (or Bank; degrees) • Pitch (or Elevation; degrees) • Yaw (or Heading True North; degrees) • Velocity North (m/s) • Velocity East (m/s) • Velocity Down (m/s) • Speed (m/s)
Serving cell parameters to be measured and reported for PCell and SCell	• Unique cell identification, this can be either: ○ eCGI or ○ MCC, MNC and ECI or ○ MCC, MNC, eNodeB and cell id ○ EARFCN • PCI • RSRP (dBm) • SINR (dB) • RSRQ (dB) • Latency (round trip, if available also separately for downlink and uplink) • Reliability (packet loss rate) • Data rate (Uplink, Downlink, PRB, UDP)
Neighbor cell measurements	• PCI (as eCGI for neighbor cells is not available in most measuring devices) • RSRP (dBm) • RSRQ (dB)

	• EARFCN • RAT
Parameters for latency measurements	• Packet size (adjustable setting in terminal) • Packet inter-arrival interval (adjustable setting in terminal) • Transport model (adjustable setting in terminal) • Round-time-trip latency (measured in terminal) If available (subject to measurement capabilities): • Uplink latency (measured in terminal) • Downlink latency (measured in terminal)
Parameters for inter- and intra-carrier handover measurements	• SIB5 info, e,g, threshX_high, threshX_low,... etc. (measured in terminal; adjustable setting in network) • SIB3 info, e.g. q_hysteresis (measured in terminal; adjustable setting in network)
Parameters for data rate measurements	• Transmission mode (measured in terminal) • Carrier aggregation (measured in terminal) • Number of scheduled PRBs (measured in terminal)
Parameters for reliability	• Packet loss rate
Measurement hardware and software	
Which measurement devices to use?	Off-the-shelf measurement devices or Custom-built solutions. Standard, off-the-shelf solutions are available from many different providers, such as TEMS [9], NEMO [3], etc. However, custom-built setups offer more flexibility to perform measurements, can be significantly cheaper, and allow full control on hardware (e.g. antenna, sensors, etc.).
Any recommended measurement software?	Standard software solutions are available on the market, such as TEMS [9], NEMO [3], Azenqos [10], Enhancell [11], Qualipoc [2], and many others that can be used.
Antenna system at the measurement device	• Antenna type • Antenna pattern • Mounting position (attitude) relative to UAV
UE class	• UE category • Number of antennas for DL and UL.

3.2. Recommendations and comments:

3.2.1. Traffic Model for C2

There is still ongoing research and standardization on the definition of C2 traffic model - thus in order to characterize a traffic model the following parameters are needed: packet size, packet inter-arrival interval and transport model. 3GPP has already defined such parameters (for more details see 3GPP TR 36.777 [8]) but the requirement on precise values still needs to be defined. First, a packet size of 1250 [bytes] has been suggested in some studies conducted as part of 3GPP. However, a value should be set depending on the type of message. In this context, a study with recommendations on detailed values of packet size and packet inter-arrival rate can be found in [9]. In this study, packet sizes starting from as low as 30[bytes] were applied in measurements.

Note that the packet size is configurable in the measurement tools already mentioned above. Important to mention, bigger packet sizes demand more resources in the frequency domain, thus this has to be considered when performing measurements. Second, particularly for latency measurements, the aforementioned measurement tools do not offer the possibility to configure the packet inter-arrival interval (higher rates demand more resources in the time domain) and transport model because they only support L3 latency measurements conducted with ICMP pings. *How to properly conduct latency/reliability/data rate measurements?* One would need a custom-built setup (with LTE modem) in order to configure these parameters, as provided in the table below. For this purpose, open-source network traffic tools e.g. iperf2, etc. and ping tools can be easily installed to perform testing by using extended command options. It's strongly recommended to measure the latency separately, i.e. downlink latency and uplink latency.

Alternatively, when utilizing hook-on devices for measurements, we use ICMP ping tests to evaluate latency.

In order to classify a C2 link as successful, upper bounded latency values combined from 3GPP (maximum of 50[ms] one-way latency between drone-to-eNodeB) and RTCA DO-377 [10] (end-to-end, i.e. drone-to-CS; for illustration refer to Fig.1.) should be combined when performing end-to-end measurements. Based on RTCA requirements, an acceptable one-way latency up to 225[ms] is evaluated.

Table: Availability of parameter settings for different measurement tools.

	Custom-built setup with LTE modem	**Hook-on devices**
Packet size	yes	yes
Packet inter-arrival interval	yes	Limited* or N/A
Transport model (TCP and/or UDP)	yes	yes (with iperf2)

(*) Hook-on devices allow testing with iperf2 as well, but they do not provide the possibility to set the parameter.

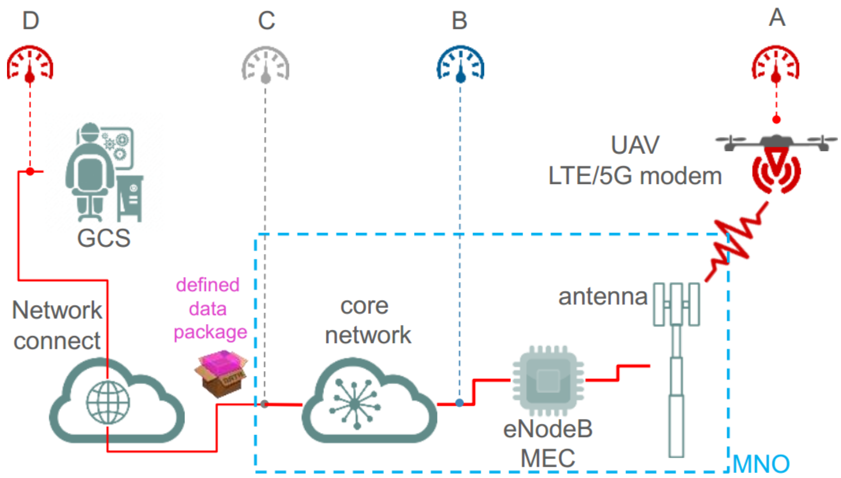

Figure 6 – End-to-end latency measurement options.

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3.2.2. Data rate

Parameters related to data rate, i.e., transmission mode, carrier aggregation, number of scheduled RBs should also be measured. Knowledge of transmission mode from the measurements provides valuable information whether boosting of reliability (transmit diversity, i.e., mode 2) and data rates (spatial multiplexing, i.e. mode 3/4) can be triggered. It is observed in field measurements that spatial multiplexing gains become less exploitable with increasing altitudes. This mainly comes due to the reduced effect of scattering in the air. Additionally, the environment type (i.e. rural, urban, etc. along with terrain data info) should be clearly distinguished when performing measurements due to impact of spatial multiplexing. Since carrier aggregation allows to increase the data rates, it would make sense to trigger it particularly where MIMO fails. Just to mention a few, Azenqos [11], Echo tools [12], etc. are measurement tools able to record such parameters.

Data rates are not considered to be a limiting factor for C2 links due to low demand (60-100 [kbit/s]). However, there are completely different requirements in the case of application data (e.g. 4K video streaming) with uplink data rates demanding up to 50[Mbit/s]. For instances, with1080p digital image transmission quality requires a data rate of around 4 Mbit/s, but 4K/8K HD video and AR/VR services require a higher data rate at the Gbps level. References and examples are provided in [13], [14].

Please note that while it is currently not a key consideration, in addition to the data rate, jitter may become relevant for BVLOS drone operations in future and thus may have to considered then.

3.2.3. Reliability

Note that since the LTE technology is designed with an optimization goal in transmission at 10% BLER, one has to be careful to define or compare reliability in terms of BLER at a lower level. Using a lower MCS, which could be enforced at the network side, can result in lower packet losses, thus increasing the reliability.

In [15] the reliability is evaluated based on latency measurements. The link is classified as reliable for C2 if x [%] of packets are within the latency threshold 50[ms], where x=99.9 [8] in LTE. In NR-5G URLLC the criteria of 99.999[%] [16] should be satisfied.

3.2.4. Handovers

Intra- and inter-carrier handovers are key events when it comes to mobility management of C2 links, e.g. [14], [17]. Well described also in 3GPP [18] and as found in field measurements that latency peaks can be observed during handover events. It's also worth noting that cell selection is affected by the carrier priority parameter (SIB5 type "reselection_priority") of each carrier that MNOs apply. Thus, in addition to "Srxlev", the drone should record mainly SIB1/SIB3/SIB4/SIB5 info and perform optimal cell selection when necessary. It was observed that Azenqos measurement tools record (very likely it's chip dependent feature) some of them.

3.2.5. Serving cell load dependency

When performing data rate or latency measurements one has to be careful of their impact on the serving cell load. Particularly high resource demanding data rates increase the cell load of the serving cell and this factor (additional to the cell loads provided from MNO) needs to be taken into account when evaluating the measurements. This has an impact on the RSRQ value.

3.2.6. SINR

SINR is a common indicator for network quality but it is not defined within any 3GPP specifications. Unfortunately, UE chipset manufacturers implement SINR measurements in different ways, and this is observed based on field experience. Similar observations are made in [19] as well. Furthermore, it was observed in field tests with a Samsung S21 phone (Exynos chipset with Azenqos license), and compared it to the OnePlus 8 (Qualcomm chipset with Azenqos license), showing two different SINR implementations.

Nevertheless, since UE does not report SINR to the network the focus should be more on RSRQ/RSSI/RSRP measurements. Yet, with the well-defined KPIs one has to expect some deviations between the individual but dependent KPIs as these are averaged by hook-on devices over different periods of time, thus introducing some inconsistencies.

3.2.7. UE antenna pattern

There are two problems with UE antennas: first, antennas mounted in UE are UE specific and not specified by vendors; second, the drone itself strongly affects the pattern of the UE. From the measurements of a UAV [20] attached LTE antenna it's observed that there are three main reasons that explain the impact of UAV: the distance between the mounted antenna and the UAV, the distance that the signal has to travel through or along the UAV and the attenuation and depolarization caused by the UAV. The signal frequency also has an effect on the antenna performance; in particular, gain fluctuations at a particular frequency might cause communication reliability issues.

Therefore, if one wants to understand the effects of UE antennas, it's recommended to build a dedicated measurement setup with external antennas.

The above parameters are important from the way of conducting proper measurements.
Ultimately, from RF perspective, it's expected that the UAV must follow the requirements on latency, reliability and data rate.

3.3. FAQ Acronyms and abbreviations

Acronym/parameter	Definition/description
3GPP TR	3rd Generation Partnership Project Technical Report
5G	5th Generation
AGL	Above Ground Level
ASTM	Americal Societey for Testing and Materials, international standards organization
BLER	BLock Error Rate
BVLoS	Beyond Visual Line of Sight
C2	Command-and-Control
CAA	Civial Aviation Authority
DL	Downlink
DO	DOcument
EARFCN	E-UTRAN Absolute Radio Frequency Channel Number
eCGI	E-UTRAN Cell Global Identifier
ECI	E-UTRAN Cell Identifier
EGM96	Earth Gravitational Model 1996
eNodeB	enhanced Node B
EUROCAE	European Organization for Civil Aviation Equipment, aviation standards for airborne and ground systems and equipment
C2CSP	C2 Communications Service Provider. An entity which provides a portion of, or all, the C2 Link service for the operation of an UAS.
CS	(Ground) Control Station
GPS	Global Positioning System
ICMP	Internet Control Message Protocol
iperf2	“software”; network traffic tool
kbit/s	kilo bit per second
KPI	Key Performance Indicator
L3 latency	Layer 3 (IP layer) latency
LAANC	Low Altitude Authorization and Notification Capability

LTE	Long Term Evolution
Mbit/s	Mega bit per second
MCC	Mobile Country Code
MCS	Modulation and Coding Scheme
MHz	Mega Hertz
MIMO	Multiple-Input Multiple-Output
MNC	Mobile Network Code
MNO	Mobile Network Operator
NEMO	“software”; drive test measurement software
NR	New Radio
OEM	Original Equipment Manufacturer
PCell	Primary Cell
PCI	Physical Cell Identifier
PFR	Post Flight Report
POC	Proof of Concept
PRB	Physical Resource Block
q_hysteresis	“hysteresis”; parameter representing hysteresis during cell reselection process
RAT	Radio Access Technology
reselection_priority	“reselection priority”; parameter that defines the absolute priority of a RF carrier
RF	Radio Frequency
RSRP	Received Signal Received Power
RSRQ	Received Signal Received Quality
RSSI	Received Signal Strength Indicator
RTCA	Radio Technical Commission for Aeronautics
RTL	Return To Launch
SCell	Secondary Cell
SDO	Stanards Developing Organization

SIB1	System Information Block 1
SIB3	System Information Block 3
SIB4	System Information Block 4
SIB5	System Information Block 5
SINR	Signal to Interference and Noise Ratio
Srxlev	parameter that defines Rx level used during cell selection process
TCP	Transmission Control Protocol
TEMS	TEst Mobile System
threshX_high	"threshold high"; parameter used for cell reselection to a higher priority RF carrier
threshX_low	"threshold low"; parameter used for cell reselection to a lower priority RF carrier
UA	Uncrewed Aircraft
UAS	Uncrewed Aircraft System
UAV	Uncrewed Aerial Vehicle
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
URLLC	Ultra-Reliable Low-Latency Communication
VLoS	Visual Line of Sight
VTOL	Vertical Take Off and Landing
WGS84	World Geodetic System 1984

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