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# Mobile Services for Smart Agriculture and Forestry, Biodiversity Monitoring, and Water Management: Challenges for 5G/6G Networks

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**Abstract:** 5G and beyond mobile networks are envisioned as the fundamental components that drive business and societal transformation. The deterioration of the natural environment and climate change have raised questions regarding the role of the mobile network ecosystem and its potential to accelerate innovations in industrial and societal sustainability. This paper describes the challenges facing 5G/6G mobile networks from sectors essential for the sustainable use of natural resources, which include smart agriculture and forestry, biodiversity monitoring, and water management. Based on recent advancements in the above-mentioned domains, the identification of use cases and their requirements are performed together with the evaluation of current and expected future support provided by 5G and 6G networks. Finally, a list of open issues and challenges to be tackled to enable the implementation of carrier-grade services for these sectors using 5G and 6G platforms is presented.

**Keywords:** 5G; 6G; precision agriculture; smart agriculture; smart forestry; biodiversity; water management; sustainability; vertical services; network slicing; UAV; V2X; MIoT; URLLC; eMBB; mMTC; HMTC; sensors; MEC

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## 1. Introduction

Sustainable use of the natural environment is becoming an increasing challenge for humanity. The growth of the world population, degradation of the natural environment, climate change, and geopolitical situation have put increasing pressure on human activity and sectors of the economy such as agriculture, forestry, water management, environmental protection, and the preservation of biodiversity. In these sectors, there has been an observed impact resulting from the obligations of international agreements and treaties, which are then transferred to regional and national legal systems and policies. The geopolitical situation, including military conflicts, and the impact of the global crisis on energy carriers [1] and the food market [2] are additional factors that complicate the situation. Hence, in the above-mentioned sectors, there is a rapidly growing need to increase efficiency [3]. One of the most common approaches is to implement the broadly understood "Industry 4.0" concept with all its underlying components such as Artificial Intelligence (AI)/Machine Learning (ML), Virtual Reality (VR)/Augmented Reality (AR) technologies, and many more [4–6].

This trend can provide business opportunities for Mobile Network Operators (MNOs), especially if associated with state policies and support [7]. This applies to regions with no such investment profitability for operators of hitherto existing technological Public Land Mobile Network (PLMN) solutions, as in highly urbanized areas. New demand should be correlated with other service needs to achieve "critical mass". Otherwise, failure to recognize or correctly estimate needs may result in incorrect investment decisions and losses in the market, where the gaps could be filled by other technologies and market offers.

The foundation is the familiarity of the sectors in focus and their contexts, conditions, needs, and subsequent use cases for communication services. A proper and cost-effective technological response to these needs must be preceded by necessary research, development, standardization, and, finally, implementation. In telecommunications, however, there exists no comprehensive domain-oriented approach that would allow the identification of the sectors in focus and their specific requirements [8]. The scattered approach obscures the picture and prevents MNOs from being well prepared to provide services.

This article addresses the telecommunications industry from research through to the development, implementation, and operation stages. This article's purpose is to present the specificity of the sectors in focus, determine their needs for communication services, analyze how the capabilities provided by the mobile networks (5G and envisioned 6G) can respond to the needs of these areas of growing economic and social importance, and, finally, identify the potential gaps and issues that may hinder the creation of a technological and service offering. Therefore, the point here is, on the one hand, to make a comprehensive reconnaissance of the entire multisectoral area because, so far, its recognition is fragmentary in the telecommunications industry, and, on the other hand, to carry out a reality check of the state of readiness of the field of telecommunications to meet the identified needs. It should be noted, however, that although the authors have the best insight into the European situation (in particular, related to the legal and regulatory system), the challenges presented here are of a global nature, including the impact of the worldwide crisis on the international market of energy carriers, which is intensified by geopolitical situations, global supply chains, and the food crisis affecting Africa and Asia as a result of the war in Ukraine, as well as the global reach of internationally agreed policies related to environmental protection and mitigation of the effects of climate change. In addition, research and experimentation related to the implementation of the Industry 4.0 concept in the sectors in focus are conducted not only in Europe but also in the Americas (e.g., USA, Canada, Brazil), Asia (e.g., China, India, Japan), and Australia.

The structure of the paper is as follows. First, a detailed description of the sectors in focus is presented (Section 2), including the legal, economic, social, and environmental aspects, and their characteristic conditions, processes, and features. Next, based on state-of-the-art works, the generic use-case groups that cover the majority of the applications in each of the sectors of smart agriculture, forestry, biodiversity monitoring, and water management are identified and described (Section 3). Using the above-mentioned groupings, as well as the reviewed research achievements and described solutions' properties, the relevant communication services' requirements are identified in Section 4. Next, Section 5 presents a high-level review of the applications for the sectors in focus that demand capabilities provided by mobile networks and the status of the relevant research advancements, which address the identified needs for communication services. Section 6 is devoted to the presentation of the mobile networks' systems, 5G System (5GS) and 6G System (6GS), including details regarding standardization, supporting technologies, envisioned future capabilities, current technological advancements, and the status of carrier-grade 5GS, as well as already deployed 5G-based solutions in the context of the needs of the sectors in focus. Section 7 describes the applicability of 5GS and envisioned 6GS to the use cases identified in Section 3 using the network feature analysis conducted in the previous sections of the paper. Based on the thorough investigation of standardization and the sectors in focus, multiple gaps and open issues are identified and discussed in Section 8. Finally, Section 9 presents a summary and concludes the paper.

## 2. Characteristics of the Sectors in Focus

To identify and respond to business opportunities properly, it is necessary to have a good understanding of the specifics, context, and conditions of the area of interest. The sectors of the economy and human activity related to the sustainable use of the natural environment in the scope of this paper, i.e., smart agriculture, forestry, biodiversity monitoring, and water management (further referred to as AFBW), are under pressure from various factors (political, legal, social, economic, and geopolitical). They force the smart agriculture, forestry, biodiversity monitoring, and water management (AFBW)s' evolution toward the implementation of Industry 4.0 principles (exploitation of Information and Communication Technology (ICT) solutions operating in real time (RT), AI/ML-based process automation and optimization, etc.). The individual sectors of the AFBW area are presented below.

### 2.1. Smart Agriculture

Smart Agriculture (SmA), also known as Agriculture 4.0 by analogy to Industry 4.0, is based on the earlier concept of Precision Agriculture (PrA), referred to as Agriculture 3.0, but armed with the latest ICT technologies. PrA is based on taking into account the high spatial variability of agricultural phenomena on careful local observation with high-resolution images and ensuring an appropriate local response in contrast to the previous approach (which is still commonly used) in which the average properties of the arable land or crop and uniform agrotechnical treatments are considered. The mentioned local phenomena include the arable land properties (soil type/abundance/reaction, terrain slope/exposure, water conditions, microclimate, the influence of the neighborhood, etc.), conditions of the crop (stage of plant development, degree of plant nutrition, presence of pests or weeds, infection or infestation symptoms, damage from harsh weather conditions or wildlife), and the yield obtained. In response to the above, the agrotechnical treatments may be locally adjusted, e.g., sowing rate, doses of fertilizers and pesticides, etc. [9].

The main difference between PrA and SmA is the integration of machines and devices (which, thanks to electronic solutions, are becoming more and more intelligent) and Information Systems (ISs) powered with AI—especially Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), or Supervisory Control and Data Acquisition (SCADA) systems adapted specifically for agriculture—into one big system that allows data acquisition, storage, and processing and is also used for the continuous monitoring, controlling, and automating of agricultural production processes and making production and business decisions. Since all components in the technical system of SmA are continuously interconnected using wireless communication technologies to provide RT data exchange and form a Monitor-Analyze-Plan-Execute based on Knowledge (MAPE-K) [10] chain, a necessarily quick, multiple factor-based and optimized response to occurring phenomena is possible, which prevents, e.g., losses due to infestation spread or the impact of the temporary underdevelopment of a crop on the yield. Furthermore, SmA support systems can also effectively reduce operating costs by optimizing the use of equipment, transportation routes, and field passages during agricultural treatments (tillage/harrowing, sowing, fertilizers/pesticides application, harvesting) based on arable land geometry, mechanical properties, etc. The first attempts to use robots in agriculture are taking place, but widespread robotization in agriculture is expected during the fifth agricultural revolution to come (Agriculture 5.0). The concept of SmA may be adapted to other kinds of farming, e.g., livestock production or fish farms [11].

The inherent foundation of agriculture from the third generation onward is the use of Geographic Information Systems (GISs). The descriptions of the arable land properties and parameters of crop conditions as spatially conditioned are tagged with geographic coordinates and then processed in the spatial aspect. This also applies to all analytics and treatment parameters (doses of means of production) that are determined to be used. The history of readings, agrotechnical procedures, and harvested crops is also stored in a geo-spatial context. For this to be possible, all devices that perform monitoring and execution processes in the MAPE-K chain (i.e., broadly understood sensors and effectors) must be equipped with devices for reading positions instantaneously with a required accuracy of several centimeters. In turn, the MAPE-K analysis and planning phases are supported by Spatial Decision Support Systems (SDSSs) on top of a GIS underlay.

The necessity of SmA implementation is globally conditioned by the pressures of the following factors:

- *Providing food for the growing population*—from 1800 to the present, the global population has grown from 1 billion to 7 billion, and the estimated population in 2100 is 11 billion [12]; at the same time, the average global life expectancy has grown from 28.5 to 73 years [13]; during the same period, the total global agricultural area has grown from 1.35 to 4.87 billion ha (i.e., an increase of 361%), and further acquisition of the acreage for agriculture would be possible only at the expense of forested areas (impossible due to global environmental protection policies); currently, the arable land needed per unit of crop production represents 30% of that required in 1961 [14] so further growth in the volume of food production can be achieved by its increase in efficiency;
- *Economical availability (affordability) of food*—not only is the production volume important but also the price for the consumer; therefore, it is necessary to increase the cost efficiency of food production, as the room for the state subsidization of it in various countries is limited; one way to enable this is, e.g., SmA-driven productivity growth in terms of both labor and equipment, which could lead to a 20–30% reduction in work time [15], as well as an 85% reduction in pesticide usage and a 10% reduction in fuel usage in agricultural treatments [16];
- *Policies on environmental protection and counteracting the effects of climate change*—an element of the prevention of environmental contamination is the increasingly strict control and limitation of the use of pesticides and fertilizers to avoid their unnecessary or excessive application (e.g., in the European Union (EU) [17,18]); there is also increasing legal pressure to reduce energy consumption, especially from fossil fuels;
- *Energy intensity of agriculture*—both agrotechnical treatments and manufacturing (mineral fertilizers, pesticides, etc.) consume energy (although the machinery consumes mainly oil-based fuels, the chemical synthesis is fueled by natural gas); further increases in agricultural production must not be accompanied by a proportional increase in energy consumption;
- *Crisis on the global energy-carrier market*—sharp increases in the prices set by energy carriers, which were triggered as early as 2021 and then accelerated by the war in Ukraine and its international repercussions (sanctions against Russia, retaliatory measures by Russia), caused a rapid rise in fertilizer prices and a drop of their availability due to the temporary limitation of their production; furthermore, Russia is one of the biggest exporters of mineral fertilizers, which have also been subject to sanctions;
- *World food crisis*—before the Russian aggression, Ukraine was globally the fifth highest exporter of wheat, the fourth highest exporter of maize, and the highest exporter of sunflower oil (about 50% of global exports) [19]; as a result of the war and the blockade of Ukraine's seaports by Russia, there was a sharp drop in food exports, which mainly affected countries in Africa and Asia; additionally, as a result of military operations, there was a significant decrease in the sown area in Ukraine, which will have an impact on the yields of the current and subsequent growing seasons in the event of a prolonged war; as a result of the above, a renewed increase in global migration is expected, especially from African and Asian countries to the EU.

The above-mentioned factors imply the need for increased efficiency in the use of agricultural inputs and the maximization of harvested yields. The capability to fill the gaps in the worldwide food supply and availability, facilitated by the widespread implementation of SmA, will be crucial in the context of global food security.

### 2.2. Smart Forestry

Smart Forestry (SmF) is another specific aspect of the general concept of Industry 4.0, which takes advantage of widespread digital transformation and ICT to automate processes. Forestry has many similarities to agriculture, so SmF can be considered appropriately modified SmA [11]; however, in the case of forestry crops, the time from sowing to harvest is much longer. There are basic differences in the forms of agrotechnical treatments, although an essential element here is also to observe the condition of crops to detect infections or infestations, quickly prevent their spread, and combat them. Moreover, as forests are habitats for many animal species, proper forest management contributes to the conservation and development of biodiversity.

A recently promoted approach is Climate-Smart Forestry, which is aimed at strategies for sustainable forest management in response to climate change. In this context, the additional role of forests is to provide a considerable contribution to global carbon dioxide sinks to meet the goals of international agreements on climate change mitigation. Thus, forest degradation on a global scale should be reduced, which prevents the further obtaining of arable lands at the same time. Although afforestation is considered a forefront response to climate change, acting in favour of carbon sequestration efforts, forest planting alone does not provide mitigation; careful forest planning, establishment, and then management are required [20].

Economic activity in forestry is mainly focused on the production of timber and biomass and their delivery to different forest product manufacturing sectors. Due to the environmental dimensions of forests, this must be done in a sustainable manner, which imposes additional management challenges. Business activities in forestry can be described as follows [21]:

- *Forest management*—forest inventory management of tree stands, silviculture, and plantations, as well as pest and disease control, fire monitoring, and strategic planning and policy making, to ensure sustainable forest management and tactical and operational planning of forest resource usage for harvesting;
- *Harvesting operations*—harvesting planning with environmental, social, and ecological considerations, as well as execution (tree felling, skidding, processing, and sorting) and land reclamation for reforestation;
- *Timber transportation*—road planning and construction, with the consideration of minimizing soil erosion and environmental disturbances; transportation planning; vehicle routing scheduling; loading/unloading; and transportation.

Similar to SmA, SmF is based on ML/AI-driven RT SDSSs founded on GIS. The latter is supplied with land and tree stand mapping and geo-spatially tagged monitoring data.

Finally, it is also necessary to mention the sensitivity of forestry to the previously described problem of the impact of the global crisis on the fuel market due to the high energy intensity of forestry activities and disruptions to the global supply chains of forest-based raw materials as a result of the war in Ukraine and sanctions against the aggressor (before the war, Russia was the fifth highest global exporter of wood with a 6% market share [22], whereas the annual wood export volumes of Belarus and Ukraine were 6.5× smaller, i.e., these three countries contributed 8% of global wood exports [23]). Therefore, there is elevated pressure to increase the cost and production efficiencies of forestry while considering the ecological constraints, which is a serious driver of SmF implementation. Autonomous harvesting and transportation are considered long-term goals in the forestry industry.

### *2.3. Ecosystem and Biodiversity Monitoring*

Activities focused on the protection, restoration, and promotion of the sustainable use of terrestrial ecosystems, the sustainable management of forests, combating desertification, halting and reversing land degradation, and halting biodiversity losses are associated with goal #15 of the United Nations (UN) Sustainable Development policy [24]. The policy has been recognized and implemented at regional and state levels. The Bonn Convention on the Conservation of Migratory Species of Wild Animals [25], ratified by 129 states, is focused on wildlife and their habitats on a global scale through the conservation of migratory species across their ranges. The Bern Convention on the Conservation of European Wildlife and Natural Habitats [26], aiming at the conservation of natural heritage in Europe, has been ratified by 45 European countries and 5 from outside Europe. In response to the Bern Convention, the European Communities (EC) have adopted the Habitats Directive (i.e., the conservation of natural habitats and wild fauna and flora) [27], which requires, i.a., regular reporting and assessing of the status of habitats and species conservation at 6-year intervals. The directive has also established a network of protected and conservation areas across the EU to protect species and habitats, the so-called "Natura 2000" network. The second pillar of the harmonized EU policy dedicated to the preservation of biodiversity is the Bird Directive (i.e., the conservation of wild birds) [28].

Biodiversity monitoring is performed through the collection of information, which allows for the determination of the conservation status of current species and habitats in the context of changes due to various anthropogenic and natural impacts and predicted threats, as well as existing protection methods [29]. In the case of natural habitats, it is related to their conditions and changes, changes in their area of coverage, as well as their structure and function. In the case of species, it is related to the conditions and changes in their range, size, and structure of their populations, as well as the area and quality of the habitats with which they are associated. One of the important aspects of biodiversity monitoring is the detection and response to the threats posed by invasive alien species, i.e., animals and plants that have been introduced (either accidentally or deliberately) into an environment where they normally do not occur. Such introductions have serious negative consequences for their new environment and the native plants and animals found there and cause environmental and economic damage (e.g., to agriculture or forests). When implementing the monitoring, one should take into account the necessity to refine and adapt the methodology for the monitored species and habitats, which implies a wide variety. There are, however, two basic approaches to biodiversity monitoring: in situ and remote sensing [30,31] using satellite- or Unmanned Aerial Vehicle (UAV)-based technologies [32]. It should be mentioned that biodiversity monitoring is not limited to land areas, including inland waters, but also includes seas and oceans. Another element of ecosystem monitoring is the observation of meteorological parameters, as well as air quality, composition, and pollutants (also in urbanized areas with higher spatial resolution). Biodiversity monitoring is also used in cities and suburbs (the aspect of wildlife invasiveness in inhabited areas, especially species that threaten humans).

### *2.4. Water Management*

Water management is one of the components of natural resources management with special environmental and societal implications. It has a direct impact on the preservation of ecosystems, food production in agriculture, as well as the health and fundamental living conditions of humans. The UN's Sustainable Development policy goals include ensuring the availability and sustainable management of water and sanitation for all [33]. Within the EU, the Water Framework Directive has been adopted to establish coordinated action in the area of water policy [34], which commits the member states to achieve good qualitative and quantitative status of all ground and surface water bodies (rivers, lakes, transitional waters, and coastal marine waters up to one nautical mile from shore). The member states are also obliged to develop water management plans for each national river basin district as a basis for making decisions that affect the state of water resources and the principles of their management in the future. These plans affect not only the shaping of water management but also other sectors including industry, municipal management, agriculture, forestry, transport, fishing, and tourism.

An important element of integrated water management is continuous water monitoring, which applies to surface- and groundwater and covers many quality control aspects: biological—fish, benthic invertebrates, and aquatic flora; hydromorphological—river bank structures, river continuity, or substrates of river beds; physical–chemical—temperature, oxygenation, and nutrient conditions; and chemical—environmental standards for river basin-specific pollutant concentrations. The purpose of monitoring is to determine the quality status of water bodies and thus to form the basis for taking the necessary improvement actions. This is the foundation of water protection, especially protection against pollution, including pollution that leads to eutrophication, mainly from the housing and municipal sector and agriculture (biogenic pollution), and industrial pollution. An important constituent of operational water management is also the remote management and operation of hydraulic structures in the water industry, especially in the areas of flood protection, drought prevention, and water supply.

## 3. Use Cases

The identification and relevant characterization of use cases are vital to assessing the service requirements that have to be satisfied by the mobile networks. AFBW require a spectrum of solutions to enable their operation in different timescales and satisfy divergent requirements in terms of Quality of Service (QoS): bandwidth, latency, reliability, and the density of devices in the area of concern. The massive amount of sensor-like components for environmental monitoring, the automation of processes (e.g., SmF operations), and high-speed data transfer (4K video, AR/VR) are fundamental to the majority of the services covering SmA, SmF, biodiversity monitoring, and water management. The dominant direction of data transmission, either downlink (DL) or uplink (UL), should also be noted.

The most challenging aspect, however, is the fact that the AFBW sectors are spatially conditioned. Although urban and built-up land, where the interests and efforts of MNOs are focused, cover an area of 1.5 million km$^2$, i.e., 1.4% of the Earth's habitable land, the agricultural, forest, and freshwater lands encompass, respectively, 51 million km$^2$ (49%), 39 million km$^2$ (37.5%), and 1.5 million km$^2$ (1.4%) [14]. Therefore, the greatest challenge will be to ensure the required QoS in areas many times larger than before.

**UC1 Precise position sensing:** The precise determination of an object's position is crucial in all applications using GIS, especially in SmA (e.g., planning agricultural treatments and then running machinery in rows with centimeter accuracy) [35–37] and biodiversity monitoring (observation of slow spatial migrations, e.g., movement of coastal sand dunes or range spread of a particular species of plants) [38]. For such use cases, the accuracy of several meters typically provided by Global Navigation Satellite System (GNSS) receivers is inadequate. Therefore, the real-time kinematic (RTK) positioning readout correction technology is the most commonly used, which provides an accuracy of less than 3 cm, based on the corrections streamed over IP networks from RTK reference stations [39] using low bit-rate protocols (such as RTCM SC-104 or CMR/CMR+). The frequency of position readouts in GNSS receivers is also important in the case of objects in motion. The typical maximum frequency is 10 Hz, which corresponds with ∼13.9 cm spot spacing at a 5 km/h velocity ("high-end" receivers support 50 Hz so 5× denser spacing). The RT correction of position readouts is highly important [40].

**UC2 Field mapping:** This use case covers the in situ spot measurements of a variety of soil parameters with geo-spatial tagging and includes its electrical conductivity (representing salinity, soil grain size and type, depth of rock, hardly permeable layers, and groundwater), reaction [pH], organic carbon content, and compactness [41–43]. The measurements are typically performed "on-the-go" with time intervals of 1–25 s (based on the specifications and data samples from commercial solutions). Hence, their approximate spatial resolution is 1.4–34.7 m at a 5 km/h velocity and a 10 Hz position sampling frequency. Field mapping is performed relatively rarely, every few months/years [44,45], and the RT aspect of the communication is not critical.

**UC3 Remote evaluation of plants and crop properties:** For the assessment of a plant's health and development stages during the vegetation season, contactless spectral analysis is used, most often in visible light (350–700 nm) and near-infrared (IR) wavelengths (700–1000 nm, and less frequently at 700–2500 nm [41,42,46]). The spectral signatures (i.e., specific shapes of spectral characteristics of a given plant species at a specific development stage) can be used to determine whether a plant is healthy, dying, or dead. The concept is based on the "red edge" phenomenon, i.e., a strong change in the vegetation reflectance at the border of the red and near-IR regions. The observation of plants at high resolution (not only the colors of the visible spectrum but also the way they are distributed on a plant's surface) allows for the determination of their nutritional status, deficiencies of individual nutrients, and identification of infections or infestations.

The assessment can be performed in either active (stimulated reflection) or passive mode (reflection of solar radiation). The former, being daylight condition-independent, is used in low-distance applications (handheld equipment or equipment mounted on agricultural treatment machinery, e.g., on booms of a tractor or cultivation set) to provide instant data that can be used for an immediate local calculation for a relevant response, e.g., a dose to be applied (both readouts and responses are then recorded with a time-spatial stamp). The latter is mainly used in photogrammetry with the assistance of diverse flying objects, among which drones are of importance due to their high achievable resolution (on the order of a single centimeter or less per pixel). Image acquisition is carried out by a set of narrow-band sensors in a specialized camera or RGB visible light channels and the IR channel in simplified solutions. The sets of band images with the necessary high terrain overlap are combined into orthophotomaps and further analyzed with specialized software to produce a map of a specific phenomenon's intensity using various algorithms with different and complementary properties, which is a highly computationally complex process that cannot be performed onsite. Additionally, this technique can be used for field mapping to detect heavy and light mineral soil or peat soil.

In SmA, the use of drones to create orthophotomaps could, in the future, be relatively frequent, at least several times during a growing season. In particular, if an infection or contamination is detected, the rapid assessment of its extent and the immediate action that needs to be taken will be important to prevent the further spread of the phenomenon and minimize the use of pesticides, which will help to reduce losses and production costs and minimize the negative impact on the environment. Therefore, it will be necessary to transmit very-high-volume images from the drone to the SmA IS quickly, without limiting the flight speed for the drone buffer memory overflow avoidance in order to start the data processing as soon as possible and to provide feedback to the staff and equipment waiting onsite.

**UC4 Remote sensing using Light Detection and Ranging (LiDAR):** The LiDAR technique allows precise distance measurements of objects based on the laser impulse propagation time or changes in the wavelength of light. Typically, there are two types of LiDAR sensors: passive, which use measurements based on the reflected sun rays, and active, which utilize their own light source to perform measurements. In the AFBW sectors, the LiDAR technique is mostly used for the evaluation of spatial variability and surface modeling (e.g., creating digital elevation models of catchment/sub-catchment boundaries [47], flood risk maps [48], and the evaluation of forest yields [49]) or the identification of the spatial and specific spectral properties of objects (evaluation of soil composition [50,51], classification of trees [52], forest inventory, 3D modeling of trees [53], and many more). In both cases, LiDAR imaging involves the acquisition of high-volume images, typically on the order of gigabytes (hundreds of megabytes per image file), with the size dependent on the image resolution, applied compression, etc. [54]. In addition, LiDAR sensors are applied to both ground-level and in-air operations, which can imply the need to meet additional transmission requirements depending on the storage and processing capabilities provided onboard a flying vehicle (e.g., UAVs). It has to be noted that both UC4 and UC3 are similar in terms of communication requirements, with the exception of the data processing approach. Typically, LiDAR applications do not require near-real-time data transfer and processing to facilitate real-time decision-making processes (e.g., determining the dose of insecticide or fertilizer to be applied to a plant) as opposed to UC3.

**UC5 Yield mapping:** This is used for the evaluation of agrotechnical treatment efficiency throughout a growing season. The yield and harvesting process parameters depend on the harvested crop and the design of the combine harvester, which contains multiple onboard sensors providing geo-spatially tagged readouts with a 1–5 s resolution [41,42]. The need to continuously transmit yield monitoring data is dependent on the farm size and the requirements of its management model (e.g., centralized RT farm activity monitoring).

**UC6 Stationary or quasi-stationary sensing:** The monitoring of information from stationary or quasi-stationary sensors for various purposes will, in the future, be common in all the AFBW sectors. In SmA, permanently installed sensors can provide insights into the local situation in distant arable lands, e.g., weather stations or soil moisture sensors. In the case of SmF, in order to track forest growth and health, the sensors can be used to monitor environmental parameters, such as air temperature and relative humidity, carbon monoxide and dioxide, wind speed, rain, insolation (illuminance), soil moisture, and temperature, as well as abrupt changes for fire monitoring and prediction parameters such as illuminance (both visible and IR spectra), temperature, and humidity [55]. The specialized sensors can be installed in specific equipment, e.g., pest traps or hidden magnetic sensors to detect the presence of poachers. Environmental monitoring may include the above parameters, as well as air quality indicators. Monitoring in water management [56,57] can include both readings of surface water parameters, e.g., monitoring stations installed in rivers, where parameters such as flow, temperature, oxygenation, reaction, and the content of specific compounds (especially contaminants), and readings from a network of piezometers to monitor groundwater parameters. In smart water grids, the sensors can be used to measure water flow, volume, and losses, as well as water quality. An example of quasi-stationary sensing is the monitoring of vital signs, such as temperature, heart rate, etc., of free-grazing animals in pastures.

The data sources' activity patterns can be application dependent. The extreme will be, on the one hand, sources with a discontinuous and cyclical daily activity pattern, relatively low data rate and volume, sensitivity to delays, and need for retransmission, and, on the other hand, sources requiring highly reliable RT transmission on demand (e.g., fire-alerting sensors). Moreover, sensor networks are usually expected to operate for very long periods of time without the need to charge separate devices. Therefore, it is substantial to incorporate mechanisms that enable data exchange with minimal power input to extend batteries' lifetimes.

**UC7 Mobile object tracking:** The class of object tracking use cases relates to all AFBW sectors and all fields and includes the monitoring of the position and status of vehicles and specialist machinery that perform agrotechnical treatments or work in the forest, wild animals wearing special wildlife collars [32], timber batches or other raw products of the forest industry, and, finally, forestry personnel or those involved in biodiversity monitoring, including national park rangers, forestry and fisheries guards, etc. For the latter, the safety and security aspect is of premium importance because these are jobs associated with a high risk of severe accidents, as well as threats from people who commit timber theft, illegal logging, or poaching.

The tracking function of vehicles and machinery can be associated with specific business purposes, and, when extended with telemetry and telematics [58], the following can be supported: mapping of current and past locations to provide a history of their routes, optimization, and planning; RT reporting of the working mode of equipment, parameters, events, or operators; geo-fencing and limitations on working hours; and remote access to a machine's dashboard, onboard panels, or internal communication bus for diagnostic purposes.

In this use case class, very high centimeter accuracy for the determination of an object's position is not necessary, but the reliability of information transfer is crucial, especially for the safety implications of personnel tracking. Although tracking by retransmitting a position determined by a GNSS receiver will be sufficient in most cases, there may be situations where RT video stream-based tracking techniques may be required.

**UC8 Multimedia streaming and processing:** This group of use cases is associated with a very wide spectrum of needs in all AFBW sectors. It primarily involves RT situational awareness in remote locations (e.g., remote farmlands and pastures, logging zones, hydraulic structures in the water industry including their protection zones with restricted access, and the gathering points of wildlife, e.g., waterholes, watering troughs, mangers, hay racks, etc.), which is provided by audio and video (visible light and thermal cameras) monitoring [32]. Streams, primarily video and, to a lesser extent, audio, can also be processed in order to detect specific events and, if they occur, activate a live transmission for the detection and documentation of illegal activities, e.g., unauthorized access [59], damaging of crops by off-road vehicles or quads, waste disposal in the forest, illegal logging, timber theft, poaching, and illegal fisheries. The application of image recognition methods to video streams can be used for advanced process automation, e.g., recognition of individual farm animals and their behavior analysis, filing/recording, and individualized feeding [60]; species identification [32]; and video/still image series streams from biodiversity monitoring camera traps. Similar possibilities are provided through the analysis of audio streams. Through analysis and comparison with reference time-spectrum patterns, it is possible to analyze bio-acoustic landscapes and identify animal species (especially birds) [32]. Using the same algorithms, it is possible to detect acoustically illegal hunting or poaching, the unauthorized use of chainsaws, machinery entry into forests, etc.

It should be noted that there exist solutions providing local multimedia processing that are able to send notifications about detected events (e.g., acoustic detection of gunshots or chainsaws and the identification of the occurrence of some specific species), thus having low requirements for connectivity and are able to be assigned to UC5. However, mainly due to power consumption and dimension constraints, their processing capabilities, and hence the scope of application, are limited (e.g., a limited number of detectable patterns). Once installed in a low-performance access network, even though they are usually built on re-programmable generic hardware platforms, they do not also offer advanced remote management capabilities, e.g., Over-The-Air (OTA) functional and configuration updates and upgrades of the patterns, databases, etc.

**UC9 Programming of effectors:** Effectors are diverse, electronically controlled mechatronic elements and systems in machinery, which perform specific treatments. They refer especially to the agrotechnical equipment that can be used in agriculture or forestry. The direct remote control of effectors is uncommon. They are managed mostly by specialized onboard controllers, which act according to a defined operation program, which triggers the appropriate effector in a specific location or moment [41]. In the case of machinery supporting autonomous driving during treatments, an effector also refers to autonomously controlled steering according to a map of a treatment route, where an operator is onboard supervising the treatment. The programming of effectors is performed through the upload of a configuration file and is completed without causing significantly noticeable delays in work or downtime, i.e., within a subjectively short time according to a context.

**UC10 Remote control and distributed control systems:** In the water industry, the executive elements of hydraulic structures or smart water grid effectors are part of hydrotechnical systems managed by distributed SCADA systems. In modern SCADA solutions, the central IS does not directly control technical devices, but this is performed via Remote Terminal Units (RTUs), the role of which is played by Programmable Logic Controllers (PLCs) or specialized units adapted to work in the network and managed by a central unit. In SmF, the application of remote control systems is often mentioned in the context of the automation of tree harvesting, where they are used to improve control over a slew of motions of forestry cranes [61,62]. The specificity of the detailed solutions and the dynamics of the managed process imply a requirement for connectivity, but the basic expectation, especially in the few cases where direct control is needed, is the reliability and resilience of data transmission.

**UC11 Drones:** The class of drone applications used in AFBW is part of a much larger area for their potential uses. The specificity of these sectors is conditioned by their spatial characteristics; therefore, Beyond-Visual-Line-of-Sight (BVLOS) flights are of particular importance. An omnipresent communication platform is needed to support the [63]:

- Command and Control (C2) of flights, either directly controlled or performed along a pre-programmed route (programming/correction of the route, in-flight parameter monitoring);
- connection with the Unmanned Aircraft Systems Traffic Management (UTM) system (airspace management, flight coordination—transmission of telemetry data such as the position, azimuth, speed, etc.);

- First-Person View (FPV) for the remote pilot (RT high-definition video streaming from the camera with a 360° viewing angle);
- flight purpose-specific data transmission (so-called "payload data" transmission).

The flights of drones may be associated with:

- photogrammetric or LiDAR data collection;
- situational awareness: crops, pastures, forests, infrastructure, and wildfire monitoring;
- crop pest control by air-dropping pest antagonists [64];
- planting trees [65];
- the eradication of rats by air-dropping pellets with rat attractants [66,67];
- combating invasive plants [68];
- the eradication of rabies in wildlife by air-dropping oral vaccines [69];
- the extension of coverage using base stations carried by drones [70].

**UC12 Communication between vehicles or self-propelled machines:** This relates to the functionality of the synchronous operation of multiple vehicles or machines based on the mechanisms of location sharing, information on the azimuth and ground velocity, and the occasional usage of FPV. In SmA, it can be used for the operation of multiple machines in formation following a human-controlled or even autonomous leader [71–73]. In SmF, in addition to the possible agrotechnical cultivation of land during the reclamation of land for afforestation, off-road truck platooning can be used for the transportation of timber [74].

**UC13 Remote robots:** Remote AFBW robots [42,73,75–78] are based mainly on wheeled or tracked Unmanned Ground Vehicles (UGVs). There also exist underwater or floating solutions [79,80]. There are three basic modes of operation: remote-controlled, teleoperated, and autonomous. The difference between the first two lies in the visual line of sight (VLOS) and BVLOS control, respectively. Although VLOS-operated robots can be controlled using direct wireless links, teleoperated robots are comparable to BVLOS in UC11 (without links to UTM). The operation of UAVs has some similarities to UGVs, although, especially in wooded areas, providing coverage at ground level is more challenging than at drone flight altitudes of up to 120 m. For semi-autonomous robots (ambiance awareness, plant row detection, or driving according to a sowing map with high-precision GNSS positioning), the needs include:

- communication for, e.g., the uploading of work scenarios and updates to the knowledge base (weed patterns, pest presence symptoms, trees or signs of infestations that are found);
- remote computing for offloading the local processing onboard the robot;
- transmission of information (using video streams) to the robot operator or supervisor.

**UC14 Support for field personnel:** To support field workers in the era of Industry 4.0, online access to the supporting ISs is a given, e.g., a personal terminal (tablet) receiving information from a GIS based on the current position (soil property maps and water relations, sown plants or forest inventory, historical records regarding agricultural treatments at the site, previous photos, etc.), enabling the quick familiarization by the staff member of the situation without the necessity of their previous presence onsite. In the future, the wide application of AR technology is expected to enrich observed images with contextual information (e.g., labels of recognized objects and their components, descriptions of their properties, operation schemes, etc.). AR imposes high demands for connectivity and extremely high-quality video streaming in RT, with a maximum latency of 20 ms for good QoS [81] (cybersickness becomes perceptible above 40 ms and significantly intensifies above 75 ms [82]).

A list of the occurrences of the described use cases in particular AFBW sectors is presented in Table 1.

**Table 1.** Use cases by sector.

| Use Case | Sector | | | |
|---|---|---|---|---|
| | **Smart Agriculture** | **Smart Forestry** | **Biodiversity Monitoring** | **Water Management** |
| UC1 | ✓ | ✓ | ✓ | |
| UC2 | ✓ | ✓ | | |
| UC3 | ✓ | ✓ | ✓ | |
| UC4 | ✓ | ✓ | ✓ | ✓ |
| UC5 | ✓ | | | |
| UC6 | ✓ | ✓ | ✓ | ✓ |
| UC7 | ✓ | ✓ | ✓ | |
| UC8 | ✓ | ✓ | ✓ | ✓ |
| UC9 | ✓ | ✓ | | |
| UC10 | ✓ | ✓ | | ✓ |
| UC11 | ✓ | ✓ | ✓ | ✓ |
| UC12 | ✓ | ✓ | | |
| UC13 | ✓ | ✓ | ✓ | ✓ |
| UC14 | ✓ | ✓ | ✓ | ✓ |

## 4. Requirements

The relevant identification of the requirements for each specific use case belonging to UC1–UC14 that have been distinguished in Section 3 is troublesome. It has to be noted that the restrictions are related to the specific application, e.g., the data rate consumed in UC8 will vary depending on the video resolution, frames per second, etc. Therefore, to enable later assessments, the peak requirements of the most common applications found in each use case group have been identified. The analysis has been performed based on the relevant 3GPP Stage 1 documents for 5GS [83–85], as well as applicable scientific papers. It has to be noted that several use cases are not yet well described in the literature or identified by the 3rd Generation Partnership Project (3GPP) standardization groups. Therefore, if non-existent, the requirement assessment has been performed by calculations using the data from the deployed systems or their typical setups. Such an approach has been taken in the case of field mapping, the remote evaluation of crops/plant properties, yield mapping, and effector programming (UC2, UC3, UC5, and UC9, respectively) in which the volume of data produced per hectare of operation has been calculated (based on SmA-specific data sources) and combined with information about how often the data have to be sent to the processing entities to maintain the proper functioning of the system. The details can be found in [58].

The identification of the requirements for each use case includes the traffic intensity, type of data exchange, data rate, maximum latency, and reliability, as presented in Table 2.

**Table 2.** Peak service requirements for the analyzed use cases.

| Use Case | | Parameters | | | | |
|---|---|---|---|---|---|---|
| | | Exchange Intensity | Exchange Type | Data Rate | Max. Delay | Reliability |
| UC1 | | high | stream | 2.4 kbps | — | high |
| UC2 * | | low | burst | ≤1 kbps | — | low |
| UC3 | S1: photogrammetry * | high | burst | ∼Gbps | 200 ms | low |
| | S2: local sensing | low | burst | ≤1 kbps | — | low |
| UC4 | | high | burst | ∼Gbps | — | low |
| UC5 * | | low | burst | ≤1 kbps | — | low |
| UC6 | | low | burst | ≤1 kbps | — | low |
| UC7 | | high | stream | 120 Mbps | ∼ms | high |
| UC8 ** | | high | stream | 120 Mbps | 20 ms | 99.99% |
| UC9 * | | low | burst | ∼Mbps | — | low |
| UC10 | | high | burst | ∼Mbps | ∼ms | very high |
| UC11 ** | S1: C2 | high | stream | 28 kbps | 40 ms | 99.9% |
| | S2: UTM | low | stream | ∼kbps | 500 ms | 99.9% |
| | S3: FPV, video streaming | high | stream | 120 Mbps | 20 ms | 99.99% |
| UC12 ** | | high | stream | 65 Mbps | 20 ms | 99.99% |
| UC13 ** | | high | burst | 1.1 Gbps | 2 ms *** | 99.9% |
| UC14 ** | | high | stream | 0.1–1 Gbps | 10 ms | 99.99% |

* Requirements calculated using sector-specific data-source characteristics [58]. ** Requirements derived from the 3GPP standardization documents [83–85]. *** Achievable in low-area campus networks only.

The first observation is the diversity in the requirements of the use case groups in the case of data rates and latencies. It has to be noted that several use cases also require large data rates in the UL, e.g., UC3, UC4, and UC13. The majority of the use cases need low to moderate reliability with the exception of distributed control systems due to the crucial role played by the UC10 group.

The most demanding use case belonging to UC10 is the real-time control (RTC) smart water grid. In order to enable automated control and maintain the faultless operation of the water distribution system, requirements similar to those for the automation and monitoring of critical infrastructure (e.g., electrical smart grids) have to be met. Ultra-reliable communication, as well as millisecond-order latency, is, e.g., required to regulate and maintain appropriate pressure levels in the distribution system pipes by controlling pressure-reducing valves [86].

To implement accurate object tracking methods (UC7) based on RT video analysis, both the video resolution and frame rate have to be relatively high. According to [87], the accuracy improves with the increase in the video frame rate, resulting in a higher algorithm processing time. Considering the algorithmic complexity (video of only a few frames-per-second is usually used for tracking [87]), process offloading to external processing units can be required. Regarding the required latency, the majority of objects move with relatively low speeds, except UAVs (e.g., SmA/SmF use case of aerial seeding). In such cases, the millisecond-order latency should be ensured to allow the collection of near-RT location data samples (for 160 km/h, ∼20 ms is needed to provide 1 m accuracy). In addition, the reliability of transmission has to be high in order to deliver RT accurate positioning.

The creation of orthophotomaps (UC3) requires a very high degree of image overlap: 30% inter-row and 60–80% intra-row [88]; for a 42.4-megapixel photogrammetric camera with 14-bit coding, 1 cm per pixel, and 80% linear overlap, the uncompressed data volume is about 9.5 gigabytes per hectare per band. In the case of UC4, the volume of data is on the order of hundreds of megabytes per hectare [89]. The required data rate, however, will be largely dependent on the imaging configuration, such as the image resolution or a number of frequency bands in which the LiDAR image is taken (aggregate volume on the order of multiple gigabytes per hectare).

Finally, it has to be noted that the AFBW use cases will be generally implemented in distant rural areas or span very wide areas. To this end, the provision of coverage and connectivity extension to the areas of concern can result in immense costs (building regular infrastructure, networking, provision of computation power, energy supply, etc.) and could be a major obstacle to the implementation of the given use cases.

## 5. Related Works

According to the initial visions of the International Telecommunication Union (ITU), the three fundamental "wide" scenarios of usage for 5GS have been identified and further commonly followed by the industry: Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communications (mMTC), and Ultra-Reliable Low-Latency Communication (URLLC) [90]. However, the AFBW sectors were not indicated among the example applications. The popular and dominating vision of communication services applications for the AFBW sectors, which drives scientific efforts and further start-ups, associates the needs with "low-end" Internet of Things (IoT) sensor networks, i.e., mMTC, and works on different approaches are uncommon. This is most likely due to the pragmatism associated with the current capabilities of the existing networks, which determines the prospects for rapid implementation.

The framework for the radio network planning of nomadic 5G campus networks to automate and optimize the DL coverage of base stations is presented in [91] and targets the altitudes of the receivers relevant in scenarios for the use cases mentioned above (0.1–1.5–3.5 m). An ad hoc 5G network built on a platform of drones [92] provides agricultural IoT data collection from sensors in rural areas with bad coverage. At the same time, the platform's drones can perform remote crop inspections with onboard cameras and sensors. The optimization method for drone-based relay systems that support agricultural robots with URLLC services has been proposed [93]. The described iterative algorithm allows for the determination of the optimal location (especially altitude) of a drone and the beamwidth of the antenna, changing the power, and varying the block length allocations per robot inside the circular cell while aiming at the minimization of the average overall decoding error. In a 1000-cow dairy farm, the system used for image recognition for RT individual dairy-cow monitoring, behavior analysis, and feeding has been developed using drones supported by cameras and communication over a 5G network [60]. An electronic fence composed of a set of 5G-connected cameras enhanced with image recognition is presented in [59], which enables the RT monitoring and detection of unauthorized access to farms to reduce potential damage or thievery.

A fire detection system based on 5G communication using hybrid edge-cloud computing, which applies AI for video-analytic mechanisms, has been presented in [94]. Another approach [95] exploits the tactile internet concept, which provides ultra-low latency with extremely high availability, reliability, and security via mobile edge computing and data transmission over a 5G network, to enable advanced AI-based video stream analysis algorithms for fire detection in uncertain environments with smoke, fog, and snow. A UAV-based platform for forest wildfire detection with onboard laser-ranging, non-contact temperature, and photoelectric sensors, as well as IR and visible light cameras, uses 5G transmission [96]. The algorithms of RT object detection in forests from images acquired by remote 4G/5G-connected cameras have been validated in terms of accuracy and latency [97] within the framework of the 5G Connected Forest project (see below).

A cloud-based multi-modal data acquisition and analysis system for urban waterway monitoring is trialled in [98], in which the sensor data and video streams from the multicamera unit are transmitted via a 5G network. A prototype of a solar-powered floating platform with various water quality sensors and a 4G/5G communication module is developed for RT river environment monitoring in [99]. A trial solution for the dynamic monitoring of coastal water quality around islands using an unmanned surface vehicle with onboard sensors exploits a 5G network for C2 and the transmission of the collected data to the server [100]. A concept for an autonomous underwater robot for invasive weed monitoring and harvesting in lakes, which integrates AI, IoT, and 5G URLLC, is presented in [101].

EU bodies are becoming aware that transformative 5G solutions in agriculture and forestry should not be limited to the IoT and should be leveraged by AR, automation in real time, and teleoperation [102]. Multiple projects dealing with the needs of AFBW have been launched within the EU Horizon program. The IoF2020 project [103] demonstrated five trials (concerning arable, dairy, fruits, meat, and vegetables) in an operational farm environment throughout Europe that showed the applications of IoT technologies in 19 agriculture use cases. However, LoRa and 3G/4G mobile networks were used instead of 5G. The 5G-HEART project [104] delivered trials of healthcare, transport, and aquaculture use cases, such as in-vehicle and see-through situational awareness for platooning (vehicle-to-vehicle (V2V) bidirectional connectivity: 80 Mbps, 99.99999% reliability, 5 ms latency); teleoperated driving (connectivity: 20 Mbps/20 ms); and remote monitoring of the quality of water and fish, and automation and actuation in aquaculture using eMBB, URLLC, and mMTC service slices. The 5GENESIS project demonstrated the support of a drone or agricultural robot with a 5G-connected camera providing crop images to the image recognition system for the detection of weeds, as well as the application of relevant herbicides [105]. The 5G!Drones project [70] integrated the domains of aviation (drone control and traffic management) and telecommunications in some scenario trials, including remote inspection, drone-enhanced IoT data collection, and connectivity extension by an onboard 5G base station. The EU–Korea collaboration, the PriMO-5G project [106], studied the use of 5G communications and UAVs for supporting firefighting operations with immersive videos both for both forest and urban fires. The recently started 5G-TIMBER project plans to conduct advanced, large-scale field trials on 5G deployments in the timber industry. The ETHER project [107] develops the 3D architecture, mechanisms, and technologies of integrated terrestrial/non-terrestrial network to support, i.a., global coverage, seamless vertical handovers, and unified terminals, also handheld, even in such safety-critical applications like airborne operations.

In the United Kingdom, the 5G Connected Forest project has been initiated as part of the 5G Testbed and Trials program [108]. It is aimed at the assessment of the 5G application potential for the historical site of Nottinghamshire's Sherwood Forest area. The project is focused on three research areas: visitor economy (5G-enabled applications to support forest visitors, including AR and multi-media content delivery), robotic environmental management (airborne and ground robotic forest rangers, forest management systems, forest health-sensing systems), and skills and innovation (adoption of 5G technologies to stimulate the economic growth of Nottinghamshire).

Mobile network alliances have used various approaches. The Global System for Mobile Communications Association (GSMA) targets AFBW in multiple documents. In SmA case studies, the IoT in agriculture is presented for the promotion of 4G NB-IoT Radio Access Technology (RAT), featuring low data rates and high latency [109], and the application of 5G services for autonomous agriculture robots performing the selective application of herbicides is described, where the image data captured by the onboard cameras are sent to a cloud-based edge computing server for AI-based weed recognition (entire decision cycle lasts $\sim$250 ms, including 20–25 ms for data transmission; peak UL data rate 120 Mbps) [110]. In the report dedicated to natural resources management, three opportunities for MNOs are identified: open AI toolkit support, ecosystem services payment support, and IoT demands up-scaling support [111]. According to the GSMA, the water management issue can also be addressed by IoT technologies [112]. However, there are programs, such as "AgriTech" and "ClimateTech", that have been initiated by the GSMA. 5G Americas is technology-oriented, and AFBW or their associated needs are listed as customers of massive-scale

IoT networks (forestry and farming, both crops and livestock) [113], time-critical services (agriculture, forestry) [114], smart-grid support (water management), and the integration of Non-Terrestrial Networks (NTNs) with 5GS (agriculture) [115].

## 6. Mobile Networks

A mobile network is an attractive candidate for a uniform communication platform for AFBW. Although competitive RATs exist (e.g., WiFi, LoRa, Bluetooth, etc.), they have significant drawbacks that limit their applicability. Their main disadvantage is their operation in the commonly used unlicensed Industrial–Scientific–Medical (ISM) bands in which there is no protection against interference from other devices operating in the same band, i.e., the transmission reliability cannot be guaranteed, especially in the case of RT applications with an impact on safety. Most of these RATs provide small transmission ranges, and, in addition, the achievable range competes strongly with the offered data rates. Access control and privacy features are limited. The user typically needs to act as a network operator, especially to ensure coverage in the area of operation. Hence, competitive ISM RATs cannot individually support such a wide variety of needs as those listed above.

The pre-5G mobile network technologies (2G, 3G, 4G) were designed as general-purpose ubiquitous mobile networks with a uniform architecture. With 4G, there was a paradigm shift–the implementation of the "All-IP" principle and the separation of IP-based network access from services built on top of it. However, even in 4G networks, the user plane (UP) still consists of continuous tunnels from user equipment (UE) terminated at the central point of the network, and possible customization takes place at the junction of the mobile network and the Internet (so-called "SGi LAN"). The already impressive performance provided by the latest 4G releases (LTE Advanced PRO), which includes up to 2 Gpbs peak data rates and latency below 10 ms, did not enable it to address the requirements posed by the emerging and advanced use cases. The primary reason was connected with the systems' designs, which limited the capabilities regarding the customization of services and, in effect, the enforcement of the diverse QoS requirements of the network. Consequently, the above-mentioned performance can be perceived as a best effort. Since the early days of 5GS, the need for adaptable connectivity has become a major target. The 5GS fundamentals were introduced in the preliminary vision of the IMT-2020 [90] proposed by the ITU. The document outlined the need for future PLMNs to be adaptable to specific communication requirements originating from the three main scenario groups that would be at the core of future industries and services, namely eMBB, URLLC, and mMTC. Moreover, a large performance boost has been promised to address the needs of the future digitized society and leverage business with a focus on vertical industries. The 3GPP standardization follows this approach, aiming to deliver customizable network services with up to 10–100× performance improvements in comparison to 4G (described in Section 6.1). It is expected that 6GS will follow in 5GS' footsteps and introduce further technical improvements, as well as higher flexibility (see Section 6.2). It has to be noted, however, that with the progressing standardization within Releases 18 and 19, the full scope of 5G capabilities has not yet been established and can be widely extended until the arrival of the first 6G specifications. The 6G study documents are estimated to be a part of Release 20 and arrive at the end of 2025 [116].

### *6.1. 5GS Capabilities*

The generic 5GS architectural framework introduced by 3GPP [117] envisions multiple functionalities and mechanisms that enable not only the provision of communication satisfying the diverse and specific QoS requirements but also provide added value. The primary network features that can bring benefits to the vertical industries are described below.

**Performance and QoS control**: The main peak 5GS performance indicators include data rates of up to 20 Gbps, latency reaching 1 ms, up to a million devices per $km^2$, and very high reliability and support for objects moving at speeds of up to 500 km/h. The specific QoS targets can be enforced on the UP level by assigning the user data traffic a relevant 5G QoS

Identifier (5QI)—the identifier associated with a set of QoS parameters (communication type, priority level, delay, errors, etc.) [117]. So far, 32 different standardized categories have been specified by 3GPP, but the list can be dynamically extended by an MNO for private use if needed.

**Programmability**: The 5GS architecture design incorporates softwarization, virtualization, Software-Defined Networking (SDN), and other cloud-native approaches as the basis for operation. This facilitates the programmability of both the Control Plane (CP) and UP. The CP functionalities can be extended by any Network Function (NF), e.g., generic Application Functions (AFs), as long as compatibility with the Service-Based Architecture (SBA) is provided, i.e., communication with other CP NFs using RESTful Application Programming Interfaces (APIs), JSON serialization, usage of HTTP/2 in the application layer, and TCP for transport. The UP operation can be enhanced by chaining atomic functions that improve UP traffic handling with regard to use-case specificity or service requirements. Example extensions involve deep packet inspection, firewalls, selective marking or altering, packet classification and encapsulation, anti-virus protection, parental control, traffic forwarding or redirection, etc.

**Network Slicing**: Network Slicing (NS) is a concept that allows the creation of a "federation" of virtual parallel networks over a shared infrastructure, with each network tailored to the requirements of the specific supported services (joint usage of certain mechanisms, e.g., mobility or user capability subscription management). At present, there exist five network slice types defined by 3GPP [117], with future extensions possible, namely eMBB, URLLC, Massive Internet of Things (MIoT), Vehicle to Everything (V2X) (since Release 16), and High-Performance Machine-Type Communications (HMTC) (since Release 17). The adaptation to the requirements can involve the integration of slice-specific CP functions with 5GS CP (using SBA CP communication bus-separation mechanisms) and slice-specific user traffic processing chains (individualized traffic operations, e.g., flow duplication for URLLC to improve reliability). The necessary support for slice selection and admission control has to be provided on the network side, as well as the UE side, to enable the on-demand attachment to one or multiple slices.

**Integration of third parties with 5GS Core Network (CN)**: The 5GS CP incorporates multiple mechanisms that facilitate the network capabilities' exposure, integration with external entities, and reuse of already deployed functionalities among multiple stakeholders. Firstly, the 3GPP functions implement a unified northbound interface API framework, i.e., Common Application Programming Interface Framework (CAPIF) [118]. The adopted framework enables the secure exposure of the 5GS CNs' APIs to external consumers and standardizes the exposure of the third parties' APIs to the 5GS CN. The Service Enabler Architecture Layer for Verticals (SEAL) framework provides the means for sharing already developed core functions and mechanisms among the industries implementing the parallel use cases. It standardizes the interconnection process and interservice communication in order to enable distributed deployment and access [119]. Finally, a Network Exposure Function (NEF) provides the mechanisms for the network capabilities' (e.g., native CP mechanisms) exposure for integration with external systems. In addition, to tighten the integration, the special AFs, which act as mediators for the Application Plane (AP) services, can be deployed to cooperate with the CP NFs.

**Network coverage**: The 3GPP standardization process of 5GS has reached maturity and the technology is currently being intensively deployed across the world. In the case of the EU, it is estimated that in total, around 72% of the EU population already has access to 5G network services [120]. With wide network coverage, it is possible to deliver specific services in a cost-efficient manner, i.e., without heavy infrastructural investments. However, as the majority of the population inhabits urbanized areas, the actual network coverage in rural environments can be very limited or non-existent. In such cases, coverage improvements [121] can be carried out, to a certain extent, by MNOs via innate 5GS Radio Access Network (RAN) mechanisms such as beam management (beamforming, beamsteering) or massive Multiple Input Multiple Output (MIMO).

**Additional support**: 3GPP defined multiple NFs and CP services that can bring additional benefits by improving the operation of network slices. The major functionalities include:

- *Data analytics*—An Network Data Analytics Function (NWDAF) gathers and processes data from all 5GS NFs to perform analytics and predictions in eight categories [122] related to the slice load level, observed service experience, NF load, network performance, UE, user data congestion, data congestion, and QoS changes. Some examples of the information that can be provided by an NWDAF include predictions of QoS changes in geographical areas, QoS degradation and risk of communication loss, UE mobility, UE abnormal behavior identification, and many more [123].
- *Location services* [124]—Location Services (LCS) enable the provisioning of the location data of specific UE, maintaining data security (UE anonymity, access using codewords, LCS client whitelisting). The location information can be obtained using UE-assisted and network-based (using RAN nodes) mechanisms and can include the velocity and geographic and civic location of the UE. However, the 3GPP system assumes achieving a maximum location accuracy equal to 0.2 m (horizontal and vertical plane) under very strict conditions regarding the distance between the localized objects and 5GS positioning nodes [83]. The most common scenario (for rural and urban environments) enables a 1 m horizontal and 2 m vertical accuracy with a 95% confidence level. Therefore, in more demanding use cases, which require centimeter-level accuracy, other localization technologies should be used such as RTK.
- *Security*—5GS provides authentication and authorization capabilities via special dedicated NFs, which enable high-grained control over the admission of individual UEs to the network and specific network slices, also with the involvement of the third parties' ISs through the exposed CP API. Moreover, the 5G-Equipment Identity Register (5G-EIR) entity enables the verification of devices registered on the network and the mitigation of issues caused, e.g., by missing device capabilities, unprivileged access (using stolen equipment), etc.
- *Mobility*—The mobility aspects of connected UEs are handled by the Access and Mobility Management Function (AMF) entity, which is also a signaling proxy for interactions with UEs and New Radio (NR), e.g., to provide location information based on RAN measurements [125].
- *UE energy saving*—5GS provides multiple mechanisms that enable battery-saving support on the UE side. The most important ones include Discontinuous Reception (DRX)–a terminal that is in the active state only for the data transmission; scheduler-level mechanisms, such as cross-slot scheduling (sending data in between control channel messages) or grant-free access (skipping transmission channel allocation procedures); and paging mechanisms (early paging indication and UE sub-grouping, allowing a decrease in false paging alarms), as well as mechanisms allowing for small data transmissions in the uplink while in an inactive state (in channel-access procedures) [126,127].

**Edge computing**: Tight integration of 5GS with edge computing platforms, such as European Telecommunications Standards Institute (ETSI) Multi-Access Edge Computing (MEC) [128], enables the offloading of efficient computations by forwarding the computationally intensive operations to the local compute units close to the RAN nodes (e.g., AI-based image and video processing) instead of transmitting the data to remote servers. In addition to considerable bandwidth savings, it enables latency reduction due to spatial proximity between UEs and edge applications.

### *6.2. Evolution Toward 6G*

Currently, with 5G commercial networks already being deployed, both industry and academia are already starting to work on the definitions and capabilities to be offered by 6GS. The major 6G Flagship project [129], coordinated by the University of Oulu, has already been launched. Its primary goals revolve around the work on key 6G technology enablers, the deployment of the nationwide testbed, the trialing of demanding vertical applications, and the pioneering development of the 6GS vision based on the recent market and technological trends. The early concepts envision the process of evolution from 5G to 6G as a transition from "connected things" to "connected intelligence" due to the deep integration of AI in the network, accompanied by global connectivity and support for larger numbers of devices. The expected key capabilities of 6G include [130]:

- *Increased performance*—Operation in a higher-frequency spectrum in sub-THz (cf. Figure 1) and potentially THz bands, together with enhancements of the resource scheduling mechanisms, will enable the provisioning of data rates of up to 1 Tbps [131] to network users. Moreover, due to the projected technological improvements, 6GS will target latencies below 1 ms in CP and below 0.1 ms in UP [131], exceptional reliability (frame error rate below $10^{-9}$), and 10× higher spectrum efficiency than in 5GS (capacity growth) [132].
- *Ubiquitous availability*—6GS is envisioned to support worldwide service availability by tight integration with NTN (satellite systems, airborne platforms, etc.) and support for nomadic cells. The currently ongoing standardization efforts regarding the integration of 5GS with NTN systems (focus on architectural design and coverage and availability extension) are considered to be the initial step in unleashing the full potential of the unified terrestrial and satellite ecosystem [133].
- *Robust communication*—Highly flexible, coherent, and ultra-reliable services will be facilitated by a newly redesigned CN that will be built according to "software-only" paradigms. The new approach will contribute to the aspects of network scalability and mobility support by adapting cloud-native service state sharing and migration.
- *Heterogeneity of infrastructure owners*—The improved security and trust mechanisms with support for deterministic QoS and governance in multi-administrated environments are expected to facilitate network deployments on multiple administrative domains. This will allow for capitalizing on the cloud and edge infrastructure providers, leveraging the availability of network services.
- *Sustainability*—By exploiting AI-driven optimization techniques and reducing network overhead, the reduction of the carbon footprint of mobile networks both on the network side and the UE side is planned.
- *Ultra-precise positioning*—Due to the operation in higher THz bands, 6G-based localization techniques will enable finer spatial and temporal resolution. Moreover, it is expected that RAN nodes will support ultra-massive MIMO that can also contribute to finer angular resolution in Angle of Arrival (AoA) localization methods. Altogether, a precision of 1 cm in 3D is targeted as an ultimate goal.
- *Support for a very large number of devices*—The adoption of advanced RAN mechanisms, such as massive MIMO, as well as complete RAN reorganization toward cell-free networks, is expected to allow a supporting device density of up to $100/m^3$ [134]. Moreover, solutions that support low-energy or battery-free IoT devices are planned to be incorporated such as Intelligent Reflective Surface (IRS)—a massive number of reflecting elements that allow for the achievement of high passive beamforming gains [135].
- *Advanced cognitive insight*—The adoption of AI-based mechanisms, enhanced localization, and sensing will allow for more accurate predictions regarding UEs and network events. The more precise knowledge and advanced deep integration with AI can further contribute to network management and orchestration of automation and optimization [136].

The 6G network is expected not only to fulfil unmet 5G promises but also to pave the way for the next generation of use cases. To this end, several new service classes that target more specialized use cases are being proposed, such as Human-Centric Services (HCS), Multi-Purpose Services (MPS), reliable eMBB, Mobile Broadband Reliable Low Latency (MBRLLC), or Massive Ultra-Reliable Low Latency Communication (mURLLC) [137], which will offer 10–100× improvements in the connection QoS parameters (in comparison to 5G). The categorization, as well as the precise requirements for each new service class, are still a matter of discussion and speculation. A detailed comparison of the network evolution in terms of performance is presented in Table 3.

**Table 3.** Comparison of performance peaks offered by 4–6G mobile networks (based on [90,138–140]).

| Key Performance Indicator (KPI) | Mobile Network | | |
|---|---|---|---|
| | **4G** | **5G** | **6G** |
| Peak data rate [Gbps] | 1 | 20 | 1000 |
| User-experienced data rate [Mbps] | 10 | 100 | 1000 |
| Spectrum efficiency [bps/Hz] | 6 | 20 | 100 |
| Mobility [kmh] | 350 | 500 | 1000 |
| Latency [ms] | 10 | 1 | 0.1 |
| Connection density [devices/km$^2$] | $10^5$ | $10^6$ | $10^7$ |
| Area traffic capacity [Mbps/m$^2$] | 0.1 | 10 | 1000 |
| Network energy efficiency | 1× | 100× | 200× |
| Reliability | – | $10^{-5}$ | $10^{-7}$ |

In terms of spectrum allocation, the 6G operating bands are expected to overlap the ones already occupied by 5GS, i.e., the FR1 (410–7125 MHz, sometimes split into the FR1 low band 410–1000 MHz and FR1 mid-band 1000–7125 MHz), FR2-1 (24.25–52.6 GHz), and FR2-2 (52.6–71 GHz) bands, as well as open new bands in the 5G and sub-THz range. Most often, three 6G spectrum ranges are projected (cf. Figure 1): *low* (410–1000 MHz), *mid* (lower mid, 1–7.1 GHz, and upper mid, 7.1–24 GHz), and *high* (mmWave range of 24.25–92.0 GHz and sub-THz above 92 GHz and up to 300 GHz). It has to be also noted that since Release 16, 5GS supports operation in an unlicensed spectrum, i.e., the n96 (5.925–7.125 GHz) and n263 (57.00–71.00 GHz) bands, which are potentially exploitable by 6GS. Some sources also expect 6GS to exploit the THz bands; however, there exist overwhelming obstacles such as i.a. high penetration loss, very poor propagation characteristics, and very high losses due to channel attenuation and scattering [141], resulting in short coverage ranges (the approximate cell radius is up to 200 m) and limiting real-life deployments in urban spaces. Moreover, operation in the THz bands requires specifically crafted transceivers [142], further questioning the possibility of the effective exploitation of this frequency range in commercial deployments.

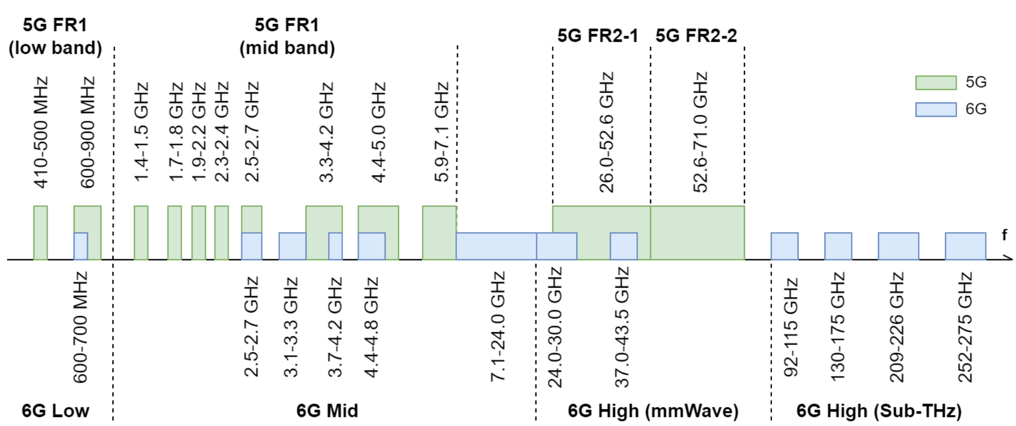


**Figure 1.** Spectrum allocation for 5G [143,144] and foreseen 6G bands [142,145].

## 7. Mobile Networks Support for the Sectors in Focus

In order to confirm the necessary support of a PLMN for the specific AFBW use cases, two primary conditions have to be met:

- *Availability of the relevant service class*—each use case should be implementable using one of the 3GPP service classes, i.e., Slice/Service Type (SST) [117], coupled with its general characteristics and the use-case specifics;

- *UP performance*—it has to be ensured that the QoS requirements of the use case can be met by the UP entities. The availability of a 5QI fulfilling the use-case requirements confirms the UP support.

Therefore, to evaluate the network support for the AFBW use cases, the above-mentioned approach is followed. First, the mapping of UC1–UC14 to the relevant 3GPP SST was performed based on the requirements identified in Section 4. The results of the assignment are presented in Table 4.

**Table 4.** SST supporting analyzed use cases.

| SST | Use Cases | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **UC1** | **UC2** | **UC3:S1** | **UC3:S2** | **UC4** | **UC5** | **UC6** | **UC7** | **UC8** | **UC9** | **UC10** | **UC11:S1** | **UC11:S2** | **UC11:S3** | **UC12** | **UC13** | **UC14** |
| eMBB | | | ✓ | | ✓ | | | ✓ | ✓ | | | | | ✓ | | | ✓ |
| MIoT | | ✓ | | ✓ | | ✓ | ✓ | | | ✓ | | | | | | | |
| URLLC | ✓ | | | | | | | | | | ✓ | ✓ | ✓ | | | | |
| V2X | | | | | | | | | | | | | | | ✓ | | |
| HMTC | | | | | | | | | | | | | | | | ✓ | |

The five SST classes defined by the 3GPP cover all of the identified AFBW use cases. Nonetheless, the implemented Network Slice Instances (NSIs) have to follow the specific QoS constraints dictated by each use case regarding UP transmission, such as traffic priority, (non-)guaranteed data rate, packet error rate, delay budget, etc., with regard to the tenants' demands or adopted UP architectures. An example allocation of 5QI is presented in Table 5.

**Table 5.** 3GPP 5QIs [117] and PQI [146] supporting the analyzed use cases.

| 5QI | Resource Type | Priority Level | Delay | Packet Error | Max. Data Burst Volume | Use Case ID |
|---|---|---|---|---|---|---|
| 6 | Non-GBR | 60 | 300 ms | $10^{-6}$ | N/A | UC2, UC5, UC9 |
| 7 | GBR | 70 | 100 ms | $10^{-3}$ | N/A | UC3:S1, UC4 |
| 8 | Non-GBR | 80 | 300 ms | $10^{-6}$ | N/A | UC3:S2 |
| 70 | Non-GBR | 55 | 200 ms | $10^{-6}$ | N/A | UC6, UC11:S2 |
| 80 | Non-GBR | 68 | 10 ms | $10^{-6}$ | N/A | UC8, UC11:S3, UC14 |
| 82 | Delay-critical GBR | 19 | 10 ms | $10^{-4}$ | N/A | UC1, UC10 |
| 83 | Delay-critical GBR | 22 | 10 ms | $10^{-4}$ | N/A | UC11:S1,UC12 |
| 88 | Delay-critical GBR | 25 | 10 ms | $10^{-3}$ | 1125 bytes | UC7 |
| 90 (PQI) | Delay-critical GBR | 25 | 10 ms | $10^{-4}$ | 2000 bytes | UC12 (direct D2D communication) [146] |

GBR–Guaranteed Bit Rate.

The relevant 5QI can be assigned to almost all of the identified use cases, except for UC13, due to the required latency of 2 ms (the lowest supported delay is equal to 5 ms). However, such extremely challenging delay limits may not be required in every case so the QoS targets should be evaluated individually. For the direct Device to Device (D2D) support in UC12, the appropriate PC5 5QI (PQI) can be matched [146]. The lack of an extremely high data rate and very low latency class can potentially limit the efficient implementation of use cases that incorporate promising AI-based operations (e.g., federated learning, which requires the transfer of AI models among several system agents). Nonetheless, 6GS is expected to introduce the separate slice category of MBRLLC, which should be accompanied by the relevant UP QoS profiles. In addition, it has to be emphasized that MNOs can define their own 5QI values with the QoS requirements of their choice [117]. However, the sharing of 5QI values among MNOs is not obligatory. As a consequence, with custom-defined 5QIs, the support for roaming services can be limited or non-existent, which can be an obstacle for some AFBW use cases (e.g., monitoring or tracking of endangered animal species).

In terms of communication performance, 5GS can theoretically fulfil the vast majority of requirements of the AFBW sectors. The fundamental issue lies within the 3GPP definition of the basic service requirements for rural macro scenarios ([83], clause 7.1), as the maximum user-experienced data rate is 50 Mbps for the DL and 25 Mbps for the UL (traffic capacities that are equal to 1 Gbps/km$^2$ for the DL and 0.5 Gbps/km$^2$ for the UL). For comparison, the urban macro scenario ensures 200× higher data rates and 100× better traffic capacities for both the UL and DL. Consequently, according to the current 3GPP standardization, some of the AFBW use cases cannot be implemented due to capacity impairments.

The improvements promised by 6GS are expected to be more than adequate in terms of the data rate, latency, reliability, and network capacity in both urban and rural environments. It has to be noted, however, that 6GS can contribute notably to several AFBW use cases via introduced mechanisms and features, including, in particular:

- *Network omnipresence*—Coverage extensions achieved through integration with NTN will provide massive benefits to use cases that involve large amounts of spatially distributed sensors (e.g., UC6, UC10). The exploitation of satellite systems will enable the building of AFBW systems with lower overheads regarding infrastructural costs, contributing to the profitability of both MNOs and service providers. Although the 5GS roadmap gradually includes NTN feature integration (Release 16—satellite access in 5G; Release 17—IoT/NR over NTN and satellite components in the 5G architecture; Release 18—IoT/NR NTN enhancements and IoT NTN management architecture/mechanisms [147–149]), it is 6GS where terrestrial and non-terrestrial access will be unified [133].
- *Positioning with an accuracy of 1 cm in 3D*—The accuracy assumed by 5GS (30 cm precision with a 1 s latency [83]) is still far from sufficient in the most demanding AFBW cases. The built-in 6GS location mechanisms eliminate this issue by providing better performance, thus allowing for backup measurements (e.g., for security purposes) or resignation from the RTK solutions. Moreover, embedding location capabilities into the terminal allows for better power management and the extension of battery lifetime (network-side localization).
- *Flexible service deployment*—The support for deployment over heterogeneous infrastructure will contribute to service availability and resilience, which is especially important in remote edge environments.

In the context of mobile network support for the AFBW sectors, the application layer support offered by edge cloud computing platforms such as ETSI MEC cannot be neglected (e.g., UC3:S1, UC4, UC13, and UC14). However, the standardization of their integration with 5GS is not yet finished, raising multiple questions regarding functional overlap, scalability, and redundant complexity [128].

## 8. Open Issues

5GS already provides multiple opportunities that can leverage the AFBW use cases, but there are still some challenges that are either roadmapped in the 3GPP standardization or should be included in the research and then in the future scope of standardization:

- *Availability of NS-enabled 5GS*—At present, the vast majority of commercial 5G network deployments implement a non-standalone deployment architecture [150], which does not support NS. As a consequence, a 5G network can be perceived as an improved version of a 4G network ("boosted" eMBB-only network), which does not provide the capabilities needed to offer commercial AFBW services.

- *Dynamic NS*—In the centralized approach to NS currently adopted by 3GPP, there exist no touch-points for interaction between an MNO and slice tenants; no relevant interfaces are specified in the Operations Support System (OSS)/Business Support System (BSS), which could be used for slice negotiation, slice request, slice management, etc. This severely impacts the dynamicity of slice deployment and exposure to specific verticals, thus limiting the NS business potential [151].
- *Lack of direct Device to Device (D2D) link*—This is needed to provide short-distance direct communication between UEs, especially vehicular ones (automotive, UAVs, UGVs, etc.), regardless of the serving PLMN. Such communication is extremely important for, e.g., information (presence, location, etc.) broadcasting in the neighborhood or data exchange in objects' swarms. Its standardization is still ongoing within the 3GPP Release 18, "5G Advanced" (to be completed by the middle of 2024) [149].
- *UAV support in NR*—UAVs will play a key role in the AFBW use cases; however, the support of some important generic 5G RAN mechanisms has already been included up to Release 17 [148], and the dedicated support of UAVs in NR is available only in the scope of Release 18 [149].
- *Seamless edge application context switching* (change of the edge cloud or server)—A PLMN should have the ability to predict a network-level handover, forward the served application's context in advance to the target server, and then perform a correlated AP-level and network-level handover; the required delay limit for latency-critical services may not be met during the context transfer [152] due to the procedure definition [153] and virtualization aspects [154,155]. The answer to this problem is user-context transfer control by the application [152]. Nevertheless, the issue of integration of various architectural frameworks (e.g., 5GS, virtualization, and edge computing frameworks) with functional overlaps still exists and needs a thorough redesign of the integrated architecture to avoid the uncoordinated competition of overlapping mechanisms, unstable performance, etc. [128].
- *Lack of mechanisms for proactive, on-demand coverage adaptation*—There are no interfaces exposed by a PLMN to serve the requests for coverage improvements in the specific area; with dedicated RAN controllers, such as Open RAN (O-RAN) that support applications dedicated to RAN optimization and expose a controller's API, such mechanisms may be provided [156]. 5GS and O-RAN have not been integrated yet, but there exists a proposed solution [157].
- *National roaming for specific groups of UEs*—Coverage problems in a specific PLMN could be solved by the permission of a re-connection to another PLMN providing the required QoS in the problematic area. However, the visited PLMN must be aware of, e.g., the need to provide a Local Break-Out (LBO) of the traffic to the home PLMN's MEC or temporarily host the relevant edge cloud application. Appropriate inter-PLMN AP-level and network-level handover coordination must be ensured.
- *Cross-border and roaming operations*—The EU rules of the "free movement of goods and services" and "Single European sky" (the ability of a UAV to operate in any EU country) have implications for communication services for the AFBW sectors; service availability or continuity abroad has to be provided, including the integration of the exposed mobile network control mechanisms with the vertical industry's ICT environment. Wide implementation of LBO roaming architecture (so far, practically unused due to the problem of needing a home PLMN to verify the charging information reported by the visited PLMN), either standalone or hybrid with Home Routed (HR) for specific transmission channels, will have to be implemented based on NS and differentiation of user plane function (UPF), as well as a way of building the inter-operator trust [158]. This problem will be particularly important in the case of UAV applications but also in the case of commercial highly-specialized robot service providers, wildlife migration monitoring with tracking collars, etc.

- *End-to-End (E2E) feature span*—PLMN capabilities extend as far as the N6 interface and its termination in a Data Network (DN). Hence, despite a plethora of 5GS mechanisms, e.g., for data ciphering, integrity protection, authentication of NFs or UEs, secure integration with other PLMNs, or non-3GPP access, exploiting their full potential is limited. Although some partial solutions exist [63], a generic mechanism is needed to enable the extension of these mechanisms beyond the scope of the 5G network. The same issue can be observed in the context of NS. The PLMN network slices and hence the QoS and security control mechanisms (non-repudiation of data, data integrity, the confidentiality of identities, etc.) inherently do not go over the UPF termination point in a DN (N6 interface). This problem is fundamental in the case of low latency and critical communication, where the QoS violation impacts the safety of operations. To maintain full E2E control over the performance and security and thus mitigate the risks, a PLMN should span the vertical industry's ISs hosting environment or host their ISs on the PLMN's premises.

Finally, the complexity of the AFBW sectors is overlooked by the Standards Developing Organizations (SDOs), which manifests in the non-comprehensive approach, resulting, e.g., in an insufficient network capacity for rural locations. To this end, to provide economic benefits, the AFBW sectors should be further investigated by the SDOs in the domain of telecommunications, and the standardization of the ICT ecosystem should be better aligned with the challenges posed by the AFBWs' conditions.

## 9. Summary and Conclusions

In this paper, the challenges facing 5G/6G networks from the AFBW sectors, whose social and economic importance is growing on a global scale, have been described. Following the detailed description of the above-mentioned sectors, 14 groups of use cases have been distinguished together with the associated communication requirements. In addition, an analysis of the mobile networks' support for the use cases has been conducted, showing that 5GS with NS technology enables the satisfying of the requirements of almost all the use cases, with the exception of demanding robotic applications (UC13). However, for some use cases, the PLMN capacity will be insufficient. The impact of using 6GS as the basis for AFBW services has been discussed, showing multiple benefits. The most important gains include improved performance, wider coverage due to integration with NTNs, accurate network-based localization, and better-adjusted service support due to the introduction of new network slice types.

Despite the promised exceptional capabilities of 5GS, multiple issues are yet to be resolved, which include the availability of NS-enabled 5GS, a lack of specific network mechanisms (device-to-device links, edge-context switching, UAV-specific support, interfaces for coverage adaptation), service continuity in roaming, and actual E2E QoS enforcement, among others. Finally, more efforts should be made by the SDOs in order to identify the potential synergies between the mobile networks and AFBW sectors. The cooperation and individual domain treatment will help to better adjust the network solutions to fully support the specific sectoral needs and, as a result, contribute to the acceleration of the transformation of societies into sustainable ones.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| 3GPP | Third-Generation Partnership Project |
| 5G-EIR | 5G-Equipment Identity Register |
| 5GC | 5G Core |
| 5GS | 5G System |
| 5QI | 5G QoS Identifier |
| 6GS | 6G System |
| AF | Application Function |
| AFBW | smart agriculture, forestry, biodiversity monitoring, and water management |
| AI | Artificial Intelligence |
| AMF | Access and Mobility Management Function |
| AoA | Angle of Arrival |
| AP | Application Plane |
| API | Application Programming Interface |
| AR | Augmented Reality |
| BSS | Business Support System |
| BVLOS | Beyond-Visual-Line-of-Sight |
| C2 | Command and Control |
| CAPIF | Common Application Programming Interface Framework |
| CN | Core Network |
| CP | Control Plane |
| D2D | Device to Device |
| DL | downlink |
| DN | Data Network |
| DRX | Discontinuous Reception |
| E2E | End-to-End |
| EC | European Communities |
| eMBB | Enhanced Mobile Broadband |
| ERP | Enterprise Resource Planning |
| ETSI | European Telecommunications Standards Institute |
| EU | European Union |
| FPV | First-Person View |
| GBR | Guaranteed Bit Rate |
| GIS | Geographic Information System |
| GNSS | Global Navigation Satellite System |
| GSMA | Global System for Mobile Communications Association |
| HCS | Human-Centric Services |
| HMTC | High-Performance Machine-Type Communications |
| HR | Home Routed |
| ICT | Information and Communication Technology |
| IoT | Internet of Things |
| IR | infrared |
| IRS | Intelligent Reflective Surface |
| IS | Information System |
| ISM | Industrial–Scientific–Medical |
| ITU | International Telecommunication Union |
| KPI | Key Performance Indicator |
| LBO | Local Break-Out |
| LCS | Location Services |
| LiDAR | Light Detection and Ranging |
| MAPE-K | Monitor–Analyze–Plan–Execute based on Knowledge |
| MBRLLC | Mobile Broadband Reliable Low Latency |
| MEC | Multi-Access Edge Computing |
| MES | Manufacturing Execution System |

| | |
|---|---|
| MIMO | Multiple Input Multiple Output |
| MIoT | Massive Internet of Things |
| ML | Machine Learning |
| mMTC | Massive Machine-Type Communications |
| MNO | Mobile Network Operator |
| MPS | Multi-Purpose Services |
| mURLLC | Massive Ultra-Reliable Low-Latency Communication |
| NEF | Network Exposure Function |
| NF | Network Function |
| NR | New Radio |
| NS | Network Slicing |
| NSI | Network Slice Instance |
| NTN | Non-Terrestrial Network |
| NWDAF | Network Data Analytics Function |
| O-RAN | Open RAN |
| OSS | Operations Support System |
| OTA | Over-The-Air |
| PLC | Programmable Logic Controller |
| PLMN | Public Land Mobile Network |
| PQI | PC5 5QI |
| PrA | Precision Agriculture |
| QoS | Quality of Service |
| RAN | Radio Access Network |
| RAT | Radio Access Technology |
| RT | real time |
| RTC | Real-Time Control |
| RTK | Real-Time Kinematic |
| RTT | round-trip time |
| RTU | Remote Terminal Unit |
| SBA | Service-Based Architecture |
| SCADA | Supervisory Control And Data Acquisition |
| SDN | Software-Defined Networking |
| SDO | Standards Developing Organization |
| SDSS | Spatial Decision Support System |
| SEAL | Service Enabler Architecture Layer for Verticals |
| SmA | Smart Agriculture |
| SmF | Smart Forestry |
| SST | Slice/Service Type |
| UAV | Unmanned Aerial Vehicle |
| UE | user equipment |
| UGV | Unmanned Ground Vehicle |
| UL | uplink |
| UN | United Nations |
| UP | User Plane |
| UPF | User Plane Function |
| URLLC | Ultra-Reliable Low-Latency Communication |
| UTM | Unmanned Aircraft Systems Traffic Management |
| V2V | Vehicle to Vehicle |
| V2X | Vehicle to Everything |
| VLOS | Visual Line of Sight |
| VR | Virtual Reality |

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