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FACT

FUTURE ALL AVIATION CNS TECHNOLOGY

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Abstract

The primary goal of the project FACT is to evaluate the feasibility of a Performance-Based Integrated CNS (iCNS) concept, in order to support today's and tomorrow's air traffic challenges in the most cost-effective way without negatively affecting the overall operational safety. In particular, the project focuses on selected elements of iCNS concept exploring primarily a potential use of cellular networks (4G and 5G) as a complement to the existing CNS technologies within ATM and U space environment, with a particular focus on GA and drones' operations.

Within this document, the overview of all performed validation activities together with main project's findings is provided and resulting conclusions and recommendations are formulated. Beyond the validation work already described in previous WP5 deliverables (D5.2 and D5.3), this document also includes description of complementary technical work performed to investigate selected elements of cellular network technologies which were not addressed within the project's operational demo and were considered relevant for potential use of these technologies for air traffic management.

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1 Executive Summary

The primary goal of the project FACT is to evaluate the feasibility of a Performance-Based Integrated CNS (iCNS) concept, in order to support today's and tomorrow's air traffic challenges in the most cost-effective way without negatively affecting the overall operational safety. In particular, the project focuses on selected elements of iCNS concept exploring primarily a potential use of cellular networks (4G and 5G) as a complement to the existing CNS technologies within ATM and U space environment, with a particular focus on GA and drones' operations.

Aim of this document is to provide a compact and consistent overview of:

- The operational validation context as described in the project's Concept of Operations (D2.3), Functional architecture (D2.4) and System requirements (D3.3);
- Technical description of main challenges related to the potential use of cellular network for airborne operations
- Summary of all performed project's validation activities that cover work performed for preparation and execution of operational demo and described in detail in D5.2 and D5.3, as well as additional technical validations of selected elements of cellular network technologies which are relevant for their potential used in air traffic management, and
- Summarize main findings from the above validation work

The document is concluded with overall project's conclusions and recommendations with regard to use of cellular network technologies for air traffic operations.

2 Introduction

2.1 Purpose and Scope of this Document

This document aims to conclude WP5 by summarizing outcomes of all project's validation activities. It covers (and shortly reminds) the results obtained during preparation and execution of operational demo (and documented in detail in D5.2 and D5.3 deliverables) as well as complementary technical evaluations performed in parallel to get additional insights on potential use of cellular network technologies for air traffic management. In this document, these results are taken into account all together and general conclusions/recommendations are formulated.

2.2 Deliverable Structure

After the introductory section in chapter 2, the document shortly outline overall validation context as described in the project's concept of operations (D2.3), functional architecture (D2.4) and system requirements (D3.3). The summary of all performed validation activities is also included at the end of chapter 3. Potential use of cellular network technologies for air traffic is described in chapter 4 together with main challenges. Main project's findings resulting from performed validations are summarized in chapter 5. Finally, chapter 6 provides main project's conclusions and recommendations. Detailed description of the technical validations which were not included in previous deliverables is then provided in Appendix A.

2.3 Acronyms and Terminology

ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance – Broadcast
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
C2	Command and Control
CIS	Common Information Sharing
CNS	Communication, Navigation, Surveillance
EDGE	Enhanced Data rates for GSM Evolution
eID	Electronic ID
EIRP	Effective Isotropic Radiated Power
eMMB	Enhanced Mobile Broadband

EPC	Evolved Packet Core
E-UTRA	Evolved Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access
FIS	Flight Information Services
GA	General Aviation
GSM	Groupe Spécial Mobile
HSPA	High-Speed Uplink Packet Access
ISM	Industrial, Scientific and Medical (radio spectrum)
ITU	International Telecommunication Union
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Networks
LPWAN	low-power wide-area network
LTE	Long Term Evolution
M2M	Machine to Machine
MIMO	Multiple Input Multiple Output
mMTC	massive Machine-type Communications
mmWave	Millimeter Waves
NB-IoT	Narrow Band Internet of Things
QoS	Quality of Service
SA	Situation Awareness
TCAS	Traffic Alert and Collision Avoidance System
TDD	Time Division Multiplex
TIS	Traffic Information Services
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UMTS	Universal Mobile Telecommunication System
URLLC	Ultra-Reliable Low Latency Communication
USSP	U-Space Service Provider

WiMAX	Worldwide Interoperability for Microwave Access

3 Validation Context

The primary goal of the project FACT was to evaluate the feasibility of a Performance-Based Integrated CNS (iCNS) concept, focusing on a potential use of cellular networks (4G and 5G) as a complement to the existing CNS technologies within ATM and U space environment, and considering GA and drones' operations as primarily targeted airspace users.

This general objective was refined within the Concept of Operations (D2.3) and the project's operational scope was narrowed to the following set of CNS applications:

- Ground surveillance service (using vehicle's report such as ADS-B, eID (U-space) or similar, and/or ground-based positioning (if complexity allows to include it)): Proof-of-Concept (POC) implementation is planned for position reporting using cellular network.
- Information Sharing service (uplink of operational information from ATM/U-space to vehicle, FIS/TIS like services): POC implementation planned for traffic information service and geofence information sharing.
- Situation awareness applications for GA, drone's remote pilot and ATCo benefiting from the above two services: POC implementation planned using dedicated displays.
- CPDLC or similar type of communication between vehicle/pilot and ATC/U-space service provider: requirements analysis planned.
- CNS applications supporting 4D trajectory management (ground conformance monitoring, airborne capability to adhere to agreed 4D trajectory, etc.): requirements analysis planned. POC implementation of conformance monitoring and associated alerting planned as well.

As already indicated in the list, not all of these applications were planned to be addressed through project's validation activities, some of them being analysed only through literature survey and discussions with experts.

FACT's validation activities themselves can be divided into two groups:

1. Preparation and execution of the operational demo evaluating the practical use of cellular network for real end-users' applications.
2. Technical evaluations of different elements of cellular network technology allowing to assess its suitability for different types of ATM application.

The outcomes of the first group of validations were provided in D5.2 and D5.3 reports. For the second group a part of results was included in D5.2 while the rest is addressed within this document (primarily in Appendix A) and used to support project's conclusions and recommendations.

The overall context of the operational demo and its realization is shortly summarized in the following section 3.1 (details can be found in D5.3 deliverable) while an overview of all project's validation activities is provided in section 3.2.

3.1 Operational Demo

Within the operational demo, the project FACT focused on CNS enablers allowing to demonstrate the following applications:

- Situation awareness applications for individual users: enabled by traffic surveillance profiting from new position reporting over cellular network and ADS-B. Possible data integrity enhancements using cellular network positioning will be also explored.

- Conformance monitoring & alerting functions required for efficient use of trajectory-based strategic deconfliction. For the operational demo, strategic deconfliction will be applied only within flight planning phase while the project will focus on performance evaluation of supporting real time functions/enablers critical for definition of safe operational buffers around strategically deconflicted flights: realistic trajectory conformance performance of drones as well as on efficiency and latency of conformance monitoring & alerting.

- Emergency voice link between ATCo and remote pilots.

Figure 1 (adopted from D3.3) shows the simplified functional overview of the two first applications.

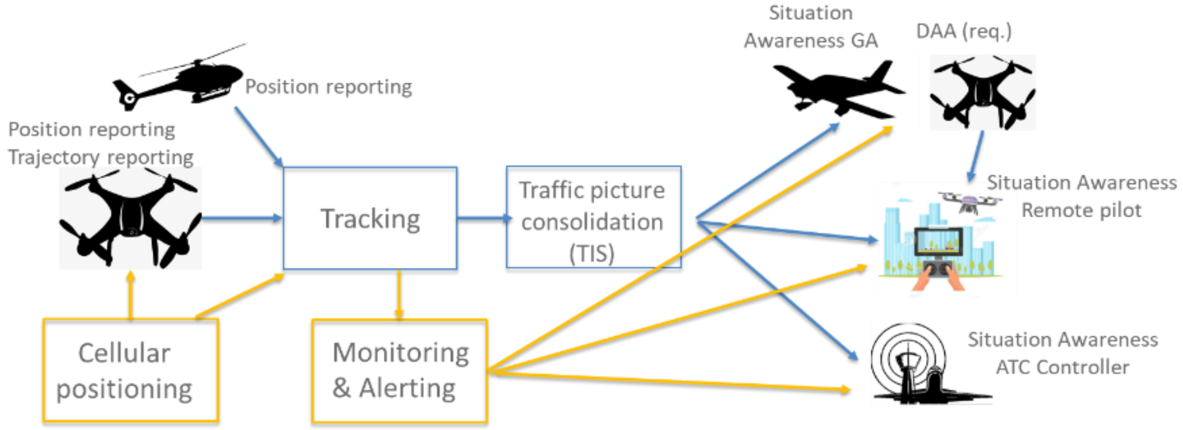

Figure 1: Situational awareness applications with considered enhancements supporting strategic deconfliction.

These applications were enabled by a set of main CNS-based systems/functions which will be included in the project's validations and are schematically shown in Figure 2. Functionally the core elements are:

- Position reporting function – hosted on-board the targeted users – GA, rotorcrafts, and drones;

- Trajectory/intent reporting function – hosted on-board the drones performing automated flights, namely, drones within the FACT project. This information can cover both 3D and 4D (3D + time) information depending on the capability of the vehicle's guidance functions. Considering typical equipment of today's drones, only 3D trajectory information will be used during the project's validation activities.

- Aircraft tracking implemented on the ground.

- Conformance monitoring and alerting implemented on the ground.

- TIS/FIS information provision implemented on the ground
- Situation Awareness (SA) processing functions (including TIS/FIS reception) of individual users (GA pilot, remote pilot, ATCo) processing and showing received data on human interface. TIS information is also received onboard drones as it is considered for potential use by Detect And Avoid (DAA) system. While this system was out of scope of the FACT project, the performance of traffic surveillance over cellular network is analyzed with respect to its needs.
- VoIP link between ATC and remote pilots and between pilots (regardless whether local and remote).

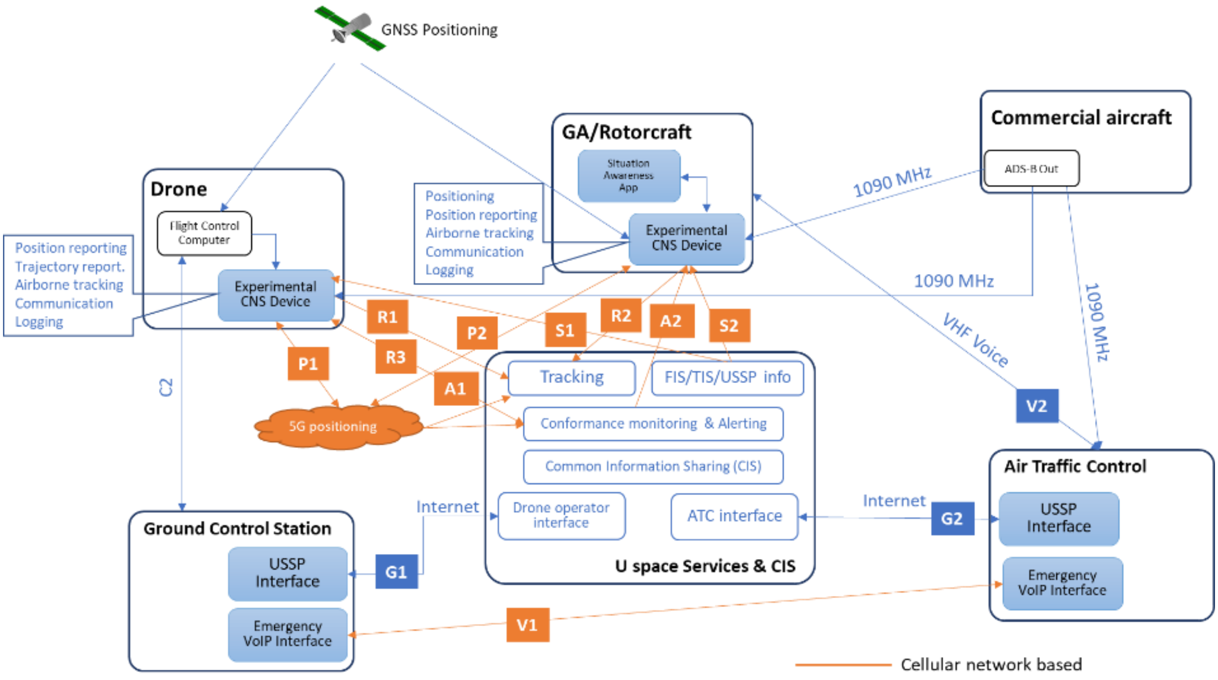

Figure 2: FACT system and functional overview.

These functions were implemented within the following systems (Figure 2) and they are further described and specified in D3.3. The systems represent communication nodes for the overall communication architecture discussed in this document:

- GA Experimental CNS device (position reporting, communication, SA processing)
- Drone's Experimental CNS device (position & trajectory reporting, communication, pre-processing of ground data for possible DAA implementations)
- USSP/CIS cloud platform (aircraft tracking, conformance monitoring & alerting, TIS/FIS)
- Remote pilot ground control station (SA processing, VoIP)
- ATC controller working position (SA processing, VoIP)
- GA situation awareness device (SA processing function is decomposed between Experimental CNS devise and this device).

3.2 Overview of Validation Activities performed within the project

The following validation activities were performed during project and their outcomes are considered in the discussions provided in Sections 5 and 6.

Validation activities related to the preparation of Operational Demo:

- Selection and evaluation of suitable LTE and 5G modem

  Performed in 2021 and description provided in the D3.2 Step 1 Technological Demonstrators

- Selection and evaluation of next required components – LTE antennas, 5G antennas, ADS-B Out, ADS-B In

  Performed in 2021/2022 and described in the D3.4 Final Technological Demonstrators

- Test of experimental CNS ability to connect to private 5G network in Nokia laboratories in May 2022
  - Performed in May 2022, successful test of the connection to the same type of dedicated 5G network which was originally planned for official flight demonstration. Configuration parameters for CNS device determined.

Project’s flight demonstration in Eskisehir, performed in July 2022:

- Evaluation of regular communication (position reporting) – overall latency, packet loss
- Evaluation of one-time communication (alerts, geofences) – overall latency, packet loss
- Data from cellular network – signal strength, handovers, quality parameters
- Pilot’s feedback of situational awareness application – usability, readability etc.
- Comparison of messages loss - ADS-B Out and position reporting via cellular network

Detailed results were provided in the D5.3 Second Validation Report, brief summary in the 5.1.1 and 5.1.2 subsections of this document.

Technical validation of selected 4G/5G features to evaluate their potential use for ATM applications:

- Measurement of NB-IoT network addressing possible reduction of altitude impact on network performance

  Performed in 2021 and results provided in the D5.2 First Validation Report and briefly later in Appendix C. Validation included car and drone tests (altitudes 60, 90, 120 m).

- Evaluation of raw positioning method based on Timing Advance parameter in LTE network

  Performed in May 2022 and results provided in this document in Section 5.1.4

- Verification of dedicated 5G network focused on impact of background load of the network on quality of service
  - Performed in summer 2022 and results are provided in Appendix A of this document.

3.3 Main Deviations from Validation Plan

There was one important deviation from the original project plan that directly affected main project's objectives:

Use of public LTE network rather than originally planned dedicated 5G network for Operational Demo	
Justification	This deviation was caused by global situation with suppliers of the chips during the last two years. Within the project it was first needed to agree and get approval of regulator for use of a dedicated spectrum. Unfortunately, once this step was successfully completed, Nokia's suppliers were not able to deliver ordered chips in time to use them for demo. The issues with purchasing HW components were faced multiple times during the project but in this case it was not possible to find a different solution.
Impact	This fact had primarily impact on technical evaluations as it is expected that a private (stand-alone) 5G network will be the most suitable business solution satisfying performance requirements of safety critical air traffic applications. As the project addressed both use of public network (Solution 1) and dedicated network (Solution 2), as the result of this deviation the focus of operational demo was moved from Solution 2 on Solution 1.
Measures took to minimize impact	In order to reduce impact of this deviation, the project team was looking for an alternative opportunity how to perform technical evaluations in dedicated 5G network. Beyond testing in Nokia Lab in Stuttgart, additional (originally unplanned) experimental measurements were agreed with Technical University n Brno (Czechia).

In addition, technical difficulties during execution of flight demo prevented to collect direct feedback from involved GA and rotorcraft pilots on usefulness of onboard situation awareness application. As result, the feedback was collected through discussions after flights and during workshops.

4 Public vs. Private 5G Networks and Technical Challenges

In Chapter 3, the operational context of the project's activities was described together with overview of main performed validation activities. Nevertheless, to fully understand the project's result and conclusions it is important to complement that operational perspective as well with technological context. This is the purpose of this chapter.

Project FACT considered two different technological solutions when addressing operational needs described in chapter 3:

- Use of public 4G/5G cellular networks for low altitude operations (Solution 1); and
- Use of dedicated 5G network for complex low altitude operations (Solution 2).

While nearly all activities associated with preparation and execution of the operational demo and driving project's finding covered in chapter 5 were related to Solution 1, there were several complementary activities addressing elements relevant to solution 2. Although these results did not allow to form a complete operational validation they were considered when formulating project's conclusions and recommendations for future research.

In order to better understand context of complementary activities as well as overall project conclusions provided in chapter 6, the main differences between public and dedicated 5G networks are shortly discussed within this chapter together with main technical challenges of their use for aerial operations as well as potential mitigations that were considered.

4.1 Public Vs. Private 5G NR Network

Public 5G networks, owned and operated by mobile network operators, also face significant challenges for widespread adoption. Coverage is one of them. Mobile network operators tend to deploy networks in areas with large numbers of subscribers in pursuit of revenue to cover deployment costs. This may result in poor network coverage in less populated urban areas and even no coverage in more remote zones. Coverage in indoor locations with harsh radio frequency (RF) conditions may also be unsatisfactory. As a result of these shortcomings, private networks, which are also termed non-public networks in the 3rd Generation Partnership Project (3GPP), have attracted significant interest.

A private 5G network is a local area network based on 5G New Radio (NR) technology for dedicated wireless connectivity in a specific region. It is emphasized that not every local 5G network is a private network. The radio access network (RAN) part of the private configuration comprises one or multiple base stations, which can scale according to capacity and coverage requirements. The core network part of a private 5G system is relatively lean compared to its public counterpart. Physically, it can be a separate entity in the network or collocated with the base station in the same box. A private 5G network can be deployed for a specific industrial application and multiple industrial functions with diverse requirements. Private networks are also referred to as nonpublic networks (NPNs) in the 3GPP.

The unique aspect of private 5G is that it empowers industrial players to run their local networks with dedicated equipment and settings. Private 5G delivers the following advantages:

- Dedicated coverage: Private 5G networks offer exclusive coverage at a facility or location. This is particularly important for industrial sites, which are often located in remote areas where public networks do not exist or indoor coverage is not robust. Such dedicated coverage is crucial to achieving very high availability for industrial operations.
- Exclusive capacity: A private 5G network uses the available capacity. There is no contention from other network users, as there is a public system.
- Intrinsic control: A private 5G network offers its owner the possibility of complete control, something that is not possible on public systems. Private operators can deploy their security policies to authorize users, prioritize traffic, and, most importantly, ensure that sensitive data do not leave the premises.
- Customized service: A private 5G network can be customized per the requirements of specific industrial applications. Such customization is not possible on a public network. Moreover, a private 5G network can be efficiently shared among multiple industrial applications.
- Reliable communication: The dedicated nature of private 5G networks, coupled with customized service, intrinsic control, and uRLLC capabilities, provides reliable industrial wireless communication with guaranteed QoS like low latency.

4.1.1 Spectrum Opportunities for Private 5G Networks

Private 5G networks can be deployed in three different types of the frequency spectrum.

- Licensed Spectrum: Like public cellular networks, private 5G systems can be deployed in the licensed spectrum. Operation in the licensed spectrum provides greater performance certainty with little risk of interference. It is particularly attractive for mobile network operators (MNOs) deploying private 5G networks. MNOs can dedicate a portion of their licensed spectrum for private network operation in a specific geographical area, such as an industrial site. Regional regulatory bodies can also allocate spectrum for industrial networks, like the 3.7–3.8 GHz band in Germany.
- Unlicensed Spectrum: Another option for deploying private 5G networks is the unlicensed spectrum, e.g., in the 2.4-GHz band, the 5-GHz band, and the recently opened 6-GHz band. These spectrum bands are harnessed by Wi-Fi, Bluetooth, ZigBee, and various other technologies, and they are inherently open for shared usage. Operation in the unlicensed spectrum has received significant attention in the context of 4G LTE networks. There are two main scenarios for operating private 5G networks in unlicensed bands, as summarized in the following:
    - Stand-alone unlicensed operation: In this case, private 5G networks operate entirely in the unlicensed spectrum. Unlicensed operation of 5G NR is under investigation within the 3GPP. Such process is desirable for non-MNOs, as private 5G networks can be deployed without dependency on the licensed spectrum. The 4G counterpart is MulteFire, which supports unlicensed LTE operation. MulteFire implements a listen-before-talk procedure to coexist efficiently with other spectrum users in the same band. Stand-alone unlicensed deployments are more appropriate for noncritical use cases.
    - Licensed anchor operation: This is similar to LTE's licensed–assisted access operation. In this case, process in the unlicensed band is supplemental to operation in the

licensed band, i.e., the unlicensed spectrum is aggregated with the licensed spectrum. This is particularly attractive for operator-deployed private networks seeking extra capacity.

- Shared Licensed Spectrum: The third option for private 5G deployment is the shared licensed spectrum. Operation in the shared licensed spectrum opens a new range of possibilities, especially for non-MNOs. Prominent examples of the shared licensed spectrum include the 3.5-GHz citizen broadband radio service (CBRS) band in the United States or the 3.8–4.2 GHz band in the United Kingdom. Unlike the unlicensed spectrum, coordinated and dynamic spectrum access paradigms are emerging for the shared spectrum, providing guarantees of interference-free operation similar to the licensed bands. One example is the three-tier CBRS sharing model in the United States. In addition to the incumbents, two types of spectrum users have been introduced: priority access license (PAL) and general authorized access (GAA). PAL users are licensed and must be protected from interference caused by other PAL users and GAA users. GAA users are license-exempt and not entitled to protection from other tiers. A dedicated spectrum access system controls spectrum access for both PAL and GAA users. The different private 5G operation models have been summarized in Table 1.

Functional architecture	Frequency spectrum	Business opportunities	Service continuity
Stand-alone deployment	Licensed	Deployed by MNOs	Roaming agreements, dual radio (multi-rat), N3IWF based
	Unlicensed	Deployed by MNOs or non-MNOs	
	Shared licensed	Deployed by non-MNOs	
Public-private shared RAN deployment	Licensed	Deployed by MNOs	Roaming agreements, dual radio (multi-rat), N3IWF based
	Unlicensed	Deployed by MNOs or non-MNOs	
	Shared licensed	Deployed by non-MNOs	
Public-private shared RAN and control plane deployment	Licensed	Deployed by MNOs	Direct access to public network services
	Unlicensed	-	

Table 1: Private 5G Networks Operational Scenarios.

4.2 Overview of Technical Challenges

The primary technical challenge related to use of cellular networks for vehicles flying in low altitudes is the fact that with increasing altitude the number of interferences is increasing. This situation is closely tied to rapidly changing signal quality at higher altitudes and leads to frequent handovers from one base station to another. Next important challenge is the quality of service which is affected by number of users and current network load. This topic led to experiment with load in private 5G network described in the Appendix B of the document.

During the MoNiFly project where Honeywell was involved, this behaviour was documented in detail in LTE network [1]. Project results have shown that network performance is quite stable and comparable to terrestrial applications up to altitude about sixty meters. In higher altitudes strong interference and numerous outages led to decrease of throughput. Latency was strongly affected by outages of the service. Outages were caused by infrastructure configuration (interference among signals from multiple cells, frequent hand-overs between cells/frequencies, etc.). LTE network measurements were performed at two sites (Netherlands and Czech Republic) and presented results **well correlate with other sources** (e.g., [20]). Because the most probable network configuration for future aerial use is mixed 4G/5G, the observations from LTE network are still valid.

Per [20], flying above base station antenna height creates unexpected coverage conditions. On the negative side, drones are covered by only the side lobes of the elevation plane and thus suffer from lower antenna gain; but on the positive side, the line of sight probability is significantly increased since direct obstacles and shadowing occur less frequently. Aerial devices are therefore visible from more cells than terrestrial devices, and when the aerial device is at the exact zenith of a base station, it may even be possible that, because of the antenna patterns, the signal from neighbouring cells is stronger than the signal from the cell just below the device. First observations show that coverage geometry for objects above average antenna height is significantly different than the coverage experienced by terrestrial devices. Presence of aerial devices has also impact on terrestrial devices – no degradation in signal quality for user equipment, but degradation of overall network capacity.

Because of this differing geometry there is anticipated that drones will suffer from increased interference from neighbouring cells in the downlink direction, and even more interference in the uplink direction. [18] estimates that there is average impact of -9 dB on the downlink SINR compared with terrestrial device. For uplink, average SINR degradation of aerials compared to terrestrial UEs without aerial presence is not as significant, but presence of aerial user equipment generates significant uplink interference impacting terrestrial user equipment.

One of more mature generations of mobile networks was evaluated by measurements (NB-IoT belonging to family of LPWA networks). There was theoretical assumption that performance degrade appearing with increasing altitude will not be so rapid as LTE. This assumption was confirmed, but the decrease of performance was still significant.

Potential technical solutions to resolve the above-mentioned issues may be divided per stakeholder by whom they are provided:

- Capabilities provided by Mobile Service Provider.
- Capabilities provided by Mobile Technology Vendor.
- Capabilities deployable at User Equipment.

First two options will not be deeply described in this document because it is out of scope of current Honeywell activities.

4.2.1 Capabilities Provided by Mobile Service Provider

The Mobile Service Provider may leverage several technical solutions for mitigation of issues connected to aerial use of cellular network. These mitigations can be represented by:

- Radio network planning optimization taking into account the 3-dimensional coverage including antenna setup optimized for covering of low altitudes
- Network slicing available in 5G networks within Release 16 and enabling the separation of safety critical communication of flying vehicles from other types of network traffic.

Requirements and potential solutions at operator side designed specifically for UAV operation in LTE are captured in GSMA Document “LTE Aerial Profile” [15].

4.2.2 Solutions Provided by Mobile Technology Vendor

Network configuration for aerial use provided by Mobile Technology Provider can consists of following options:

- Advanced beamforming
- Full dimensional MIMO at drone base stations

Massive Multiple Input Multiple Output (MIMO) represents multi-antenna constellations originally developed for cellular communications. Main features are array gain, which translates into a coverage extension; (ii) spatial multiplexing, which permits the service of many tens of terminals in the same time-frequency resource; and (iii) the handling of high mobility through exploitation of channel reciprocity and time-division duplex TDD) operation. Substantially all signal processing complexity resides at the base station, rendering the terminals low-complexity. Massive MIMO works well both in rich scattering and line of sight environments. These features naturally make the technology suitable for drone communications [11].

While the physical phenomenon of pilot contamination is known to be a limitation in multi-cell massive MIMO systems, for drone communications, due to high coherence bandwidth (assuming the antenna array is directed upwards into the sky) the coherence interval in samples is long and mutually orthogonal pilots to all drones can be afforded. Hence, pilot contamination is not a significant issue, particularly in scenarios where the drone density is low. Field trials of Massive MIMO in high mobility have been performed for example in the pan-European FP7-MAMMOET project, and efficient hardware implementations have been demonstrated [12], [13]. In terms of digital circuit implementations, zero-forcing precoding and decoding of 8 terminals with 128 BS antennas over a 20 MHz bandwidth can be performed in real time at a power consumption of about 50 milliWatt [14]. Therefore, Massive MIMO GSs for drone communications can be realized at low cost and built from technology that is maturing [11].

4.2.3 Solutions Deployable at User Equipment

4.2.3.1 User Equipment Antenna Optimization

This work aimed to validate the assumption that use of static directional antennas (later dynamic antenna setup may also be considered), instead of generally used omnidirectional ones, will reduce the number of interferences and result in lower number of handovers. The assumption underwent several practical evaluations by a preliminary drone flight tests in Brno.

Preliminary results were promising, especially in area of number of handovers. Three setups were flight tested – the standard omnidirectional setup serving as a baseline for comparison, then directional antennas setup in geometry #1 (low inclination angle of antennas to vertical) and directional antennas setup in geometry #2 (high inclination angle of antennas to vertical). Best results were obtained from the setup of directional antennas in geometry #1.

Preliminary results from Brno testing are provided in the figure below for one of the test flights with directional antenna setup in geometry #1 and with the omnidirectional antenna setup.

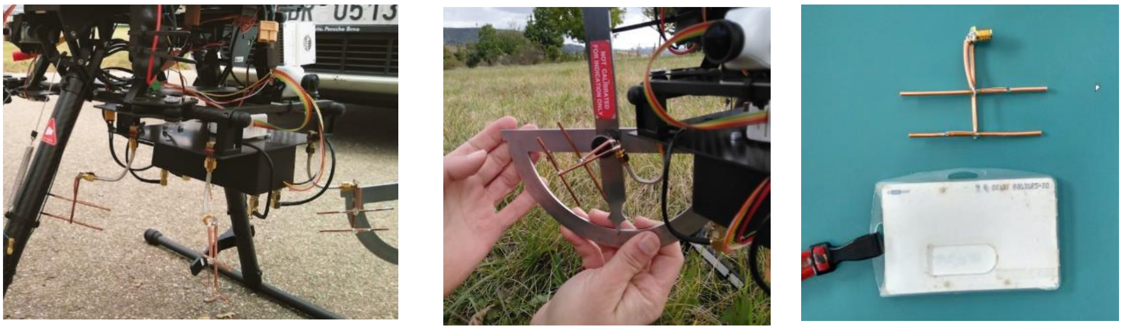

Figure 3: From left – antennas in position # 2 (high incl.), antennas in position #1 (low incl.), directional antenna prototype size

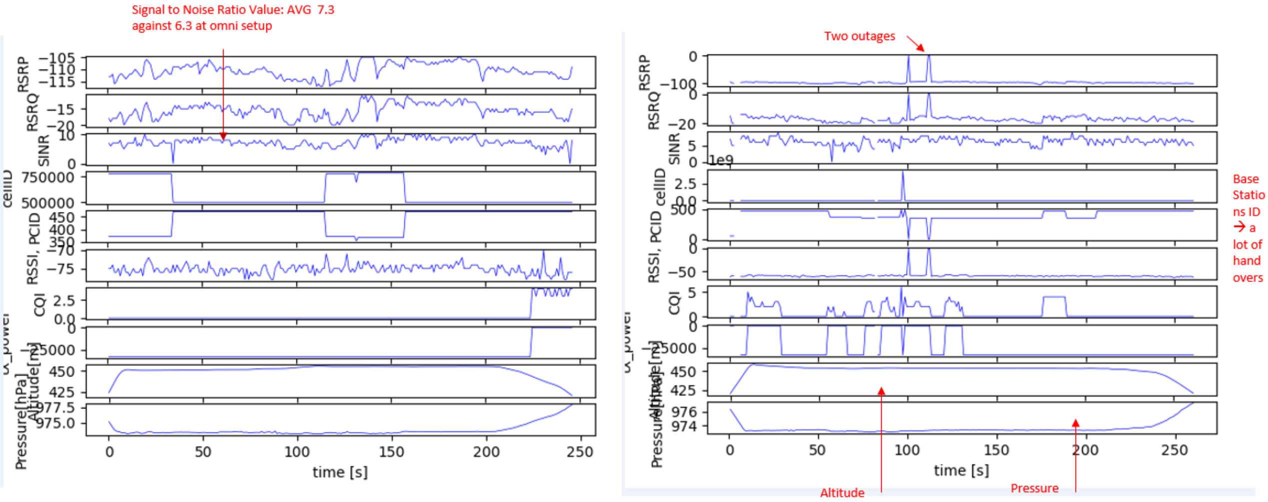

Figure 4: Comparison of directional and omnidirectional setup

Main conclusions for directional antennas can be summarized as follows:

- Significant reduction in number of handovers (5 vs. 15 during first flight, 3 vs. 14 during second flight)
- Better signal to noise ratio (10.7 vs. 10.4 dB, 7.3 vs. 6.3 dB)

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- Better Received Signal Reference Quality (-10.3 dB vs. -11.3 dB, -15.5 dB vs. -17.1 dB)

4.2.3.2 Network Performance Monitoring

Another method to mitigate negative effects in low altitudes is network performance monitoring. Continuous monitoring and precise data evaluation can be used to prevent communication outage. Timely detection of performance loss/degradation can trigger switching either to better cellular communication option (other operator, other network type) or to different communication link (satellite, for example).

Network performance monitoring was evaluated during official project demonstrations.

4.2.3.3 Combination of Cellular Datalink with Other Technology

Robustness of a communication solution based on today’s cellular network can be increased by combining cellular and other technologies. Satellite communication systems are a promising and logical candidate for this purpose.

5 Main Project's Findings

5.1 Usability of cellular network for air traffic applications

In this section, the suitability of network performance is discussed in the context of three different ATM applications discussed in project's ConOps and shortly summarized in Section 3.

5.1.1 Broadcast surveillance (position reporting & TIS)

The function of transmitting position data over the mobile network was directly tested during the official project flight tests in Eskisehir in summer 2022. This functionality was technically designed in such a way that the unit included an LTE module that transmitted position messages to the MQTT broker where other participants of the flight demonstration had access.

The transmission of position reports is a function serving for ground surveillance. The criticality of the content of the individual reports is low; a good overview of the locations of the vehicles can be obtained even if a significant number of reports are not delivered. This is a task for surveillance tracker which processes reports from all in air vehicles. Tracking function is capable to sophistically coast movement of vehicle for a certain period of time when some surveillance reports are not received. During official flight demonstration, the ground tracker was used to provide consolidated traffic data and also the smooth display output for demo operator.

5.1.1.1 Supporting validation results

Communication between on-board experimental CNS unit and ground server was evaluated during official flight demonstrations. Message loss, outages and overall latency between transmission of message on vehicle A and message delivery on vehicle B was evaluated. Strong majority of messages were delivered in interval from 0.6 to 0.8 seconds from transmission.

It must be said that outages were detected. Analysis has shown that most of them were caused by technical issues, but some of them were caused by loss of LTE signal. This was proved by rapid decrease of mobile network quality parameters measured on experimental CNS unit just before outage.

Ignoring outages, the actual parameter of the number of lost messages is in the units of percent which seems to be very acceptable result.

	Drone A - Aircraft	**Aircraft – Drone A**
Overall latency transmission – reception [s]	1.16 (st. dev. 0.61, min 0.69, max 4.2)	1.03 (st. dev. 0.96, min 0.35. max 6.78)
Median value for latency transmission – reception [s]	**0.77**	**0.67**
Latency on ground [s]	0.06 (st. dev. 0.14, min 0.01, max 3.64)	0.05. (st. dev. 0.14. min 0.01, max 2.61)

Message loss from vehicle to ground (not only in outages)	4.38 %	19 %

Table 2: Scenario 1, overall latency transmission – reception between drone and aircraft

	Drone B – Drone A	**Drone A – Drone B**
Overall latency transmission – reception [s]	1.14 (st.dev 0.61, min 0.68, max 4.47)	1.16 (st.dev 1.46, min 0.37. max 9.51)
Median value for latency transmission – reception [s]	**0.79**	**0.72**
Latency on ground [s]	0.055 (st.dev 0.049)	0.047 (st.dev 0.099)
Message loss (undelivered messages)	4.71 %	38.31 / 5.84 %[1]

Table 3: Overall latency transmission – reception between drone A and drone B for Scenario 4 of the operational demo.

5.1.1.2 Conclusions/Recommendations

Detailed measurement of LTE and NB-IoT networks performed last year within project’s activities have confirmed that the public mobile network in today’s typical configurations is in general reasonably reliable (comparable to the performance on ground) up to an altitude of around 100 metres. At higher altitudes, interference is more likely to occur, resulting in degraded signal quality parameters and, in the worst case, total loss of signal.

Nevertheless, obtained results indicate that even such degraded performance may be in may situations sufficient for basic traffic surveillance applications, if suitable traffic trackers are applied at the reception system and operational procedures (e.g., separation/well-clear buffers) correctly reflect the achievable communication performance. The key requirement is that longer outages in order of multiple tens of seconds needs to be avoided and therefore consider appropriate mitigation measures.

Conceptually, there are two types of factors affecting real network performance:

- Static – reflecting primarily local configuration of the network including antennas setup, available frequency spectrum, etc.
- Dynamic – reflecting real time factors affecting real time factors affecting network performance such as number of users currently connected at the given cell, load of the network in terms of transferred data, etc.

Mitigation of the static factors could be considered already in pre-flight stage and during flight approval and a possible mitigation can be simply the availability of some kind of coverage maps for different

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[1] This huge message loss is affected by significant outage in the second half of scenario. Omission of this outage gives results of 5.84 % messages undetected on ground.

networks/operators at the considered geographical location including variations with altitude. In this way, the flight operator can evaluate already before the flight which services can be available and check whether aircraft's equipment is sufficient for envisioned flight.

For dynamic factors, possible mitigations can rely on real time network performance monitoring services and availability of tailored procedures to safely handle the situations when communication performance is degrading.

5.1.2 Alerting for situation awareness

Alerting represents of event-base communication with high delivery probability requirements. Basic repeating of message transmission can mitigate some message losses, but in situations with poor cellular signal this mitigation could be insufficient.

There is also the issue of latency - if the first one alert message is not delivered, but one of the next repeated messages is, the latency will increase to unacceptable values.

5.1.2.1 Supporting validation results

As described in the D5.3 Validation Report, alert messages were produced in Scenario 1, Scenario 3 and Scenario 5 during flight demonstrations. Corresponding percentages of received alerts were 100 % - 80 % - 60 %.

5.1.2.2 Conclusions/Recommendations

Considering the obtained results and literature surveys, it seems that relying only on public LTE network won't be generally sufficient for this type of application. It could be potentially sufficient in very low altitudes (ignoring dynamic factors) but in general it would need a more robust multi-link solution.

Alternatively, a use of dedicated network is recommended. In any cases it is expected that some additional techniques like confirmation of reception will be used whatever technology is used.

5.1.3 UTM/ATC datalink similar to CPDLC

Datalink providing analogous functionality for communication in UTM like CPDLC in ATM (nevertheless it is expected that the datalink protocol for UTM should allow more complex communication than what is possible with today's CPDLC) has evidently the strictest performance requirements. These aspects were not directly evaluated in the project and so the below recommendations are based only on theoretical considerations and extrapolation of obtained results.

5.1.3.1 Conclusions/Recommendations

Using FACT project results it is obvious that public network will not be able to meet the criteria.

In airspace segment called very low altitude the solution could be the dedicated network – LTE may suffice, but for reaching low latencies the 5G network is definitely better choice and may be even required.

For higher considered airspace the mobile network should be combined or backed-up by some other communication link. The natural candidate is the satellite communication.

5.1.4 Positioning

Appendix C of deliverable D3.1 System Requirements has provided overview of positioning methods available in cellular networks. Experiment with positioning in LTE was performed in May 2022 using opportunity of flights under USPACE4UAM demonstrations in Brno. We have equipped prototype of experimental CNS unit by two uBlox LARA LTE modules which are able to log Timing Advance parameter. Each LTE module has SIM card from different operator to maximize probability that experimental CNS unit will be connected to two different base stations at the same time.

Timing Advance is parameter serving for handling delays in communication over mobile network per distance from base station. It is a discrete quantity defining distance from base station with step of 78.125 m (value valid in LTE network). Thus, if value of TA is e.g. qual to two, it means that device's distance from BTS is in rage from 156.25 to 234.375 meters. For aerial vehicles there is a need to consider spatial distance. Location of BTS was obtained from public database. Results should be more precise if knowledge of antennas altitude would be known or if the measurements from two modules would be synchronized in time (now they were linearly interpolated).

Figure 5: Blue point showing position estimate from Timing Advance, the yellow pin shows location per GPS.

If the location of BTS and Timing Advance value is known, the real position of device should be found at intersection of two annuli of 78.25 meters width. We have evaluated difference between GPS position and results show relative good estimate of vehicle location. Distance between GPS position and intersection point of the lines drawn through the centers of annuli were lower than step size (78.25 meters) for 87 % of time.

Precision of this localization method is physically limited by step size of TA value in given network. For 5G networks is this value approx. four times lower which gives four times smaller step. Considering the fact that one probable solution how to boost connectivity via mobile network is dual SIM solution, this method can represent very easy and practically no cost check of primary position. This method can be combined with other sensors (barometer, heading indicator) or enhanced by tracking.

5.2 Operational recommendations

5.2.1 ATC (ESTU)

Air traffic controllers provided positive feedback about the validation studies performed by FACT project. They were satisfied to have the ability control and coordination between drone operators and GA aircraft operators. The feedback from ATCOs can be summarized as follows:

- Voice communication issues between ATCO, drone operators and general aviation pilots are critical to aviation safety. They emphasized that direct communication with drone operators would be beneficial.
- ATCOs want to identify, know, and control all aircraft or flying objects in the airspace under their control with high fidelity.
- Being able to see and communicate with drones on their screens provides an advantage for ATCOs to manage their stress.
- Although it is perceived as increasing the workload of having to work with extra aircraft on their screens, this will increase the situational awareness of ATCOs and reduce the possibility of making mistakes.

The interface developed within the scope of the FACT project can be developed within the scope of the suggestions made by the ATCOs working at Hasan Polatkan Airport in the verification studies.

5.2.2 GA/Helo Pilots (SARP Air, ESTU, AOPA)

Project’s objectives addressed benefits associated with the availability of the ATM functions discussed in the previous sections (traffic awareness and alerting).

As the focus of the project was on CNS functions and not on design and validation of HMI design of pilot’s interface, only a simple “engineering” traffic situation awareness display was used during the operational demo. It is therefore important to interpret the obtained results in this context and this is reflected in the discussion below.

Pilots who participated in the flight test rated the overall benefit of situational awareness function positively. Nevertheless, they considered as useful if the system is enhanced with some level of traffic alerting and avoidance function as TCAS. This is well aligned with the work on new generation of ACAS

X system whose different version are intended to broader range of airspace users including VTOL, rotorcraft and unmanned vehicles. Independently, even for basic situation awareness it needs to be carefully evaluated which information should be shown as relevant to own flight as there is a high risk of overwhelming pilot with unnecessary details especially if multiple drones are flying in the area.

According the received feedback, some basic situation awareness functionality - at least TIS data – should become available on consumer smart phones through dedicated apps. The typical users for this would be pilots of gliders, para gliders, hang gliders sharing the low airspace with drones.

Pilots also emphasized the need of appropriate training of the drone operators which will share airspace with GA traffic including appropriate regulations, and they suggest that ATC may need to have a force to land the drone immediately to prevent the possible collision.

5.2.3 Drones operators (ITU)

Single drone operator has participated during final project flight test. Although some connection outages were appearing during particular scenarios, the overall feedback was positive. Simple and cheap way how to directly monitor live heterogenous traffic was considered as very useful.

5.3 Coverage of Planned Validation Objectives

The following table summarizes project's objectives as described in Validation Plan (Section 3.2 of D5.1) and how they were covered by the project's activities and obtained results.

Table 4: Validation objectives coverage

Objective	Rationale	Success Criteria
OBJ-1: Validate that the performance of cellular network is capable to support ground traffic surveillance based on air → ground position reporting.	Within the operational demo, the focus will be on evaluation of communication performance – therefore the success criteria are related to REQ-PERF-2-1 of D3.1 complemented with some additional criteria derived from ADS-B traffic tracker[2] requirements.	SUCC-1-1: The 95% total latency of the position reports (between aircraft transmission to ground tracker) won't be greater than 0.5s.
		SUCC-1-2: Update rate at the ground tracker (reception of the new position report) will be less than 3s (99% of time).

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[2] The generic ADS-B tracker as described in EUROCAE ED-194B (July 2020) is used as a reference.

		SUCC-1-3: No tracks within the range of demo’s operational area will be dropped by the ground tracker due to missing position reports.
Objective was fully addressed by the project and results are described earlier in this section and within D5.3. Public cellular network seems to meet the needs of traffic surveillance at least for aircraft flying below certain altitude (which vary for different geographical locations depending on the network configuration and terrain profile). Concerning the success criteria, the results indicate that: • SUCC-1-1: The latency criterium is met for messages that are well received on the ground (not lost). Because of different source of time on ground (PC time) and on onboard units (mobile network time), it is not possible to precisely evaluate one-way time. Two way time period from transmission on vehicle A to reception on vehicle B is measured precisely, also the time required for ground processing. Therefore, it is correct to deduce indirectly that if two-way communication has a median value of [0.77; 0.67; 0.79; 0.72][3], one-way communication will be approximately half of this median value. When periodic latency spikes caused by component reinitialization are omitted, the 95 % of measured values divided by two (to conform one-way latency) are under latency [0.43; 0.41; 0.43, 0.39]. • SUCC-1-2: The criterium is met. The criterium is met. Per Table 4 in the D5.3, percentage of lost messages from vehicle to ground was 4.38 % from drone and 5.11 % from aircraft. Messages were sent each second. This implies that criterion for update rate of 3 seconds was met. • SUCC-1-3: Similarly, as for previous criterium, except the long outages’ intervals, the criterium is met.		
OBJ-2: Validate that the performance of cellular network is capable to support traffic information services (ground → air) contributing to airborne situation awareness and detect and avoid functions.	Within the operational demo, the focus will be on evaluation of communication performance – therefore the success criteria are related to REQ-PERF-1-5 of D3.1 complemented with some additional criteria derived from airborne applications requirements.	SUCC-2-1: The 95% total latency of the position information about an aircraft (between reception of its position report by ground tracker to reception of TIS message by airborne users) won’t be greater than 1s.
		SUCC-2-2: Update rate of the airborne traffic tracker using TIS data (reception of the new position report) will

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[3] See Table 4 and Table 5 in the D5.3 Second Validation Report

<table>
<tr><td rowspan="2"></td><td rowspan="2"></td><td>be less than 5s (99% of time).</td></tr>
<tr><td>SUCC-2-3: No tracks within the range of demo's operational area will be dropped by the airborne tracker due to missing TIS position reports.</td></tr>
<tr><td colspan="3">Objective was fully addressed by the project and results are described earlier in this section and within D5.3. Results are very similar to position reports downlink: public cellular network seems to meet the needs of traffic surveillance at least for aircraft flying below certain altitude (which vary for different geographical locations depending on the network configuration and terrain profile). Concerning the success criteria, the results indicate that:
• SUCC-1-1: The latency criterium is met for messages that are well received on the ground (not lost). Because of different source of time on ground (PC time) and on onboard units (mobile network time), it is not possible to precisely evaluate one-way time. Two way time period from transmission on vehicle A to reception on vehicle B is measured precisely, also the time required for ground processing. Therefore, it is correct to deduce indirectly that if two-way communication has a median value of [0.77; 0.67; 0.79; 0.72][4], one-way communication will be approximately half of this median value. When periodic latency spikes caused by component reinitialization are omitted, the 95 % of measured values divided by two (to conform one-way latency) are under latency [0.43; 0.41; 0.43, 0.39].
• SUCC-1-2: The criterium is met, logically except within the long outage intervals (see D5.3 for details). Traffic snapshot was sent from ground to aircraft each second. 89 % of TIS messages were received on aircraft (there was no large outage – see Figure 40 in the D5.3)
• SUCC-1-3: Similarly, as for previous criterium, except the long outages' intervals, the criterium is met.</td></tr>
<tr><td rowspan="2">**OBJ-3: Validate that the performance of cellular network is capable to support alerting messages communicated by ATM/UTM services (ground → air).**</td><td rowspan="2">Within the operational demo, the focus will be on evaluation of communication performance – therefore the success criteria are related to requirements listed in section 5.3 of D3.1 (namely G2A ATS dedicated communication mode)</td><td>SUCC-3-1: The 95% total latency of the alerting message sent by ground services to a flying vehicle won't be greater than 0.5s.</td></tr>
<tr><td>SUCC-3-2: Maximum latency of the alerting message sent by ground services to a flying vehicle won't be greater than 5s.</td></tr>
</table>

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[4] See Table 4 and Table 5 in the D5.3 Second Validation Report

<table>
<tr><td colspan="3">Within operational demo, there were only 3 isolated events (in scenarios 1, 3, and 5) when alerting messages were sent and they were only used for drones. The data sample is therefore too small to drive some more general conclusions. Nevertheless, in these 3 specific cases the observed latency was under 0.5 second (for Scenario 1 where all alert messages were received successfully), under 1.0 second (for Scenario 2 where 4 of 5 messages were received successfully) and under 1.5 second (for Scenario 3 where 3 of 5 messages were received).

It is therefore clear that the criterion SUCC-3-1 was not met. Unfortunately, as stated above for more detailed analysis of this performance characteristics we would need much larger sample of data.

Regarding SUCC-3-2, when ignoring latencies caused by component reinitialization (clearly identified by periodical behavior), no value above 5 seconds was detected.

Performance of public network is in this context very depending on altitude. While for low flying drones the two success criteria seem to be met, for GA or rotorcraft flying higher they are not. In this context, answer is strongly dependent on local network configuration and effective altitude threshold under which the performance is sufficient is lower than for traffic surveillance application.</td></tr>
<tr><td rowspan="3">**OBJ-4: Validate that the tested applications enabled by cellular network infrastructure improve overall operational safety**</td><td rowspan="3">As the amount of data which will be possible to collect during the operational demo won’t allow to perform rigorous quantitative safety analysis, the success criteria are based on evaluating feedback of stakeholders/users involved in the demo.</td><td>SUCC-4-1: Positive feedback from ATC controller based on questionnaires and workshop discussions processed after/during demo operations.</td></tr>
<tr><td>SUCC-4-2: Positive feedback from drones’ remote pilots based on questionnaires and workshop discussions processed after/during demo operations.</td></tr>
<tr><td>SUCC-4-3: Positive feedback from GA pilots based on questionnaires and workshop discussions processed after/during demo operations.</td></tr>
<tr><td colspan="3">Objective was fully addressed by the project and results are described earlier in this section and within D5.3. All stakeholders agreed that situation awareness enabled by cellular network improve operational safety. However, open question is whether the performance of cellular network is sufficiently stable to allow potentially adapt the operational procedures (e.g., increase airspace capacity, reduce traffic segregation) based on these safety benefits. Results for the individual success criteria are as follows:

• SUCC-4-1: Positive feedback received.
• SUCC-4-2: Positive feedback received.</td></tr>
</table>

- SUCC-4-3: Positive feedback received but only based on workshop as technical difficulties prevented to collect feedback concerning use of onboard situation awareness application during real flights.

6 Conclusions & Recommendations

As discussed throughout the project's deliverables, the potential use of cellular network for air traffic applications requires primarily answers in three main areas:

- Network availability, especially in higher altitudes
- Network performance
- Minimal Quality of Service and if it can be guaranteed in some way.

One of the key motivations for use of this technology is its potential affordability due to existing infrastructure driven by other commercial applications and availability of affordable COTS communication chips. However, as there are multiple possible business scenarios that should be considered in this context and validity of these assumptions will need to be verified for each of them. In particular, the project considered the following three main network deployment options:

- Public LTE/4G network
- Public 5G network
- Dedicated 4G/5G network.

Use of public LTE/4G network

This type of network was explored within the operational demo and majority of preparatory activities. As shown also by obtained results (see D5.3), the main limitation of the public/LTE network is its availability at higher altitude due to strong interference and cells handover processes. It is caused by optimization of the infrastructure to surface users. While it could be theoretically improved by adapting the ground infrastructure (namely antennas configuration) there is a lack of business motivation due to small number of airspace users comparing to conventional cellular network business. While the network communication speed/capacity (without considering for now availability problem) is sufficient for all ATM applications considered in the project, there is no guarantee of the quality of service to the users which represents a serious problem for safety critical applications.

Knowing the above limitations, the use of this type of network for any safety critical communication does not seem acceptable. However, project's results indicate (D5.3) that if the communication outages over longer periods of time (~ multiple tens of seconds) can be mitigated and/or procedurally handled, this type of network could be usable for elementary traffic surveillance. Suggested mitigation means include:

- Use of coverage maps including altitude during flight planning and approval to correctly handle expected cellular network performance through complementary equipment or adequate procedures.
- Real-time network monitoring service/function detecting in advance possible degradation of communication performance and application of corresponding operational procedure.

- Increased robustness of airborne communication solution using multilink capabilities – whether through use of multiple cellular networks with independent infrastructure or combining cellular network with different communication technology.

Concerning positioning function, 4G provides only limited capabilities ((see section 5.1.4 for more details) which can potentially play only a supporting role in overall navigation solution.

Use of public 5G network

As described above the real challenge of public cellular network use for air traffic application does not lie in nominal latency or bandwidth but in availability of the network function and guarantee of continuous minimal quality of service. In this context, the increased transmission speed of 5G versus 4G cellular network does not represent the key benefit. However, 5G specifications include much more tools to mitigate interferences in higher altitudes (e.g., through MIMO processing and antennas setup, or NB-IoT (see Appendix C)) as well as prioritized handling of specific types of users or specific applications to manage required quality of service (see project's results described in Appendix B). In addition, 5G allows to use larger part of spectrum which can also considerably improve availability of the communication function. Furthermore, 5G 3GPP specification also includes positioning features that can provide navigation performance comparable with GPS. In this context, 5G has a potential to be considerably better solution for air traffic applications.

Nevertheless, the key challenges are related to the business aspects of the problem. Today's 5G implementations focus on bandwidth and transmission speeds as these aspects are key selling points for the conventional cellular network customers. Potential air traffic applications currently do not represent sufficient business motivation for network operators to implement additional features of 5G specs (whether URLLC or positioning). To overcome this issue, a coordinated approach with regulators and European institutions would be probably needed to make the air traffic use case attractive.

Dedicated 4G/5G network

Dedicated 4G/5G network is considered as the only option how could cellular network technology potentially meet requirements of safety critical ATM applications. Building of dedicated network would allow to address the availability at higher altitudes as well as guaranteed quality of service. Furthermore, the potential use of protected spectrum would provide additional possibilities to handle security aspects. Nevertheless, the deployment of such kind of network would require a considerably initial investment into a dedicated infrastructure and therefore sufficiently strong business case is a key enabler of such solution.

Taking into account the above arguments, it is probable that dedicated network could be built only in limited areas with high performance requirements, i.e., typically at places with high traffic density such as airspace around logistic or transportation hubs, airports and/or vertiports.

Cellular network as a possible solution of interoperability issues

Traffic surveillance is a key enabler of any traffic management. This aspect is well-known and this is why the EASA regulation for U-space aims to first enable this capability through mandated position reporting (e-Identification) both for drones and GA and rotorcraft operating in shared airspace. While it is an important step, so far it enables so far only central ground-based conflict management as it solves how to get the information about traffic to the ground (for potential use by conflict management service) but not how to share it among the different airspace users. In addition, it allows three different technologies (ADS-B Out over 1090 MHz, SRD 860 MHz, or cellular network) to be used for this reporting which does not simplify interoperability. Similar situation happened in the US, with the introduction of UAT frequency for GA ADS-B capability which led to the need of implementation of ground ADS-R (rebroadcast) services to share the received UAT reports over 1090MHz with commercial aviation. In this context, the approach used by the FACT project (and also implemented for operational demo) with TIS service distributing traffic information received on the ground among all airspace users can play a similar role and can be the missing element solving the current interoperability issues.

During the discussions with GA and rotorcraft pilots, there were several times raised the concerns that airborne traffic surveillance should not be relying on ground infrastructure and should be realized by direct V2V (vehicle-2-vehicle) link. Even if such solution would be ideal and could be complementary to position reporting on the ground, again the interoperability issues would need to be solved first and a common frequency & technology will need to be defined by a regulator to ensure interoperability among different users. While discussions how to progress with this topic are ongoing both in the US and in Europe, such standardization will yet take some time and the V2V links used so far (ADS-B FLARM, WIFI) are always limited only to a part of airspace users, and therefore does not help with the interoperability.

In addition, as commercial aviation is already using 1090MHz frequency for the purpose of V2V communication and there is a considerable risk of congestion if this frequency starts to be used by large number of new users in the same area, the new V2V link won’t be probably common with commercial aviation. This means that similarly as in the US some complementary ground service will need to be deployed anyway to handle interoperability with commercial aircraft.

In this context, while the solution based on TIS service over cellular network may have lower performance than direct V2V link, it can still represent a meaningful and affordable intermediate solution until the standardization of new V2V link covering needs of new airspace users and GA/rotorcrafts is closed, and at the same time an important complementary service helping with interoperability aspects. In this context, it is worth to mention that new ACAS Xr system developed for pilots of rotorcrafts and UAM vehicles already considers both possibilities of receiving traffic information from ground service and via direct V2V link.

Availability of advanced CNS capabilities needs to be complemented with adequate trainings

During the workshops with airspace users, it was multiple times emphasized that while advanced CNS capabilities are important enablers, appropriate training both to the new and existing airspace users will be essential to achieve the expected safety benefits. In particular, all airspace users will need to well understand rules of the air as well as their responsibilities. GA and rotorcraft pilots will need to be trained when provided with new ACAS systems, as the lessons learned from introduction of TCAS for commercial aviation showed how important such training is even for experienced pilots.

7 References

[1] Casek, Korenciak, Tomanek: D2.3 Report on Mobile Network, Deliverable from MoNiFly project, available at https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cee3b2d0&appId=PPGMS

[2] https://www.sciencedirect.com/science/article/pii/B9780128044186000091

[3] https://internetofthingsagenda.techtarget.com/definition/LPWAN-low-power-wide-area-network

[4] M. Chen, Y. Miao, Y. Hao, and K. Hwang, “Narrow Band Internet of Things,” IEEE Access, vol. 5, pp. 20 557–20 577, 2017

[5] O. Liberg, Cellular Internet of Things, 1st ed. Cambridge: Elsevier, 2019.

[6] A. Laya, C. Kalalas, F. Vazquez-Gallego, L. Alonso, and J. Alonso-Zarate, “Goodbye, aloha!” IEEE Access, vol. 4, pp. 2029–2044, April 2016

[7] A. Hoglund, X. Lin, O. Liberg, A. Behravan, E. A. Yavuz, M. V. D. Zee, Y. Sui, T. Tirronen, A. Ratilainen, and D. Eriksson, “Overview of 3GPP Release 14 Enhanced NB-IoT,” IEEE Network, vol. 31, no. 6, pp. 16–22, November 2017

[8] A. Marrotta, Network Solutions for CoMP Coordinated Scheduling, IEEE Access Vol.7, https://ieeexplore.ieee.org/document/8924659

[9] https://www.qualcomm.com/5g/what-is-5g

[10] https://www.mediatek.com/blog/5g-what-are-embb-urllc-and-mmtc

[11] http://liu.diva-portal.org/smash/get/diva2:1343849/FULLTEXT01.pdf

[12] P. Harris, S. Malkowsky, J. Vieira, E. Bengtsson, F. Tufvesson, W. B. Hasan, L. Liu, M. Beach, S. Armour, and O. Edfors, ‘‘Performance characterization of a real-time Massive MIMO system with LOS mobile channels,’’ IEEE J. Sel. Areas Commun., vol. 35, no. 6, pp. 1244–1253, Jun. 2017

[13] P. Harris, S. Zang, A. Nix, M. Beach, S. Armour, and A. Doufexi, ‘‘A distributed massive MIMO testbed to assess real-world performance and feasibility,’’ in Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring), May 2015, pp. 1–2

[14] H. Prabhu, J. N. Rodrigues, L. Liu, and O. Edfors, ‘‘3.6 a 60pj/b 300Mb/s 128 × 8 Massive MIMO precoder-detector in 28 nm FD-SOI,’’ in Proc. IEEE Int. Solid-State Circuits Conf. (ISSCC), Feb. 2017, pp. 60–61.

[15] https://www.gsma.com/iot/wp-content/uploads/2020/11/ACJA-WT3-LTE-Aerial-Profile_v1.00-2.pdf

[16] https://en.wikipedia.org/wiki/LTE_(telecommunication)

[17] https://www.motorola.com/web/Business/Solutions/Industry%20Solutions/Service%20Providers/Wireless%20Operators/LTE/_Document/Static%20Files/6833_MotDoc_New.pdf

[18] https://www.sharetechnote.com/html/5G/5G_FR_Bandwidth.html

[19] https://www.fcc.gov/BroadbandData/MobileMaps/mobile-map

[20] http://lteanddrones.com/2-lte-network-design/

[21] "Private 5G: The Future of Industrial wireless." *IEEE Industrial Electronics Magazine* 14.4 (2020): 136-145.

[22] FACT Deliverable D2.3: “Final Concept of Operations”, version 00.01.01, 2.9.2022

[23] FACT Deliverable D2.4: “Final iCNS Functional Architecture”, version 00.01.00, 12.7.2022

[24] FACT Deliverable D3.3: “Final System Requirements”, version 00.01.01, 2.9.2022

[25] FACT Deliverable D5.2: “First Validation Report”, version 00.01.01, 6.4.2022

[26] FACT Deliverable D5.3: “Second Validation Report”, version 00.01.00, 20.9.2022.

Appendix A Overview of Mobile Network Types

A.1 LTE/4G

In telecommunications, Long-Term Evolution (LTE) is a standard for wireless broadband communication for mobile devices and data terminals, based on the GSM/EDGE and UMTS/HSPA technologies. It increases the network capacity and speed using different radio interfaces together with core network improvements. LTE is the upgrade path for carriers with both GSM/UMTS networks and CDMA2000 networks.

The standard has been developed by the 3rd Generation Partnership Project (3GPP) and is specified in its Release 8 document series, with minor enhancements described in Release 9. LTE is sometimes known as 3.95G and has been marketed both as "4G LTE", but it does not meet the technical criteria of a 4G wireless service, as specified in the 3GPP Release 8, 9 and 10 (LTE-A) document series for LTE Advanced. The requirements were originally set forth by the ITU-R organization in the IMT Advanced specification. However, due to marketing pressures and the significant advancements that WiMAX, Evolved High Speed Packet Access, and LTE bring to the original 3G technologies, ITU later decided that LTE together with the aforementioned technologies can be called 4G technologies [16].

The LTE specification provides theoretical downlink peak rates up to 300 Mbit/s, theoretical uplink peak rates up to 75 Mbit/s and Quality of Service (QoS) provisions permitting a transfer latency of less than 5 ms in the radio access network (in one direction, best case). LTE has the ability to manage fast-moving mobiles and supports multi-cast and broadcast streams. LTE supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz and supports both Frequency Division Duplexing (FDD) and Time-Division Duplexing (TDD). The IP-based network architecture, called the Evolved Packet System (EPS), consists of Evolved Packet Core (EPC) and Radio Access Network (RAN). The EPC is designed to replace the GPRS Core Network and to support seamless handovers for both voice and data to cell towers with older network technology such as GSM, UMTS, and CDMA2000 [21]. The simpler architecture results in lower operating costs (for example, each E-UTRA cell will support up to four times the data and voice capacity supported by HSPA [17].

Penetration of LTE/4G is quite high and in majority of European countries reach 80 – 90 % of area. Only rural and remote areas lack of LTE/4G. In USA the penetration is around of 93 % (based on Open Signal statistics).

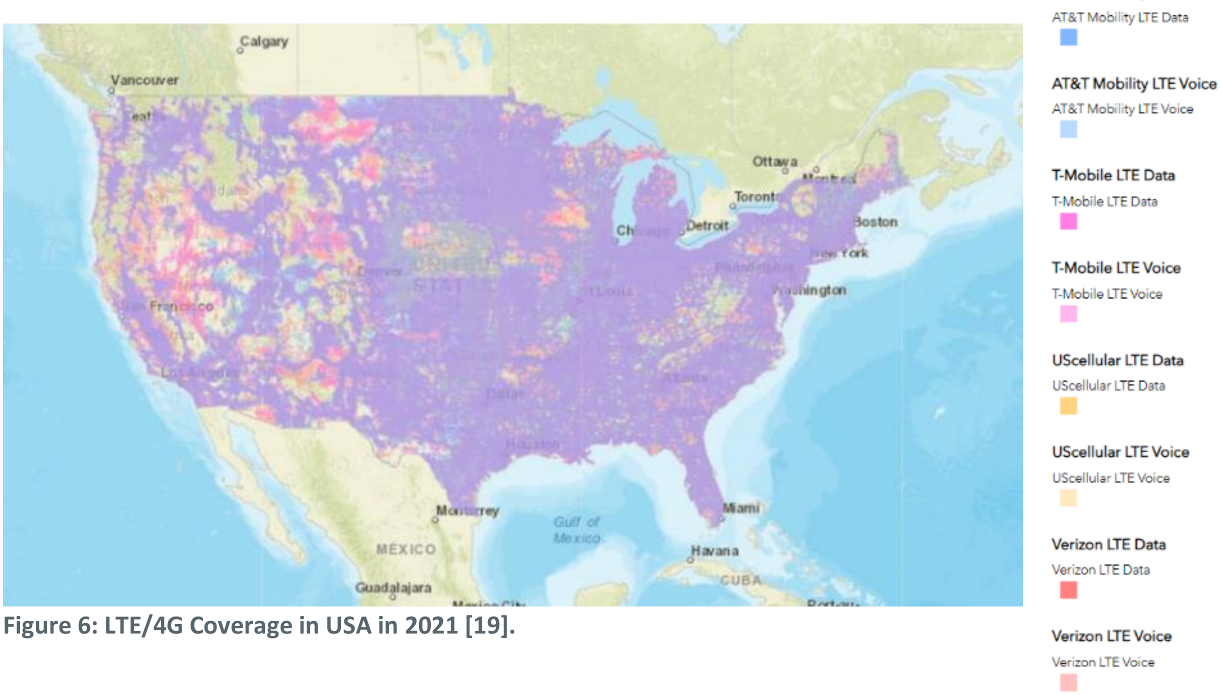

Figure 6: LTE/4G Coverage in USA in 2021 [19].

A.2 LPWAN

Low Power Wide-Area Network (LPWAN) is not a single technology, but a group of various low-power, wide area network technologies that take many shapes and forms. LPWANs can use licensed or unlicensed frequencies and include proprietary or open standard options. They are intended for interconnecting performance-limited, low-bandwidth, battery-powered devices with low bit rates over long ranges – typically a set of sensors spread through a larger geographical area often lacking power (and sometimes also alternative communication) infrastructure.

Created for Machine-to-Machine (M2M) communication in an Internet of Things (IoT) network, LPWANs operate at a lower cost with greater power efficiency than traditional mobile networks [3].

The proprietary technology Sigfox working in the unlicensed band was one of the most widely deployed LPWANs in the past. When provided as a public network in the 868 MHz Industrial, Scientific, and Medical (ISM) band in Europe or 902 MHz band in US, the ultra-narrowband technology only allows a single operator per country. While it can deliver messages over distances of 30-50 km in rural areas, 3-10 km in urban settings, its 1% duty cycle is limited to 140 downlink and 4 uplink messages per day. The maximum size is limited to 12B for a downlink message and to 8B for an uplink message. Sigfox devices broadcast their one uplink message in three different frequencies.

The second well-known representative of the LPWAN family operating in the Industrial, Scientific and Medical (ISM) spectrum is LoRaWAN which may also feature a specialized Network Join server to handle roaming between networks. In most cases, a transmission is initiated by the End Device (ED) using an Aloha-like channel access mechanism. Within the EU region, the ED selects one of up to sixteen available channels in the frequency range from 863 to 870MHz with the bandwidth of 125 or 250 kHz.

The ISM frequency band of 868MHz imposes a limitation of 1% duty cycle with the maximum Effective Isotropic Radiated Power (EIRP) of 16dBm for LoRaWAN gateway and 14dBm for User Equipment. At the physical layer, the data is transferred with a proprietary long-range (LoRa) modulation based on the spread spectrum technique named Chirp Spread Spectrum (CSS). This mechanism permits LoRaWAN to operate below the noise floor. The LoRa modulation rate can be adjusted by the spreading factor (SF) parameter, which can vary from 7 to 12. The SF value controls the modulation robustness, thus directly affecting radio coverage (communication distance). The achievable bitrate in the 125 kHz channel therefore varies from 250 (SF 12) to 5470 (SF 7) bps, which results in the maximum payload size of 51 (SF 12) up to 242 (SF 7) bytes.

Unlike the LoRaWAN and Sigfox, Narrowband IoT (NB-IoT) is a cellular technology operating in licensed bands. It was introduced in 2016 as part of 3GPP Rel. 13 with the first commercial roll-outs in the following year [4]. The system is composed of user equipment (UE), evolved Node B (eNodeB), evolved packet core (EPC), and application servers. As the terminology suggests, NB-IoT reuses a significant fraction of the existing LTE infrastructure. In most cases, the LTE system can be upgraded to support the latest specifications via a software update [4, 5]. As compared to LTE, the bandwidth of the NB-IoT system is reduced to 180 kHz carrier plus 10kHz and 10kHz guard bands from each carrier's side. Thus, it can be deployed within a single 200kHz Physical Resource Block (PRB). On top of that, NB-IoT can operate in: (i) a stand-alone mode (single Global System for Mobile Communications (GSM) carrier), (ii)using one of the LTE PRBs (in-band deployment), or (iii) in a guard band of the LTE system [5] being the latter the most common option.

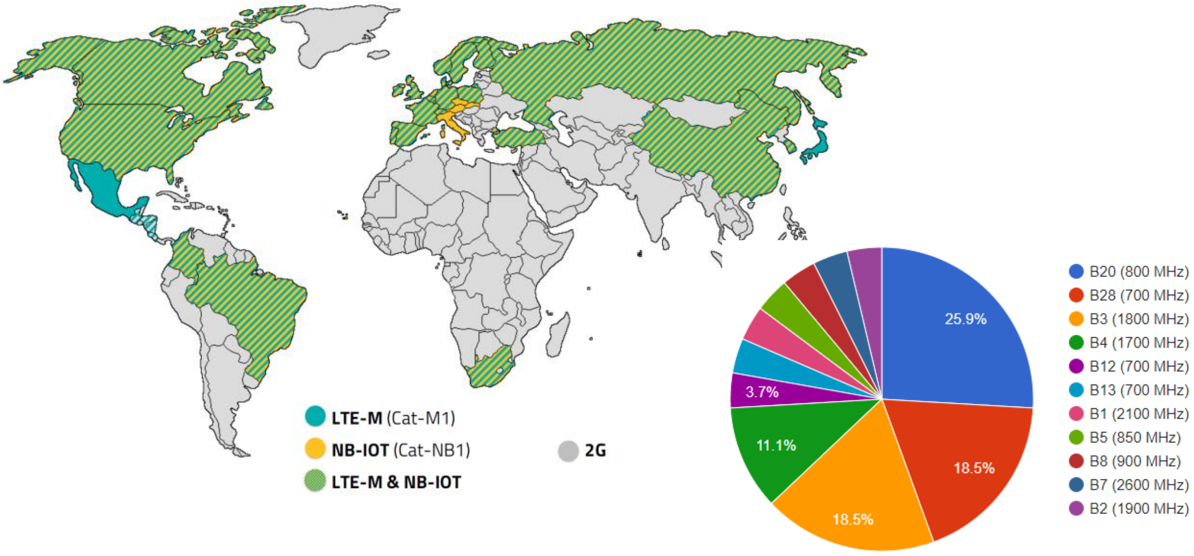

Figure 7: Licensed Spectrum LPWAN Deployment Over the World – 2020 status [18]

In contrast to LoRaWAN and Sigfox, NB-IoT uplink operation is not based on pure Aloha but utilizes its slotted version for channel access and then resorts to using the time-frequency resources allocated by an evolved NodeB (eNodeB) [6]. In addition, Frequency Division Duplex is also supported in the recent 3GPP releases. Since NB-IoT uses licensed frequency bands (predominantly, sub-GHz spectrum), there are no duty-cycle restrictions. The maximum uplink payload at the physical layer is 1000 bits (up to 2536 bits in Rel. 14) due to limitations on the transport block size (TBS). Further, the packet data convergence protocol (PDCP) layer permits the protocol data units (PDUs) with the size of up to 1600 bytes. The transmit power of the UE can be as high as 23 dBm (there is additional support for 20 dBm and 14 dBm power classes). In the case of a single tone uplink transmission, NB-IoT supports 15 and 3.75 kHz subcarrier spacing with the single carrier-frequency division multiple access (SC-FDMA). However, in practice the 15 kHz subcarrier spacing is the most frequently used option. If all the twelve tones are used, the theoretical throughput can be as high as 62.5 kbps (up to 159 kbps in Rel. 14). In the downlink, NB-IoT supports only 15 kHz subcarrier spacing with orthogonal frequency division multiple access (OFDMA). The maximum transport block size TBS is limited to 680 bits (up to 2536 bits in Rel. 14), which results in the maximum data rate of 27.2 kbps (up to 127 kbps in Rel. 14) [5], 78]. The extended coverage (+20 dB w.r.t. LTE) is achieved primarily via repetitions. The random-access channel procedure and all uplink transmissions may benefit from up to 128 repetitions [5].

A.3 5G NR Systems

During its 78th Plenary in Lisbon at the end of December 2017, the 3GPP standards body approved an interim set of specifications for 5G communications. This first set defined 5G New Radio (NR) in Non-Standalone operation (NSA), enabling 5G NR deployments using existing 4G systems.

Later, in 2018, the Standalone (SA) NR architecture has been defined, which refers to a 5G system consisting of 5G NR and 5G Core (5GC). The key difference between SA and NSA lies in the technology used for the control plane anchor operation. While NSA NR architecture refers to a system that uses LTE/evolved LTE (eLTE) as the control plane anchor for NR, in case of SA, the 5G NR is utilized as the control plane anchor.

Actually, both SA NR and NSA NR architectures consist of some variants. The five options of 5G NR deployment alternatives proposed by 3GPP are given in Figure 8, where option 2 and option 4 fall into the SA 5G NR category, while option 3 and option 7 belong to the NSA 5G NR category.

The difference between these options is that an option marked just as *N* (e.g., Option 2, see Figure 3) supports a split bearer, while option marked as *N*a (e.g., Option 4a) supports a secondary cell group (SCG) bearer, and option *N*x (e.g., Option 7x) supports an SCG split bearer, where *N* can stand for 3, 4, or 7.

Option 5 considers the case when the eLTE base station (ng-evolved Node B, ng-eNB) is connected to 5GC, and this deployment mode is not related to NR. The network migration steps from NSA 5G NR to SA 5G NR are also illustrated in Figure 8. No matter which one is deployed in the initial stage, the ultimate deployment mode is the same. SA option 2 and NSA option 3 are the typical architectures supported by mobile network vendors and operators.

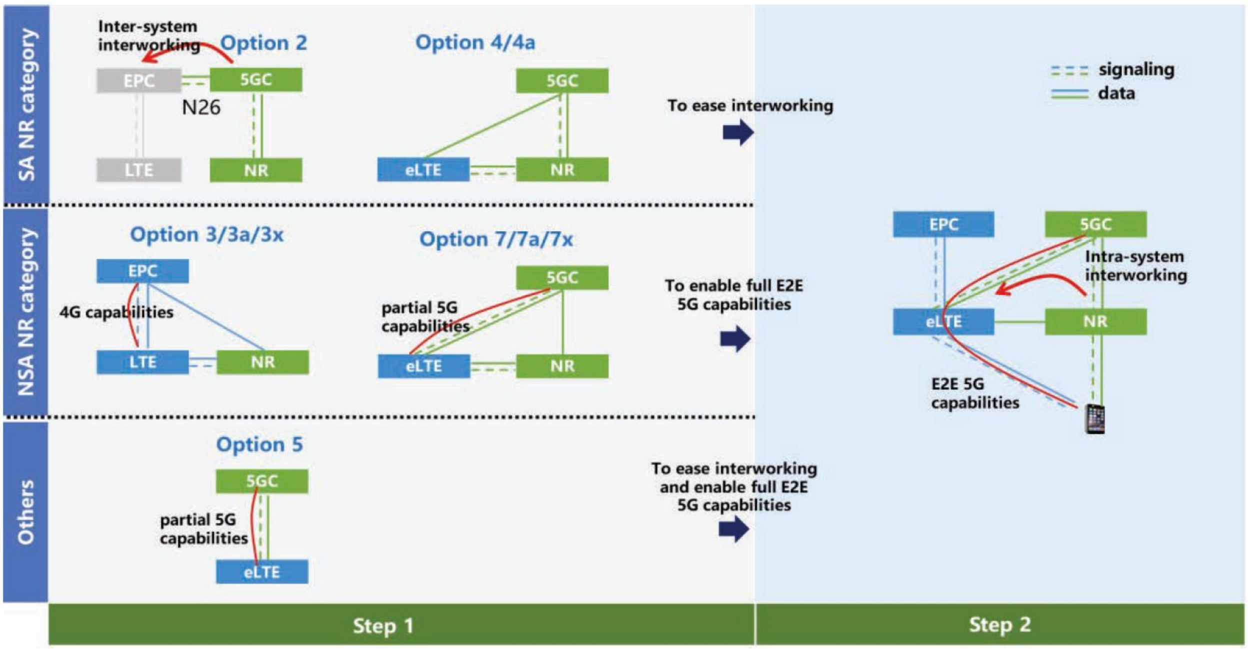

Figure 8: Five network architecture options proposed by 3GPP and the potential migration paths.

The SA architecture of 5G NR standard provides a complete set of specifications for the 5G Core Network that goes beyond NSA alternative. The 'full' 5G System includes new service classes such as:

- eMBB (enhanced Mobile Broadband),
- URLLC (Ultra Reliable Low Latency Communications),
- mMTC (massive Machine Type Communications).

Moreover, the Edge computing technique allows for lower latency or increased computational capacity.

The initial phase of 5G NSA deployments focuses on eMBB, which provides greater data-bandwidth complemented by moderate latency improvements on both 5G NR and 4G LTE. mMTC has been already developed as part of 3GPP Release 13/14 LPWA technologies, which include Narrowband IoT (NB-IoT), LTE Cat-M, and LTE Cat-1 (eventually LTE Cat-1bis) These are expected to meet most of the 5G mMTC requirements, while others that require more bandwidth with ultra-reliable low latency (full URLLC) will require the 5G Core deployment for full end-2-end latency reduction. Mission critical applications that are especially latency-sensitive will also require wide coverage, which is highly unlikely in early 5G deployments, so this development will come later with the SA architecture [10].

The technological enhancement is especially evident in case of OFDM (Orthogonal frequency-division multiplexing) which is now delivering a much higher degree of flexibility and scalability [9] and use of wider bands. In frequencies below 6 GHz the bandwidth will be 100 MHz, while mm waves frequencies could enable up to 400 MHz bandwidth [18].

Another important feature for potential aerial use cases is so-called network slicing which means option to divide network to virtual slices/layers with different features deployed.

A.4 mmWaves

Millimeter wave (mmWave) communication systems have attracted significant interest regarding meeting the capacity requirements of the future 5G network. The mmWave systems have frequency ranges in between 24 and 300 GHz where a total of around 250 GHz bandwidth is available. Although the available bandwidth of mmWave frequencies is promising, the propagation characteristics are significantly different from microwave frequency bands in terms of path loss, diffraction and blockage, rain attenuation, atmospheric absorption, and foliage loss behaviors. In general, the overall loss of mmWave systems is significantly larger than that of microwave systems for a point-to-point link. Fortunately, however, the small wavelengths of mmWave frequencies enable large numbers of antenna elements to be deployed in the same form factor thereby providing high spatial processing gains that can theoretically compensate for at least the isotropic path loss. Nevertheless, as mmWave systems are equipped with several antennas, a number of computation and implementation challenges arise to maintain the anticipated performance gain of mmWave systems [2].

Appendix B Validation of Dedicated 5G Network Characteristics

To complement project’s results obtained primarily for 4G network, the evaluation of the performance of the dedicated 5G network infrastructure to assess mainly impact of the network load on communication performance. The measurement campaign took place at the Brno University of Technology (BUT), Faculty of Electrical Engineering and Communication, Department of Telecommunications, namely at the university`s premises, the UniLab laboratory, established in cooperation with the Vodafone Czech Republic, was utilized.

B.1 Network configuration

The installed 5G network at BUT stands for the 5G NSA Option 3x deployment, i.e., the network enables 4G and 5G to share the same 4G RAN, allocating spectrum between the 4G and 5G depending on the connected users.

The RAN part is divided as it consists of the RRU at 800 MHz (band n. 20; FDD), which works as the anchor for the initial connection to the RAN (control plane/signaling). Then, the radio operating at 1.8GHz (band n. 3) is used for the data transmissions (user plane). The example of the UniLab is given in Figure 6. The current antenna configuration is MIMO 4x4.

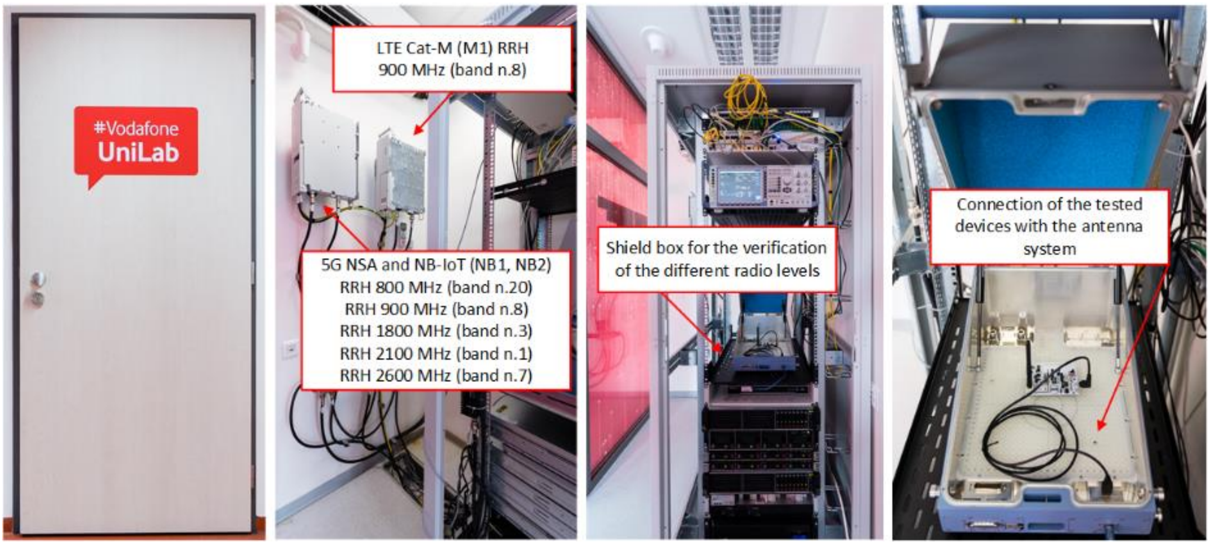

Figure 9: Vodafone UniLab test equipment.

B.1.1 Measurement Scenario

The primary motivation was to evaluate the distribution of the network resources between the connected devices concerning the communication performance and the potential benefits of the dedicated 5G infrastructure against the public one. To this end, the test setup consists of two connected devices: (i) high-performance 5G router Advantech ICR-4453 (link) and (ii) 5G devkit equipped with the Quectel RM502 module (link), which was connected to the Raspberry Pi 3B+ and acted as the primary communication interface (WAN). The critical parameters of the test configuration are summarized in Table 6. As the network is dedicated for testing purposes, only the devices mentioned above were connected, for the scenario of the private 5G infrastructure[5].

Parameter	Value
3GPP release	15
Network configuration	Option 3x (NSA)
RAN configuration	800 MHz (Anchor); 1.8 GHz (user plane)
Total bandwidth	50 MHz
eNodeB TX power	27 dBm
UL data rates (theoretical maximum)	145 Mbps
DL data rates (theoretical maximum)	750 Mbps
Maximum number of connected devices	2
Maximum bandwidth for the device 1 (router)	140 Mbps
Minimum bandwidth for the device 2 (devkit)	0 Mbps
Maximum bandwidth for the device 2 (devkit)	140 Mbps
Range of bandwidth for the device 2 (devkit)	[0 … 140; step 20]
Duration of the test	80 seconds

Table 5: Summary of the network/test configuration.

The configuration of the connected devices for the evaluation of the communication parameters was as follows:

- The 5G router Advantech ICR-4453 was set to generate the data traffic using the iPerf3 tool continuously. Therefore, the data was generated at the transport layer (L4) of the ISO/OSI reference model as the UDP data flow. The configuration was done so that the router utilized the total bandwidth of the RAN.
- The second device (in the role of the mobile device) then connected to the network and started the data transmissions. In contrast with the background traffic generated by the router, the traffic from the mobile device was generated as a time-sensitive multimedia traffic.

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[5] The installed 5G NSA network is within the public Vodafone 5G infrastructure, meaning the RAN part of the network is dedicated to the UniLab laboratory, but the RAN part is then connected to the public Core.

At the time 0s, the router started to generate the background traffic (in the uplink direction), utilizing the total bandwidth, i.e., sending the data at 140 Mbps during the whole test period (80 seconds). At the time 10s, the second device (5G devkit emulating the mobile device) has connected to the network and started to send the traffic at the bandwidth set to 20 Mbps. Since then, every 10s, the bandwidth for the second device was increased by 20 Mbps until the point the second device in the test reached 140 Mbps, i.e., the maximum bandwidth of the cell in the uplink direction. The measured data is shown in Figure 7.

The stepwise increase of the bandwidth for the second device (5G devkit) is noticeable until the bandwidth configuration for the second device reaches 50% of the total bandwidth, i.e., 75 Mbps. Since then, the network has treated both connected devices at the same level, and each device can utilize half of the total network bandwidth. This behavior is true even when the configuration of the second device differs, and the traffic should be handled as the high-priority multimedia stream (in comparison with the traffic from the first device, which is generated as the best effort volume). This is illustrated in Figure 7 by the black trend lines.

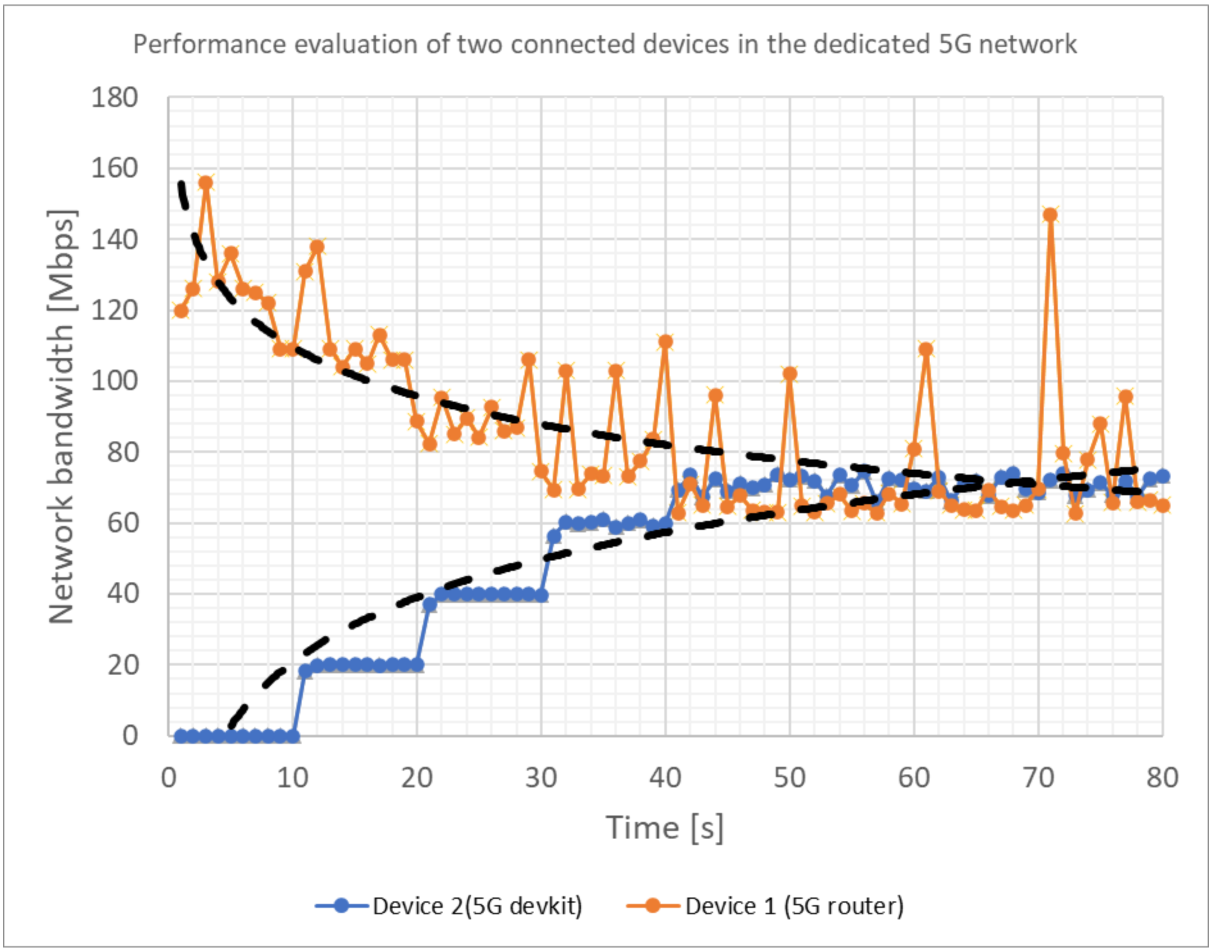

Figure 10: Performance evaluation of two connected devices in the dedicated 5G network.

Because both data transmissions were handled at the same level, from the priority point of view, we have explored how the networks manage the quality of service (QoS), i.e., DiffServ Code Point (DSCP) and Type of Service (ToS) mapping. From the captured traffic on the outbound interface of the second device, it was confirmed that the traffic was marked correctly (DSCP AF31). Nevertheless, on the inbound interface where the data was received, both data streams had the exact mapping, i.e., best effort (default DSCP mark, 0). This information has confirmed the gathered results, i.e., the equally divided bandwidth between the connected devices.

Based on the findings mentioned above, we have also received confirmation from the operator regarding the mapping configuration. The network does not reflect the different QoS configurations at the current stage (in the used network configuration). More precisely, it does not use legacy mapping. As the new 5QI to IP DSCP mapping based on the 3GPP TS 23.501 and RFC 4594 is recommended, it thus seems the network configuration is not yet completed. This fact is confirmed by the measured jitter, see Figure 8.

The value of the jitter increases steadily as the second device (5G devkit) does utilize more network bandwidth. As there is no quality-of-service treatment, the more data is sent, the higher the jitter is for 5G devkit (mobile device).

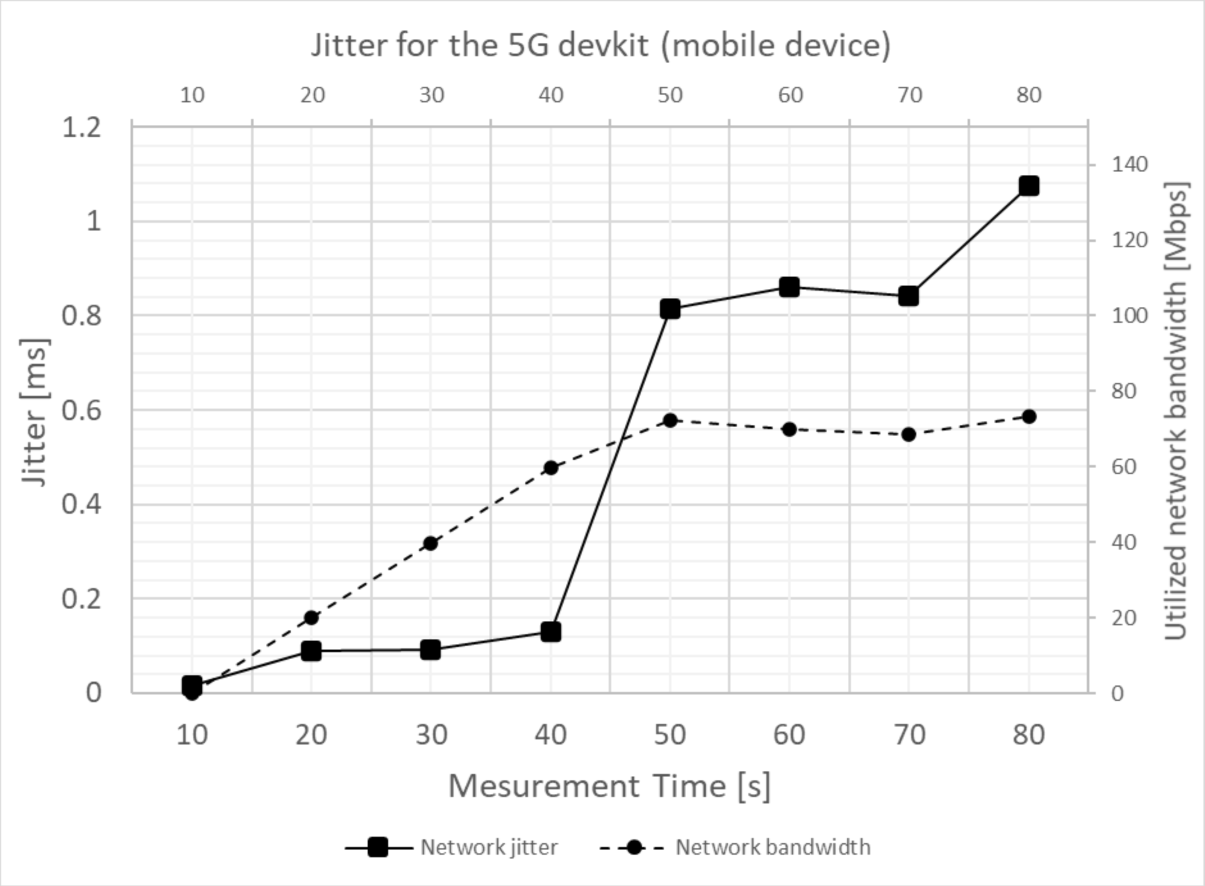

Figure 11: Measured jitter for the second device (5G devkit/mobile device)

The findings related to the jitter are further confirmed by the round-trip time (RTT) measurements. Figure 9 shows the situation where the second device (5G devkit/mobile device) utilizes 10% of the available bandwidth and sends data as the TCP data stream. The peak value of the RTT reached 80 ms as the average value oscillates around 32 ms.

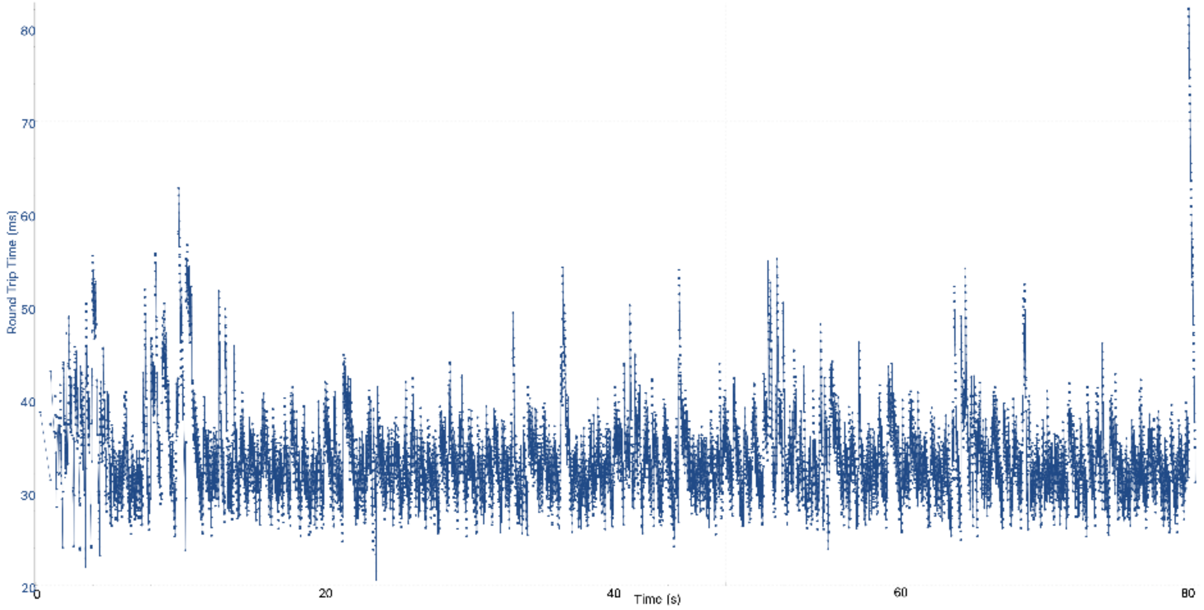

Figure 12: RTT for second devices (5G devkit/mobile device) in case 10% of bandwidth is utilized by that device.

The situation changes dramatically once 50% of the total network bandwidth, i.e., 75 Mbps is utilized by the second device, see Figure 10. The RTT increases to 135 ms at peak and 80 ms on average.

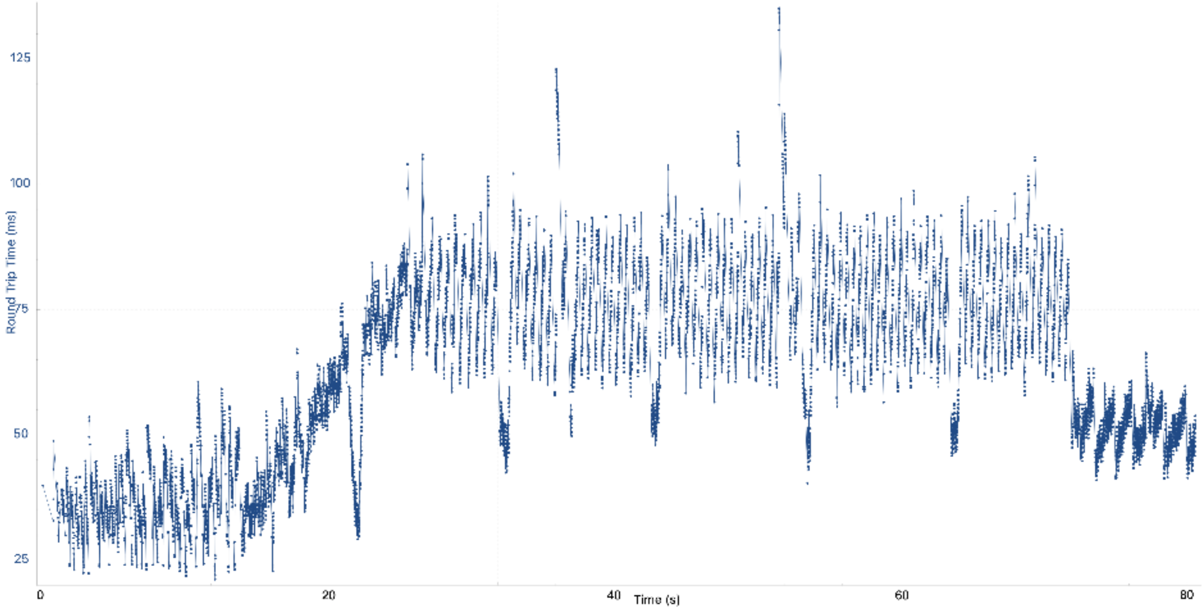

Figure 13: RTT for second devices (5G devkit/mobile device) in case 50% of bandwidth is utilized by that device.

Therefore, the operator's only differentiation and quality of service configurations are related to the configuration of the access point name (APN)[6]. The description of the QoS in 5G is provided in the following paragraph.

B.2 Definition of QoS in 5G Networks

While LTE is mainly designed for broadband applications, 5G new radio is designed for accommodating various applications, including broadband, mMTC, and URLLC, all in a single protocol. So, the QoS architecture is more flexible to provide appropriate service for all those applications. One noticeable difference is in comparing LTE QCI (link) and NR 5QI (link) tables and the length of the tables.

B.2.1 4G vs. 5G QoS

In 4G, LTE QoS is enforced at the EPS bearer level. In 5G, QoS is implemented at the QoS flow level. 4G LTE uses EPS bearers, each assigned an EPS bearer ID. 5G uses QoS Flows, each identified by a QoS Flow ID (QFI). As with 4G LTE, both non-GBR flows and GBR flows are supported in 5G, along with a new critical GBR. 5G also introduces a new concept – reflective QoS. Table 7 reflects the QoS comparison.

Table 6: 4G vs. 5G - QoS comparison.

Parameter	5G	4G LTE
QoS identifier	5G QOS identifier (5QI)	Quality class indicator (QCI)
IP Flow: UE to UPF/PGW flow	QoS flow	EPS bearer
Flow/bearer identifier	QoS flow identifier (QFI)	EPS bearer ID (EBI)
Reflective QoS	Reflective QoS indicator (RQI)	N/A

The QoS flow is the lowest level granularity within the 5G system and is where policy and charging are enforced. One or more Service Data Flows (SDFs) can be transported in the same QoS flow if they share the same policy and charging rules (like an EPS bearer in 4G LTE). All traffic within the same QoS flow receives the same treatment. There are several standardized 5QI values. The table (link), from 3GPP TS 23.501, provides the mapping from 5QI to QoS characteristics.

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[6] This statement is valid for the used network configuration, i.e., 5G NSA Option 3x.

B.2.2 5G QoS Flow Descriptions

5G Network can provide the UE, one or more QoS flow descriptions associated with a PDU session during the PDU session establishment or at the PDU session modification. Each QoS flow contains the following details:

- A 5G QoS Identifier (5QI).
- An Allocation and Retention Priority (ARP).
- In the case of a GBR QoS Flow:
    - Guaranteed Flow Bit Rate (GFBR) for both uplink and downlink.
    - Maximum Flow Bit Rate (MFBR) for both uplink and downlink.
    - Maximum Packet Loss Rate for both uplink and downlink.
    - Delay Critical Resource Type.
    - Notification Control.
- In the case of Non-GBR QoS Flow:
    - Reflective QoS Attribute (RQA).
    - Session-AMBR; UE-AMBR.

B.2.3 5G QoS Flow Characteristics

5G QoS characteristics describe the packet forwarding treatment that a QoS Flow receives edge-to-edge between the UE and the UPF in terms of the following performance characteristics:

- Resource Type (GBR, Delay critical GBR or Non-GBR).
- Priority Level.
- Packet Delay Budget.
- Packet Error Rate.
- Averaging window (for GBR and Delay-critical GBR resource-type only).
- Maximum Data Burst Volume (for Delay-critical GBR resource-type only).

The 5G QoS characteristics should be understood as guidelines for setting node-specific parameters for each QoS Flow e.g., for 3GPP radio access link layer protocol configurations. Standardized or pre-configured 5G QoS characteristics, are indicated through the 5QI value and are not signaled on any interface unless certain 5G QoS characteristics are modified.

B.2.4 5G QoS Structure

The QoS is determined/affected by almost every component involved in the communication between the parties. Still, the significant players determining QoS are those components on the bold lines in the UE + Network architecture shown below. Those components are UE, AN (RAN, gNB), User Plane Function (UPF), and Data Network (DN). Figure 3 illustrates a specific example of QoS flow so you can make more tangible sense of it.

As shown in Figure 11, the user data would flow from a source (DN in this case) and the final destination (UE in this case). Each data packet goes through a specific PDU and Data Radio Bearer (DRB). Within these pipelines can be one or more imaginary flows with different priority levels, data rates, latency, etc.

This imaginary flow is called a QoS Flow. Each QoS flow would eventually be mapped to specific items in the 5QI table. To meet the requirement in the selected 5QI, the network needs to configure all the elements from wireless physical resources through all the physical resources on core network interfaces.

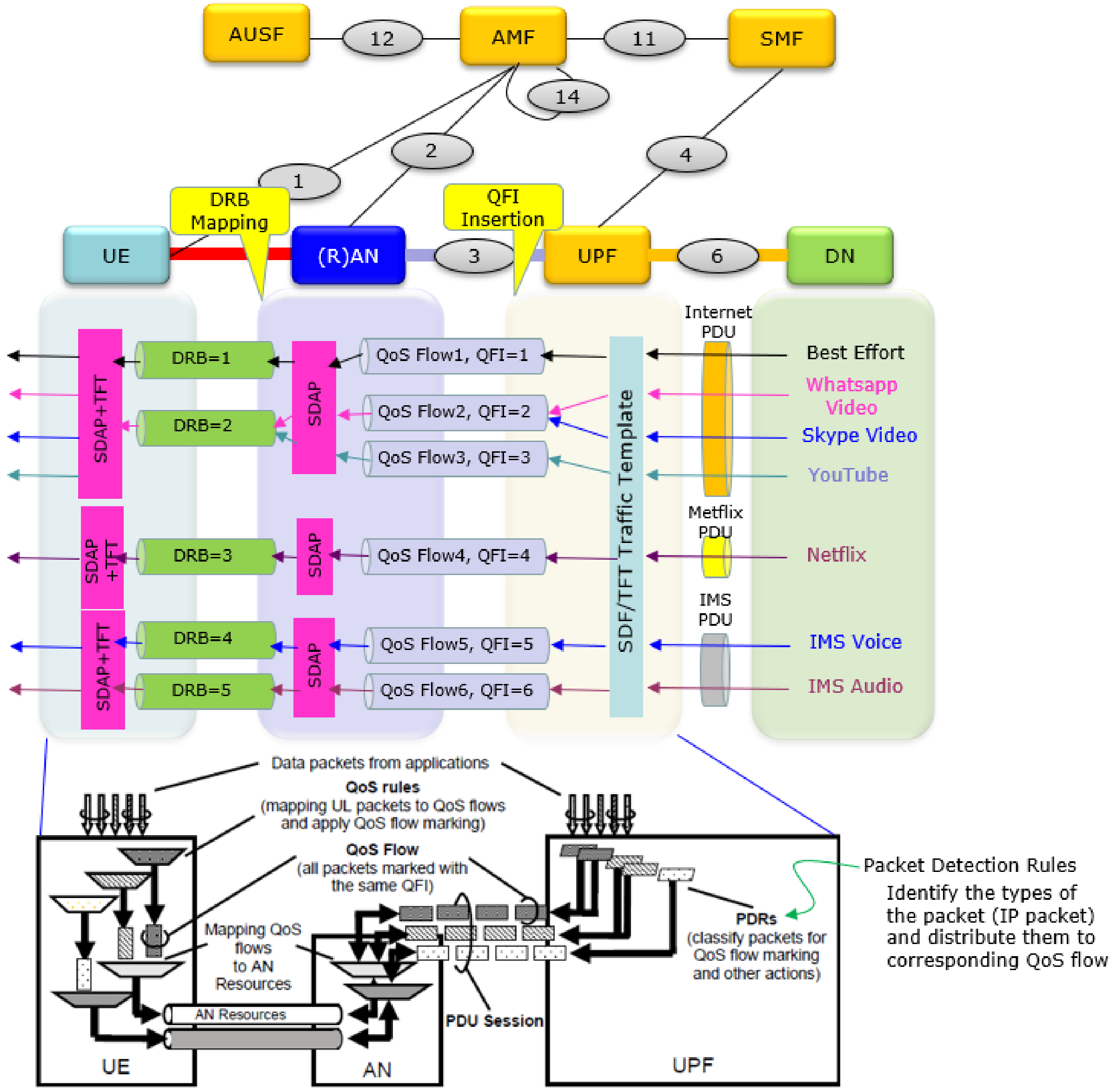

Figure 14: Reconstructed QoS structure based on 3GPP 23.501 (link) and 5G Quality of Service (link)

Appendix C Measurements of altitude impact on network performance (2021)

Measurement of Narrow Band – Internet of Things network that belongs to the 5G family was performed in 2021. Results (provided in detail in the D5.2 deliverables) have shown that that for altitudes above 100 m, service provisioning performed worse due to notably more signal outages, more time spent in ECL2, and overall less stable and less predictable radio conditions. From our observations, the ideal altitude for NB-IoT with the current network setting would be below 100 m depending on the use-case. The degrade of network performance was slightly better than degrade observed during LTE measurements (performed during previous projects). The explanation is in the band width – narrow band is more resistant to interference, but the difference is not significant enough to overcome the limitations.

Generally, it can be said that availability is the key limitation. Latency is not so heavily affected by altitude as throughput.

Point	1				2			3			4		
Height above ground [m]	60	90	120	160	60	90	120	60	90	120	60	90	120
RSRP [dBm][1]	-65	-61	-66	-66	-63	-64	-62	-59	-63	-63	-68	-66	-67
SNR [dB][1]	0	3	-1	-2	3	2	3	5	5	3	-1	0	-3
RSSI [dBm][1]	-53	-51	-53	-51	-53	-53	-51	-51	-53	-52	-54	-54	-53
ECL0 [%][2]	1	1	1	1	0	0	1	40	0	1	1	1	2
ECL1 [%][2]	73	99	49	53	100	100	99	59	100	84	79	88	20
ECL2 [%][2]	26	0	50	46	0	0	0	1	0	15	20	11	68
Number of signal meas.	495	329	418	301	352	273	279	358	434	364	240	397	401

Point	5			6			7			8		
Height above ground [m]	60	90	120	60	90	120	60	90	120	60	90	120
RSRP [dBm][1]	-62	-64	-64	-60	-65	-67	-	-64	-70	-63	-63	-65
SNR[dB][1]	2	1	2	5	1	-1	-	1	-7	2	1	-1
RSSI[dBm][1]	-51	-53	-53	-51	-53	-53	-	-53	-53	-51	-51	-52
ECL0 [%][2]	1	0	0	0	0	1	-	1	0	0	1	0
ECL1 [%][2]	99	85	100	100	100	58	-	98	0	96	82	80
ECL2 [%][2]	0	15	0	0	0	41	-	1	100	4	18	20
Number of signal meas.	328	398	365	325	289	372	-	187	333	356	393	359

Table 7: Measured communication parameters in terms of signal conditions for NB-IoT tester during flight test.

Values in Table 7 show mean values of RSRP, SNR, RSSI per altitude and point. Decrease of such performance indicators values can be observed from table. The most revealing is the ECL parameter evaluating actual performance and establishing one of three ECL categories where ECL 0 denotes normal operation and ECL 2 is the worst case. Each ECL category provides different communication robustness to provide the capability to communicate even in harsh radio conditions with a tradeoff of possible transmission delay. In summary, a device indicating ECL2 means that communication will be possible, but the delay will increase. Rows in table indication ECLs indicate a number of measurement samples in % where devices indicated the corresponding level.