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Mobile Networks' Support for Large-Scale UAV Services

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Abstract: The services based on Unmanned Aerial Vehicles (UAVs) have started to be used in many countries but not on a large scale yet. The paper describes the present status of UAV services and a concept of a solution for large-scale deployment of safe and reliable UAV services that use the 5G network for communication with UAVs. Based on the Standards Developing Organizations and related industry fora activities, unmanned traffic and airspace regulations, especially the commonly supported concept of Unmanned Aircraft Systems Traffic Management (UTM), UAV-related communication requirements and 5G System (5GS) features, we have developed an alternative approach to the integration of UAV and 5GS. The proposed concept includes a set of enablers that can be provided by Mobile Network Operators in order to not only support but also leverage UAV services. As work on many items is still in progress, we identify a list of open issues and challenges and present them at the end of the paper with the main focus on the MNO–UTM provider relationship and safe flights.

Keywords: UAV; UAS; drone; U-space; UTM; 5G; network slicing; business model; business architecture

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1. Introduction

The rapid growth of the Unmanned Aerial Vehicle (UAV) services market is commonly expected around the world (market value raising 15.5% annually from 19.3 to 45.8 billion USD between 2019 and 2025 [1]) due to the huge spectrum of UAV use cases recognized in different economic areas. Thus far, UAV-based services are used for the delivery of parcels (including medical goods), aerial photography, surveillance, agriculture, video transmissions, entertainment, and rescue missions. In Ghana, there were already about 275,000 UAV flights related to the delivery of medical parcels containing vaccines [2]. By May 2020, UPS declared over 3700 commercial drone deliveries of medical supplies in North Carolina, USA [3]. The other notable deployments of drone parcel delivery services include Manna [4] and Wing [5], both conducting over 45,000 and 100,000 flights transporting food or other light objects, respectively. Overcoming the Visual Line of Sight (VLOS) flights barrier by using an omnipresent communication platform, optionally supported by First Person View (FPV)—real-time 360° video for the UAV pilot, can further contribute to the drone market acceleration.

In fact, there are two obstacles related to the large-scale deployment of UAV-based services. The first one is the lack of airspace regulations and tools deployed needed to provide collision-free and safe UAV flights. The second one is the lack of efficient and low-cost communication between UAVs over a large area. Such communication can be provided using a commercial, wireless network. In that context, it is worth mentioning the 5th Generation (5G) network, which has many useful features—the network radio link features (user bitrate, delay) are superior in comparison to Long Term Evolution (LTE). Moreover, the 5G System (5GS) can be customized according to UAV services' needs using Service-Based Architecture (SBA) in 5G Core (5GC) and Network Slicing (NS). These features make 5GS an ideal candidate for connectivity in the Unmanned Aircraft System (UAS) ecosystem. However, some open issues listed in the paper have to be solved yet. There are also open issues related to reliable and collision-free flights of UAVs—specific requirements are already defined, but the work on some of them is still in progress. The majority of5G and UAS integration approaches focus on satisfying the UAV communication requirements without addressing some fundamental issues, such as ensuring needed coverage in the area in which the flight is conducted.

The goal of the paper is to analyze how the 5GS can support UAS in a way that fully exploits capabilities provided by 5GS enablers, including network slicing technology, SBA, and Network Data Analytics Function (NWDAF). First, we have presented the industrial and research activities concerning UASs as well as regulatory requirements, UAS ecosystem communication requirements and relations (Section 2). The overview shows that the overall complexity of UAS-related operations are, unfortunately, very high. Section 3 describes the related work and our remarks on which 5G mechanisms can be exploited to support the UAS ecosystem. Next, we performed a kind of reality check and depicted the current 3rd Generation Partnership Project (3GPP) concept of UAS support by 4th Generation (4G) and 5G networks (Section 4). The concept uses only a few of the mechanisms that are presented in Section 3. In Section 5, we have, therefore, described our approach that is going beyond the 3GPP one by the use of NS and NWDAF. The proposed approach gives multiple benefits. Open issues and future research directions are indicated in Section 6. Finally, Section 7 presents a short summary of the current state of mobile networks' support and concludes the paper.

2. UAS Ecosystem Status

The portfolio of commercial, UAV-based services and target industries is expected to grow in parallel with UAV technology advancement and wireless communication evolution. As of 2022, excluding the military use cases, the typical UAV applications include:

- inspection and monitoring—civil and critical infrastructure inspection (wind power plants, oil and gas infrastructure, and pipelines), energy efficiency and consumption (aerial thermography), surveillance, farming, and forestry;
- mapping and surveying—photogrammetry, natural resources exploration and utilization assessment, mapping of fields and crops in precision farming, etc.;
- spraying and seeding—firefighting, forestation, precision farming, etc.;
- filming and photography—entertainment, archaeology, etc.;
- transport and delivery—retail (parcel delivery), healthcare (transport of medicines, blood, tissues for transplantation), etc.;
- security, search, and rescue—assistance during natural disasters, surveillance of law obedience and enforcement, monitoring of large-scale events and state borders;
- Public Land Mobile Network (PLMN) coverage extension (occasional hovering base stations), collection of data from off-network coverage Internet of Things sensors.

The robustness of potential applications of UAVs imposes diverse requirements regarding communication (cf. Section 2.2) as well as coordination of UAV operations in space and time. Both aspects are thoroughly investigated by the aviation standardization and research organizations with the outcomes described in the forthcoming sections.

2.1. UAV in the Aviation Ecosystem

The expected growth of the aviation ecosystem will be accompanied by the increasing number of drones that will operate in the common airspace. The transition from local to large-scale UAV services imposes several issues and threats regarding the safety, security, and efficiency of UAV operations. The most common risks for UAV flights include mid-air collisions, causing harm to people or property damage, in particular critical or sensitive infrastructure. Moreover, several issues and concerns are raised regarding fair access to the airspace, potential security infringements (e.g., capturing UAVs), etc. To solve the above problems, it is required to advance in the fields of:

- *Risk management:* the methods for identification, assessment, avoidance, mitigation, and accepting risks that can occur during UAV flights;
- *Contingency planning:* defining the steps to take when the risk occurs;
- *Flight traffic management:* enforcement of mechanisms and procedures that allow for efficient management of drones in the airspace, including prioritization of operations, risk mitigation (e.g., caused by battery depletion, UAV malfunction), collision avoidance, etc.

The primary goal of aviation research bodies and standardization organizations is to deliver the set of rules and mechanisms that will address the aforementioned problems and provide the framework for safe, efficient, and secure UAV operations in the shared airspace. The works in the field are conducted by multiple organizations and initiatives. The most renowned bodies, namely International Civil Aviation Organization, Federal Aviation Administration, European Union Aviation Safety Agency, or Joint Authorities for Rulemaking on Unmanned Systems, are committed to developing common UAV regulations within the European Union (EU) and USA territory, respectively.

Currently, the ATM [6] is a platform that governs the airspace of aircraft. Its primary objectives include ensuring safe and orderly traffic flow, providing necessary information to flight crews and handling emergency situations. For that purpose, a qualified group of air traffic controllers cooperates with the flight crews exchanging the necessary information regarding the flight path (aircraft level, details regarding climb, descent operations, encountered issues, etc.). The Air Traffic Management (ATM) is also responsible for efficient airspace and air traffic flow management to avoid congestion and improve the usage of limited airspace resources. It is agreed that the ATM counterpart for UAVs, i.e., the Unmanned Aircraft Systems Traffic Management (UTM), needs to be deployed. Such a solution, defined in [7], will become the foundation for the drone management system real-time airspace monitoring and enable the coordination of multiple UAV operations and interactions between Drone Operators (DOPs) and the aviation authorities. In the EU, the UTM-related research is coordinated by the Single European Sky ATM Research organization that has already funded several projects, including Concept of Operations for European UTM Systems [8], focused on defining the drone ecosystem Concept of Operations; Eurodrone [9] that aims to provide automated and validated cloud-based UTM system architecture; Podium [10] aimed at enhancement of air traffic management efficiency, and GOF USPACE [11], which has developed an architecture for sharing information between multiple UTM systems. The verification of airspace management concepts and already developed UTM solutions are currently ongoing within GOF 2.0 [12] project activities focused on validation of existing ATM and U-space systems and services in a unified dense, urban airspace.

Currently, the EU works on a common definition of the UTM ecosystem, called U-space, to provide a unified approach to airspace traffic management over the EU territory. U-space supports all possible variety of missions concerning all drone users and every category of UAS operations, as defined by the EU Commission Regulation on unmanned aircraft operations [13], ranging from agriculture, inspections, or surveillance to future uses such as automated air taxis. The development of the system is composed of four phases [14], with a gradually increasing number of services related to EU regulations:

- *(U1) U-space foundation services*: support for e-registration, e-identification, and geofencing services;
- *(U2) U-space initial services*: support for the management of UAV operations that include flight planning, flight approval, tracking, airspace dynamic information exchange;
- *(U3) U-space advanced services*: addressing complex use cases (operations in dense areas, capacity management, assistance in conflict detection);
- *(U4) U-space full services*: provision of services integrated with systems supporting manned aviation (ATM), full operational capability of U-space, automation of offered services.

The first EU regulations that establish the rules and procedures for UAVs' operation [13,15] were adopted on 1 January 2021, which also indicates the reaching of the U1 development phase. Currently, the work on the U2 stage is in progress, and new regulations are being adopted by the European Commission. Different Single European Sky ATM Research projects conducted between 2017 and 2020 (i.e., Concept of Operations for European UTM Systems project) have demonstrated and tested a wide variety of services, including U3 services. The most recent outcomes include the work on a regulatory framework for the U-space [16], the considerable extension of requirements for manned aviation that operates in U-space airspace [17], or alterations of requirements for providers of air traffic management/air navigation services and functions in U-space airspace [18].

The envisioned U-space ecosystem [11], presented in Figure 1, is comprised of:

- *Aerial vehicles*—UAVs and manned aircraft;
- *Ground Control Station (GCS)*: the hardware and software used for remote communication and control of UAVs;
- *DOPs*—commercial or recreational;
- *U-space Service Provider (USSP)*, one or more operators of a UTM system handling flight-related procedures in a specific area;
- *Aviation Authority*: an entity responsible for the management of flight information and manned aircraft traffic;
- *Public Safety Authority*: e.g., fire companies, rescue and emergency medical organizations, police, etc.

USSP plays a key role in the facilitation of drone-based services. Its primary objective is the provisioning of information and services substantial for flight operations (flight planning coordination, flight execution, flight control, etc.). Thus far, the following categories of U-space services are distinguished [19]:

- *UAV Identification and Tracking:* services, which enable registration (including registration assistance), e-identification, position reporting, and exchange of surveillance data;
- *Airspace Management and Geofencing:* services providing geo-awareness and enabling management of aeronautical and geofence information;
- *UAV Mission Management:* services facilitating the preparation, optimization, and processing of mission plan, risk analysis [20] and enabling dynamic management of the airspace capacity;
- *UAV Conflict Management:* service group responsible for conflict resolution on a strategic (pre-flight) and tactical (in-flight) level;
- *Emergency Management:* services providing incident/accident reporting (drone pilots/operators, citizens) and DOPs' support during emergencies;
- *Monitoring:* monitoring of navigation and communication infrastructure, gathering of traffic control and all user activities that impact U-space environment;
- *Environment:* services providing information on weather conditions, geo-spatial positioning, electromagnetic interference, coverage (both navigation and communication), or population density in the area of concern;
- *Interface with Air Traffic Control (ATC)*: provision of interfaces and procedural support for communication with ATC entities.

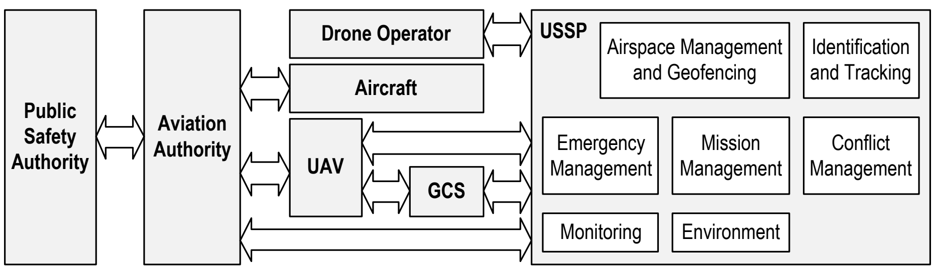

Figure 1. High-level view of the envisioned U-space ecosystem (based on [11]).

UAS needs to coexist with current airspace users. This poses new challenges from an operational, technical, and regulatory point of view (the very low-level airspace until now has rarely been used and has had a low density of operations). One of the key aspects of this integration is the interconnection of U-space services with ATM systems. The PJ34 Aura project [21] has provided a detailed schema of services and information flow between ATM systems (by Air Navigation Service Provider (ANSP)/ATC), U-space services (by USSP), and Common Information Service (CIS) (by Common Information Service Provider). The following actors are considered to be involved in the above processes:

- *Users:* aircraft and UAS operators, pilots, and supervisors;
- *ANSP:* service providers of Aeronautical Information Service, Flight Authorization, Dynamic Airspace Management, and Tactical Conflict Resolution between Manned Aircraft and UAVs;
- *Common Information Services providers:* providers of Drone Aeronautical Information Management, Emergency Management and Network Identification Data services, and Flight Plan Management, responsible for data synchronization between USSPs;
- *USSPs:* providers of U-space services, i.e., the information and mechanisms that support the operation of UTM during flight planning and flight execution phases.

The work on the scope and development of U-space services is progressing. The currently adopted European Commission regulations specify a selection of services originally proposed in [19], which include [22]:

- *Network Identification:* continuous collection of telemetry information (including location) from airplanes and UASs;
- *Geo-Awareness:* propagation of information on airspace restrictions/requirements, which enables strategic and tactical deconfliction (operational conditions, airspace limitations, existing time restrictions);
- *UAS Flight Authorization:* flight plan approval at strategic phase (covering evaluation of flight intent constraints and conditions taking into consideration all available aeronautical information, priorities of other planned missions, appropriate risk analysis and mitigation, etc.), and flight approval at tactical phase;
- *Traffic Information provision:* providing information about any conspicuous air traffic (manned aircraft and UAS traffic) that may be in proximity to the position or planned route of the UAS flight;
- *Weather Information provisioning (optional):* providing weather condition information in the area of concern during flight planning and execution phases;
- *Conformance Monitoring (optional):* checking that ongoing missions comply with the operational conditions, the EU requirements, the constraints of the airspace, and the terms of the UAS Flight Authorization;
- *CIS (optional):* providing a touchpoint for U-space actors to obtain reliable information on operations and situations that can have an impact on airspace, delivered in a timely and synchronized fashion.

The services mentioned above cover only a part of the U2 phase services of the defined U-space development plan [19] and are expected to be further extended in the upcoming EU regulations.

2.2. UAS Ecosystem Communication Requirements

The UAS ecosystem is composed of multiple entities that need to exchange information: UASs, i.e., UAVs and their GCSs, mutually interconnected UTM systems serving the UASs, etc. The wireless network in unmanned aviation has to provide communication related directly to the piloting of the drone itself (the link UAV↔GCS), to its functioning in the aviation ecosystem (mainly the link UAV/GCS↔UTM) and handle communication traffic of drone utility applications. The first two aspects of communication are sometimes referred to as "non-payload" ones, while the last, non-aviation aspect, is called a "payload" one.

The requirements associated with piloting are closely related to the UAV control mode and the nature of its flight, i.e., an increase in the level of the UAV flight autonomy will lower the Command and Control (C2) communication channel requirements. In the reverse direction, the UAV will transmit telemetry data to GCS. While in the case of VLOS or autonomous flights, the FPV feature may be optional, for manually controlled Beyond Visual Line of Sight (BVLOS) flights, it may be mandatory to provide the relevant additional link for the video stream transmission to the GCS pilot.

The fundamental requirement to enable the operation of the drone is providing support for the C2 communication. The C2 link is used to transmit the telemetry data and commands used to manage UAV between the UAV and its GCS. Typically, when UAV services are concerned, the need to establish at least two separate communication channels is necessary (one for C2 traffic and the others to convey use case-specific data, e.g., video streaming). There are some requirements concerning the connectivity parameters (including reliability), security and supplementary services already defined that can be offered by the communication system to UAS. The communication system can provide information about the network terminal's identities, their location, etc. Some requirements concern predictions of radio link quality, position, etc.

In C2 communication for the UAV operation, four basic control modes are considered, where each one is associated with a set of specific requirements regarding message intervals and sizes, End-to-End (E2E) latencies, etc. [23]:

- *Direct stick steering:* the GCS→UAV control message contains direction instructions, while the optional FPV is provided as the feedback from UAV to GCS (used in both direct and network-assisted C2 communication).
- *Steer to waypoints:* the GCS/UTM→UAV control message contains the flight declaration, e.g., waypoints (used in C2 communication in both cases: direct—VLOS and network-assisted—VLOS and BVLOS).
- *Approaching autonomous navigation infrastructure:* the UTM→UAV control message contains direction instructions, e.g., waypoints, altitudes, and speeds; during the landing/departure operations, the UAV is coordinated more closely with the locally available autonomous navigation infrastructure (used in UTM-navigated C2 communication).
- *Automatic flight by UTM:* the UTM→UAV control message contains a pre-scheduled flight plan, e.g., in the form of an array of 4D polygons (3D space dimensions with the dimension of time); UAV thereafter flies autonomously with periodic position reporting (used in UTM-navigated C2 communication).

The non-payload exchange with UTM may concern both UTM and GCS, especially the mobile (hand-held) one. It includes the telemetry data but also the flight management exchange (e.g., airspace traffic control-related commands, geofencing, etc.). In addition, drones can also directly broadcast information about their presence, location, and flight parameters to ambient objects. Payload communication will be closely associated with the specific use case (audio and/or video, still images, cargo control and manipulation, measurement data from sensors, etc.) and the characteristics of the transmitted data (streaming data, burst, and high-volume data, small datagrams with low intensity, etc.).

The 3GPP has performed an analysis and recognizes the communication-related requirements of the UAS domain [23]. The fundamental requirements refer both to the generic data transmission service with specific Quality of Service (QoS) parameters and to the functional support of aviation aspects (non-payload UAS communication) in PLMNs:

- Multiple communication links (for C2, UAS↔UTM, non-mandatory FPV, and UAV use case-specific payload transmissions) with different QoS targets.
- Non-payload connectivity QoS—depending on the control model, the required E2E latencies vary from 10 ms to 5 s, and the supported maximum UAV speeds relative to the ground are between 50 km/h and 300 km/h, and reliabilities between 99% and 99.99%. For the FPV aid in BVLOS flights (more challenging case), the video streaming QoS requirements are 4 Mbps at 720p/30 fps with 140 ms E2E latency and 99.99% reliability.
- Non-payload connectivity through PLMN (UTM↔UAV/GCS or GCS↔UAV in BVLOS) or directly in the Device to Device (D2D) model (GCS↔UAV in VLOS, UAV↔UAV, also cross-PLMN).

- Payload connectivity—the most demanding QoS targets are 120 Mbps (UAV-originated) and 20 ms.
- UAV remote identification and traffic management—association of UAV with its GCS, on-network UAV→GCS/UTM position reporting and local, D2D UAV→UAV broadcasting of the information about UAV's presence (identifier, location, flight azimuth, and speed) for collision avoidance in a small radius (600 m) with a maximum latency of 100 ms, PLMN-based UAV location with the 0.1–0.5 m horizontal and 1 m vertical accuracy and 1 s position estimation latency, and detection of UAVs operating without authorization.
- Service status monitoring—real-time monitoring of UAS links status and performance both for UTM and GCS, monitoring of the UAVs service status in a certain geographical area and/or at a specific time (refers especially to C2 communication).
- Early warning about the risk of communication loss—notification of the GCS pilot or UTM that a UAV is about to leave the 5GS UAS services' authorization space (altitude, coverage area, etc.).
- Security and trust—ensuring the traffic protection of the UAS↔UTM data and their integrity, non-repudiation, and privacy, protection from spoofing attacks of UAS identities.

In [24], the interface that enables the automated exchange of data between Mobile Network Operators (MNOs) and the UTM ecosystem with the goal of improving the reliability of coverage information is proposed. The solution includes exposed network coverage services, general architecture and interactions between stakeholders, the definition of interfaces, and relevant data models (related, e.g., to coverage data, cell information, RAN node location, antenna radiation patterns, etc.).

3. UAS Services Support by 5GS

PLMN can be used as a communication platform to provide connectivity with the required QoS level to UAS in a way agnostic to handled services. The value of the mobile network is wide-area coverage, good transmission properties (low packet loss rate), relatively high reliability, and the low cost of widely accessible network interfaces, which altogether can not only satisfy UAV communication requirements but also improve their operation (e.g., by enabling green communications [25]). The detailed analysis of mobile network features that can be exploited to support the UAS operation on the communication level, together with recent advancements in the field, can be found in multiple studies [26–28]. PLMN can offer even more services and mechanisms than pure connectivity, which can be exploited by the UAS ecosystem. However, such an approach requires deeper integration of both, which has been proposed recently by 3GPP. Moreover, multiple contributions have been provided by academia. In [29], the architecture that enables running multiple UAV services using the 5GS as the communication infrastructure has been proposed, together with its implementation used to perform trials of the selected UAV use cases. In [30], the challenges for the mobile networks in the context of integration with UTM are presented. An exhaustive review of individual studies that concern the usage of 5G and beyond networks for UAV use cases can be found in [31]. Moreover, several EU Horizon 2020 projects have been launched with a goal to exploit future mobile networks for UAV needs, e.g., NRG-5 [32]—devoted to, among others, an aerial inspection of infrastructures using video transmission and 5G!Drones [33]—trials of 12 UAV scenarios in the connected 5G network ecosystem and aviation domain systems for the identification and development of UAS-related enablers as well as validation of relevant 5G Key Performance Indicators.

The generic and simplified vision of the UAS/UTM ecosystem interconnected by 5GS is shown in Figure 2. A UAV with an on-board 5G network terminal, i.e., User Equipment (UE), exploits the communication channels needed for C2 (with optional FPV), connection to UTM and use-case-specific payload data exchange. These channels may be terminated in specific isolated Data Networks (DNs). GCS can be connected through the mobile 5G network or use a direct connection through another wireless technology. For the first case, the UTM channel will also be supplied to provide the UTM with GCS identification and location. 5GS, composed of Radio Access Network (RAN) and Core Network (CN), supports user communication in User Plane (UP) thanks to the control mechanisms implemented in its Control Plane (CP). The CP capabilities may also be exposed to the UAS/UTM ecosystem's actors (not depicted in Figure 2 for simplicity, see further in the text).

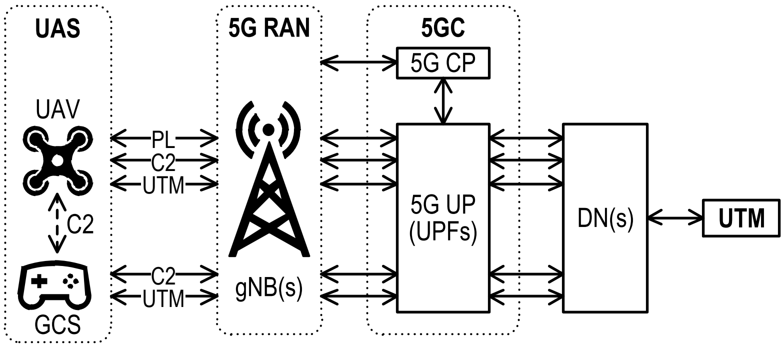

Figure 2. A simplified view on the UAS/UTM and 5GS entities (PL—payload, gNB—5G base station).

3.1. General Characteristic of 5GS

5GS is the latest generation of mobile networks developed by 3GPP. It is already under deployment all over the world. The generic 5GS architectural framework [34] envisions functionalities and mechanisms supporting fundamental UAV requirements by providing communication links satisfying specific QoS needs. Moreover, the inherent capability to program functions enables the implementation of "added-value" services. The essential features of 5GS in the context of UAV support are as follows:

- *CP programmability*, additionally boosted by its SBA, where functional entities expose services as their Producers or discover/consume them as Consumers, within the RESTful framework Application Programming Interface (API) based on JSON—serialization, HTTP/2—application layer, and TCP—transport.
- *UP programmability*, i.e., its flexible composition as a chain of atomic functions to process the UP traffic according to the specificity of the use case or communication service requirements, e.g., firewall, deep packet inspection, selective marking or altering, encapsulation, classification, forwarding or redirection of user traffic, anti-virus protection, parental control, etc.
- *NS* that breaks with the hitherto approach to the mobile network as a universal one in favor of the vision of a "federation" of virtual parallel networks, individually tailored to the specific requirements of the specific supported services but jointly using certain mechanisms, e.g., mobility or user capabilities subscription management. The adaptation to the requirements may consist of a different architecture of user traffic processing in a UP chain for each service class. Thus far, 3GPP has defined the following network slice types [34]: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), Massive Machine Type Communications (mMTC), and two additional Vehicle to Everything (V2X) classes (since the Release 16) and High-Performance Machine-Type Communications (HMTC) (since the Release 17); future extensions are possible. Slice-specific CP functions can be flexibly integrated with 5GS CP, using separation mechanisms of the SBA CP communication bus. As UE may use applications demanding various communication services, the UE ability to attach to multiple slices on-demand has to be supported with proper network-side mechanisms of selection and admission control.
- *Embedded analytics and prediction capabilities* regarding UE (mobility, abnormal behavior, traffic volume, etc.), QoS changes in geographical areas, congestion, observed service experience, and more [35].
- *Location Services (LCS)* [36] framework enabling the provisioning of target UE location information (geographic location, velocity, or civic location), taking into consideration the security policies. The privacy control is enabled by several mechanisms that include, among others, aliases for UE anonymity maintenance, access restrictions by

codewords, whitelisting of LCS clients, etc. In the LCS framework, both UE-assisted and network-based (using RAN node mechanisms) locations are supported.

- *Network capabilities exposure*, which enables the 5GS control and management mechanisms integration with external systems (e.g., of vertical industries). The native mechanisms of CP can be exposed, as well as the special Application Functions (AFs), acting as "embassies" of the Application Plane services, can be hosted by CP.
- *Common Application Programming Interface Framework (CAPIF) [37]*, i.e., a unified northbound interface API framework for 3GPP functions, which allows secure exposure of 5GS CN APIs to external consumers. It also specifies how the third parties can define and expose their own APIs.
- *Service Enabler Architecture Layer for Verticals (SEAL)* enables reusing the core functions and mechanisms already developed by industries in parallel use cases via a standardized framework. The interconnection and inter-service communication has been specified to enable distributed deployments and access [38].

Another technology, which is envisioned to be widely used by UASs, is edge computing. This technology allows the offloading of UASs' computing units and moving the computing-intensive operations to the edge of the network (such as image/video processing). Edge computing reduces the latency and saves bandwidth for systems that would normally transmit a huge amount of data to far remote servers for further processing.

3.2. A Discussion on 5GS Support of Generic UAS Solution

In this subsection, we will discuss how different mechanisms of 5GS mentioned in the previous subsection can support U-space services. The concept of such a solution is presented in Figure 3. The design uses a basic 5GS architecture [34] as its foundation extended with LCS [36] and analytics. To enable UAS support and facilitate deep integration with UTM, some of the native 3GPP 5GS functionalities or mechanisms require modifications or enhancements. The roles of individuals and modifications (if necessary) of network functions and entities essential in the context of UTM integration and UAS support are presented below.

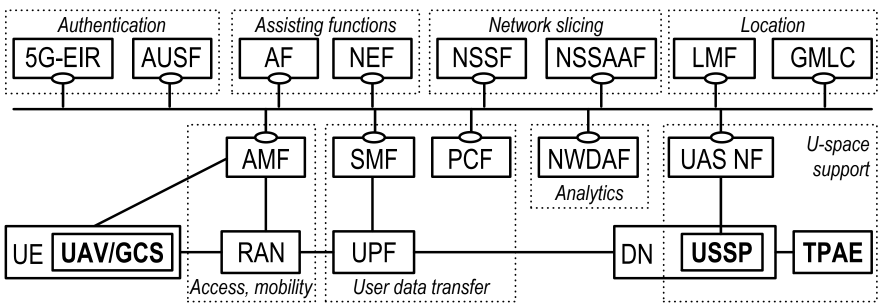

Figure 3. Integrated U-space and 5GS ecosystems based on [34,39].

- *Network access and mobility*—access to network resources is enabled by RAN nodes and the Access and Mobility Management Function (AMF). The most significant RAN mechanisms that benefit UAS refer to proactive coverage improvement [40] by, e.g., beam management (beamforming, beam steering) or massive Multiple Input Multiple Output (MIMO). The AMF is responsible for handling mobility aspects of connected UEs (UAV/GCS) and can be treated as a CP proxy for interactions with UEs and New Radio (NR) (used, e.g., for requesting positioning information based on RAN measurements [41]).
- *Authentication functions*—the primary functions that handle UE authentication are Authentication Server Function (AUSF) and 5G-Equipment Identity Register (5G-EIR). The foremost is responsible for conducting procedures that allow for UE authentication and authorization [42]. The 5G-EIR entity allows the identification of the on-board UE as UAV-capable that can be used during admission or the 5G network registration phase.

- *Location*—UE location services, i.e., LCS, are provided by the Location Management Function (LMF) and exposed by Gateway Mobile Location Centre (GMLC). The alternative source of a precise location of the requested UE (or a group of UEs) can be useful, e.g., for the purpose of validation of location data provided by UAV/GCS or in case of on-board navigation malfunctions. The provided location data can be delivered in a request-response, periodic, or triggered manner and extended by estimations of UE velocity and location accuracy assessment.
- *User data transfer*—User Plane Function (UPF) enables user data flow forwarding in the network under given QoS requirements and its routing to the DN (e.g., Internet access, 3rd party services). The individual UPF and the context of the established data session are managed by the Session Management Function (SMF). The transferred user data is charged on the basis of policies specified in Policy and Charging Function (PCF), which can be implemented with respect to different business models of 5G UAS.
- *NS-associated functions*—they include NSSAAF, which is responsible for the authentication and authorization of the UE that tries to attach to the slice. It can be used to elevate the security of the slice and mitigate the admission of unprivileged UEs. Network Slice Selection Function (NSSF) cooperates with Network Repository Function (NRF) to validate, determine, and select Network Slice Instances and AMFs to serve the requesting UAV/GCS UE.
- *Data analytics*—NWDAF enables the collection of data from all 5GS Network Functions (NFs), processing of the data, and performing analytics and predictions on their basis. It can assist UAS by providing real-time UAS links monitoring, communication loss risk detection, or possible QoS degradation (e.g., due to network congestion), by improving the security of UAS operation, e.g., by the identification of abnormal behavior of connected UAV/GCS UEs. The NWDAF enables triggering UE-specific threshold crossing events, which can assist UAS in the context of risk management procedures.
- *Assisting functions*—3GPP allows the extension of CP by implementing its own functions on the basis of a generic AF. This opportunity can be leveraged by the aviation ecosystem to extend network capabilities to match their specific needs (e.g., enhance admission procedures). The exposure of all network functionalities is performed by Network Exposure Function (NEF)/Service Capability Exposure Function (SCEF).
- *U-space support entities*—communication between USSP and 5GC is facilitated by the Unmanned Aviation System Network Function (UAS NF), which can be treated as the interface and a wrapper of functionalities that may be of interest to the USSP. UAS NF supports functionalities related to UAV identification, authentication, authorization, and tracking, as well as Remote Identification [39]. Moreover, it exposes services of location reporting, presence monitoring, obtaining a list of UAV-UEs in a geographic area, and control of QoS/traffic filtering for C2 communication.

4. 5GS and UAS Ecosystem Integration According to 3GPP

The full support for UAVs has not been provided within 5GS yet. Its first standardization is currently underway as a part of Release 17 [43] and is expected to be one of the major fields for study in Release 18 [44]. Within Release 17, 3GPP has recently proposed a framework that shows how UAV services can be supported at the PLMN level mechanisms (both 5GC and Evolved Packet Core (EPC)) [39] and application layer mechanisms [45] with the use of SEAL. The overall concept applicable to 4G and 5G networks is shown in Figure 4. In the case of 5GS, the support is going beyond pure, service agnostic connectivity offered by the 5G network; however, in the case of 4G, only transparent connectivity is proposed.

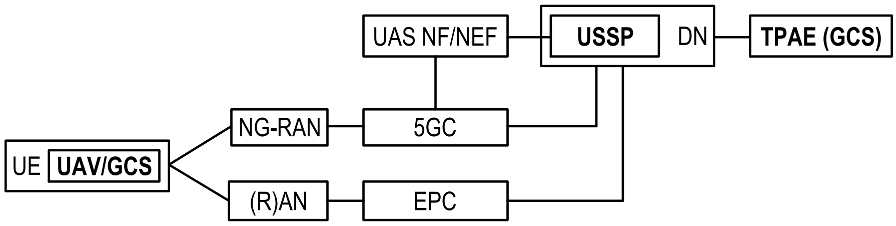

Figure 4. 3GPP framework for 4G/5G integration with UAS (based on [39]).

In both cases, the USSP and the Third Party Authorized Entity (TPAE) (GCS lawfully taking over the C2 or the entity, which gets information on sets of GCSs and UAVs) components of the UAS ecosystem are external to PLMNs and are connected to PLMNs via SGi (EPC) or N6 (5GC) interfaces. Such an approach raises the issues of communication QoS and security (there is no ciphering nor integrity checking in the link between EPC or 5GC and USSP/TPAE).

In the case of 5GS, the SBA approach has been exploited, and a new component, called UAS NF, has been added to the 5GS CP (see Figure 5). UAS NF is used for UAV flight authorization, UAV-GCS pairing authorization, location reporting, presence monitoring, obtaining a list of Aerial UEs in a geographic area and control of QoS for C2 communication. The component supports UAV so-called Remote Identification (Remote ID). The Remote ID functionality is the ability of a UAV to provide identity and tracking information to other parties during flight. The Remote ID may include the Serial Number or Session ID assigned to the UAV, location of GCS, emergency status indication, etc. The UAS NF may also support CAPIF.

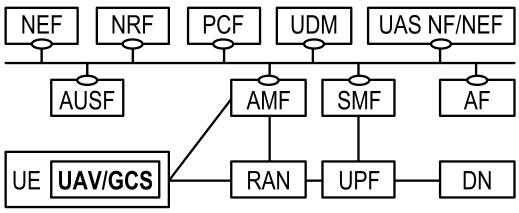

Figure 5. The 5GS non-roaming architecture for a UAV, defined by [39].

Despite USSP being an external entity to 5GS, the 3GPP has introduced a USSP functionality called USS UAV Authentication & Authorization (UUAA), which provides the authentication and authorization of UAVs with the support of EPC or 5GC. UAVs are registered with the USSP either before connecting with the 3GPP system and have an aerial subscription in Unified Data Management (UDM). The UAS NF operations exploit other NFs connected to SBA to obtain their generic services. It concerns UDM, LMF, GMLC (for location and providing a list of Aerial UEs in a specific area), and PCF. It also needs UAS-specific services provided by:

- *NEF:* for authenticated/authorized communication with USSP (an external entity). A NEF dedicated to UAS can be used;
- *AMF:* for triggering the UUAA Mobility Management (UUAA-MM) procedure for a UE requiring UAV authentication and authorization by a USSP when registering with 5GS;
- *SMF:* may trigger the UUAA Session Management (UUAA-SM) procedure for Aerial UE requiring UAV authentication and authorization by a USSP when requesting UP resources or may trigger the authorization of the UAV–GCS pairing or during the establishment (modification) of the DN connection for C2 communication.

Alternatively, the UAS ecosystem can also access the required mechanisms by using a SEAL-based application layer. The expected support involves mechanisms of direct and on-network broadcast communication, network capability exposure, and management related to QoS provisioning [46].

The proposed approach for integration is not complete but solves important problems related to UAS implementation. It ignores, however, some mechanisms offered by 5GS, such as NS or NWDAF, that can be of benefit to UAS operation. Moreover, the approach might require some modification of some 5GC NFs, as additional procedures are introduced (e.g., extensions to AMF, SMF).

5. Network Slicing-Based Approach to 5GS and UAS Integration

5GS offers NS as a solution that enables the programmability of grouped CP and UP components that can be dynamically deployed. NS has a clear borderline between the network and dynamically deployed services. A concept of 5GS UAS support by network slices and NWDAF are presented in Figure 6. For UAS, three slice types are needed: C2 and payload ones (for each type service) per DOP, and the UTM slice that is common for all UAV operations (UAV location is reported here for ATM, also Lawful Intercept). Slice can provide the required QoS per operator (Service Level Agreement can be defined) and allows for the deployment of different templates according to DOP needs. Part of the DOP platform can be deployed as a slice, which can be easily upgraded. Communication mechanisms (including security) with external entities can be done on a per slice basis. Unfortunately, a slice cannot go "beyond" 5GS, which raises issues regarding the maintenance of E2E QoS on the desired level.

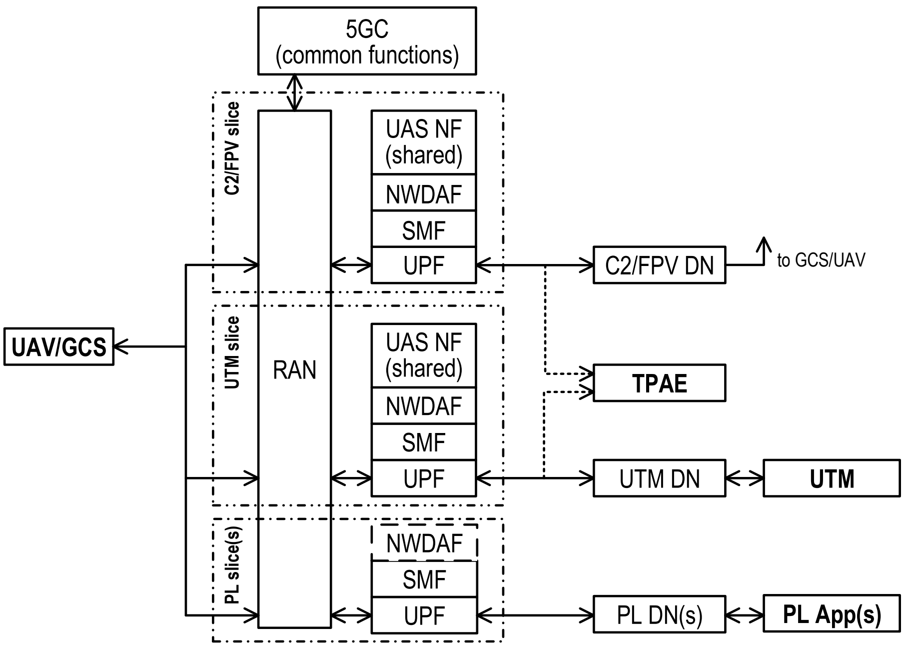

Figure 6. 5GS UAS support by network slices and NWDAF (PL—payload).

NWDAF provides analytics and prediction capability that is essential for C2 operations but also can be exploited by UTM. One of the vital features of NWDAF is the possibility to deploy multiple engines that address specific goals and attach them on a per slice basis. The main analytic capabilities (specified by the 3GPP, cf. Section 3.2) provided by NWDAF, which can be of benefit to the UAS, include data and predictions regarding network coverage quality, QoS and its potential changes, UE abnormal behavior detection, UE mobility analytics, and alerting (handovers, threshold crossings, radio link failures, etc.). To provide the analytic services, the NWDAF can interact with multiple data sources that include 5GS operations, administration, and maintenance, NFs or external data repositories. The provided analytics, however, are generic and do not consider specific needs of the aviation ecosystem, e.g., exposure of coverage prediction in the area of concern for the purpose of flight plan validation. Therefore, one of the major enablers is the UAS-specific NWDAF, which aims to supplement the UTM with the missing data, e.g., by implementing interfaces proposed by Aerial Connectivity Joint Activity [24]. In Figure 6, it is encouraged to attach one or more NWDAF instances to each of the three slices to leverage their operation (optimization, security improvements, etc.).

As the UTM and C2 slices need to be able to access the USSP-exposed services to perform operations described in previous sections (cf. Sections 4 and 3.2), therefore, the shared UAS NF has been attached to UTM and the C2 slice. Each of the slices also exploits the common 5GS CP functions that have been presented in Section 3.2, excluding SMF and UPF, which are instantiated on a per-slice basis.

6. Open Issues Related to Mobile Network Usage for UAV Services

5GS already provides multiple opportunities that can leverage the UAS operation, however, certain challenges still have to be addressed:

- *Lack of direct D2D link* to provide the ability of short-distance direct communication among all the UAVs, including those served by different PLMNs. This type of communication is widely used in aviation to broadcast location/telemetry information. It is also one of the main enablers for inter-UAV communication in UAV swarm. Its standardization is still ongoing within Release 18, named "5G Advanced" [44].
- *UAV support in NR*—while the support of some mechanisms important for UAS support in 5G RAN have already been included up to Release 17 (e.g., RAN slicing, NR MIMO, enhancements of NR positioning and coverage, etc.) [43], the dedicated support of UAVs in NR is only in the scope of Release 18—to be finished in the middle of 2024 [44].
- *Seamless edge applications context switching*—the problem is linked with seamless context switching of edge applications (change of the edge cloud or server). The network should be able to predict handover and forward the whole application's context in advance, e.g., GCS, from one server to another, and to switch between different instances of the applications. However, the time duration of context transfer can exceed the tolerable delay for latency-critical services [47] due to the standardized procedure [48] and virtualization aspects [49,50]. This problem can be solved by giving control over the user context transfer to the application, as described in [47]. Additionally, there is still an unresolved general problem of integration of various architectural frameworks having functional overlaps and hence subject to suffering from the uncoordinated competition of overlapping mechanisms (e.g., 5GS, virtualization, and edge computing frameworks) [51].
- *Lack of sharing of 3D RAN coverage information and network planning itself*—up to now, PLMNs were planned to handle terrestrial communication and were optimized to provide the best coverage at the fixed, average human-height-optimized level. When UAS are considered, they will operate at completely different and variable height levels. The network planning tools as well infrastructure itself (e.g., thanks to the beamforming feature), should be capable of dynamic, case-by-case, adaptation to different coverage requirements (providing the required QoS for different missions). Another aspect of network coverage is the ability to share this information with third parties. Based on the business value of this information, it was common that MNOs were not sharing reliable details of these assets. Now it becomes required by flight planning and flight validation processes: it is a part of risk analysis and risk mitigation to foresee and predict the planned and guaranteed availability of network coverage and quality. This data should be shared at the mission planning stage for DOPs as well as with USSPs to validate the operational flight plans. The data should describe coverage and quality data in 4D (space and time) to confirm given PLMN's quality in a particular time frame corresponding to the planned time of the mission. As of today, however, there exist no interfaces in the 5GS management system that allow for exposing coverage data to external, trusted entities. An exemplary solution to the issues mentioned above is presented in [52], where a function called U-space Coverage Correlation (UCC) has been introduced. The UCC entity is an intelligent, crowd-sensing database that cooperates with MNOs in order to provide reliable PLMNs quality information in each of the flight phases to DOP and UTM.

- *Lack of mechanisms for proactive coverage improvements on demand*, e.g., by UTM during flight execution. Despite the provisioning of low-level mechanisms (e.g., beam management), no interfaces are exposed by the operator to request coverage improvements in the specific area. Such capabilities can be offered, however, by using dedicated RAN controllers, such as Open RAN (O-RAN) that enable the deployment of applications dedicated to RAN optimization. The exemplary UAS-oriented applications include flight path-based UAV resource allocation, radio resources allocation for UAV applications, massive MIMO optimization (e.g., for adaptive beam management to follow UAV swarm) etc. [53]. Moreover, the generic application template has been defined that allows a free extension of RAN controller functions (e.g., by APIs exposure). However, 5GS and O-RAN are not integrated yet, making the cooperation of systems problematic. A proposal to address this issue has been described in [54].
- *Internal roaming for UAS*—significant communication coverage improvements could be achieved by allowing the UAV to connect to any operator providing the best quality of network in the area of concern. To that end, the currently non-existent internal roaming policies regarding UAV-UEs traffic should be established between PLMNs.
- *Cross-border operations*—the paradigms of "Single European sky" (UAVs operations in any EU country, regardless of the country of UAV registration and pilot certification) as well as "free movement of goods and services" in the EU imply the demand for low latency services (FPV 20 ms) in roaming, hence the Local Break-Out (LBO) roaming architecture (alone or hybrid) has to be used. Thus far, although also defined for LTE, it was practically unused due to the problem of home PLMN to verify the reported charging information about the usage of data transmission in visited PLMN, so in practice, only the implementation of the Home Routed (HR) model is encountered. As UAVs, while roaming, may require safe and dedicated communication channels both within the country of operation and to the home country, the mixed LBO/HR architecture may be necessary to be supported with either LBO or HR network slices (e.g., to visited and home UTM, respectively). Special focus should be paid to the problem of cross-border flights, where the continuity of flight control/traffic management, exchange of geofencing tokens, etc., must take place while simultaneously changing (re-selecting and re-registering) the area-specific UTMs and PLMNs. These problems have been described in detail together with proposed solutions in [55], but they are not addressed in the standardization yet.
- *Integrated UTM and PLMN interconnect architecture*—the deep integration of UTMs and PLMNs, especially the joint authentication and authorization procedures (UUAA-MM, UUAA-SM), imposes the need to develop an effective interconnected architecture. While in the case of national roaming, the number of direct interactions between different UTMs and PLMNs operating in the same area is reasonable, in the case of international roaming of UAVs, there will appear interactions between visited and home UTMs/PLMNs. Hence the number of potential bilateral interactions becomes unmanageable. The E2E joint authentication and authorization procedures involving UTM and PLMN in the home country, providing the proof of UAV network and air domains identity, as well as the ones hosting the UAV in the visited country, should be agreed between the UAS and telecommunications Standards Developing Organizations to optimize the interconnect architecture.
- *Lack of E2E security mechanisms*—5GS has a rich set of security mechanisms that can be used for data ciphering, integrity protection, and authentication of nodes as well as UEs. It is also possible to interact securely with other PLMNs and integrate non-3GPP access securely. The security mechanisms of 5GS cannot be, however, extended beyond the N6 interface, i.e., for the interconnection with external DNs. This problem has been partly resolved by additional authentication mechanisms described in Section 4, but a generic mechanism for providing harmonizing security with external data networks and service platforms is needed.
- *Lack of real E2E slices*—the slices offered by MNOs extend as far as the UPF termination point in DN, meaning that the QoS, as well as security measures, cannot be ensured

in the E2E manner as the operator does not control the in-DN routing policies. This issue is especially important in the context of low latency and critical communication, such as C2, where the risk of QoS validation is high and can impact the safety of UAV operations. Moreover, the ensured by 5GS, non-repudiation of data, data integrity, the confidentiality of identities, and other features of interest to UAS are also not guaranteed. To mitigate the mentioned threats, PLMN should reach the USSP services' hosting environment. Alternatively, the PLMNs can host the USSP services on the operator's premise to maintain full control over transmission performance and security.

7. Conclusions

In this paper, the support provided by the mobile networks in the context of large-scale UAV services has been investigated. From the aviation ecosystem perspective, the legislation phase is still in an early stage and satisfies the requirements of the basic UAV services (currently in phase U2 of the U-space development). On the other hand, the 5GS has reached considerable advancements in the context of UAS services, which include QoS enforcement, extended security measures (authentication, authorization), and additional supplementing services and mechanisms (NS, LCS, analytics, network extensions) that can leverage UAS operation. However, the integration of 5GS with the aviation ecosystem proposed by 3GPP raises significant concerns. Therefore, the alternative integration of 5GS UAS that involves all beneficial network-embedded mechanisms (NS, NWDAF, etc.) has been proposed. Nonetheless, several major obstacles remain to be resolved on the operator's side in order to facilitate large-scale UAV services.

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Abbreviations

The following abbreviations are used in this manuscript:

3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
5G-EIR	5G-Equipment Identity Register
5GC	5G Core
5GS	5G System
AF	Application Function
AMF	Access and Mobility Management Function
ANSP	Air Navigation Service Provider
API	Application Programming Interface
ATC	Air Traffic Control
ATM	Air Traffic Management
AUSF	Authentication Server Function
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CAPIF	Common Application Programming Interface Framework
CIS	Common Information Service
CN	Core Network
CP	Control Plane

D2D	Device to Device
DN	Data Network
DOP	Drone Operator
E2E	End-to-End
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
EU	European Union
FPV	First Person View
GCS	Ground Control Station
GMLC	Gateway Mobile Location Centre
HMTC	High-Performance Machine-Type Communications
HR	Home Routed
LBO	Local Break-Out
LCS	Location Services
LMF	Location Management Function
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
mMTC	Massive Machine Type Communications
MNO	Mobile Network Operator
NEF	Network Exposure Function
NF	Network Function
NR	New Radio
NRF	Network Repository Function
NS	Network Slicing
NSSF	Network Slice Selection Function
NWDAF	Network Data Analytics Function
O-RAN	Open RAN
PCF	Policy and Charging Function
PLMN	Public Land Mobile Network
QoS	Quality of Service
RAN	Radio Access Network
SBA	Service-Based Architecture
SCEF	Service Capability Exposure Function
SEAL	Service Enabler Architecture Layer for Verticals
SMF	Session Management Function
TPAE	Third Party Authorized Entity
UAS	Unmanned Aircraft System
UAS	NF Unmanned Aviation System Network Function
UAV	Unmanned Aerial Vehicle
UCC	U-space Coverage Correlation
UDM	Unified Data Management
UE	User Equipment
UP	User Plane
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communication
USSP	U-space Service Provider
UTM	Unmanned Aircraft Systems Traffic Management
UUAA	USS UAV Authentication & Authorization
UUAA-MM	UUAA Mobility Management
UUAA-SM	UUAA Session Management
V2X	Vehicle to Everything
VLOS	Visual Line of Sight

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