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RESEARCH ARTICLE

MEC in 3D-Networks: Supporting Application Controlled QoS

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ABSTRACT Multi-Access Edge Computing (MEC) applied to three-dimensional (3D)-Networks comprising space, air, and ground layers, bear the potential to combine benefits of all these domains and globally provide low latency services. These networks leverage technologies such as non-terrestrial networks (NTN) and advanced computing frameworks to provide real-time services and extend connectivity to remote regions. Especially for MEC-App developers, knowledge of the underlying network topology and link characteristics is required to meet QoS targets, which has not been considered by current standardization. Based on the smart agriculture and video distribution use cases, we investigated on MEC in 3D-Networks, the architectural enablers, and necessary extension of current standards including mobility. For this we reviewed the current Application Programmable Interfaces (APIs) of the ETSI MEC standard and propose updates. Main update is the inclusion of topology information that can be used by MEC applications to achieve low latency and ultra-reliable services.

INDEX TERMS 3D-networks, aerial communication, MEC, QoS, satellite communication, smart agriculture.

I. INTRODUCTION (DLR)

Multi-Access Edge Computing (MEC) is a technological building block to address Ultra-Low Latency and High Reliability requirements that opens the door for a variety of new services. It brings the cloud closer to the User Equipment (UE) and provides for instance caching, location, identity, Radio Network Information (RNI) and control services. The latter are enabling MEC-applications to get network and radio information of network nodes and base stations and to reserve resources in order to satisfy Quality of Service (QoS) demands. MEC decentralizes data processing and storage.

Moving from 5G to 6G, three-dimensional (3D)-Networks are investigated with a unified Radio Access Network (RAN) and unified system aspects in terrestrial, aerial and space domain (i.e., non-terrestrial networks, NTNs) [1]. Integrating MEC into this 3D-architecture combines advantages of all domains with those of MEC to provide ubiquitous low-latency services, but it brings also challenges for network architects and MEC application developers since access links for each of the different domains have different characteristics in terms of latency, throughput, jitter or loss rate which might be temporarily changing due to the moving infrastructure in the RAN and transport network. They might use different bandwidths and frequency ranges having different impairments.

Figure 1 shows the 6G 3D-architecture providing radio access from different domains. In principle, MEC nodes can be hosted at each network node, i.e. at the UE side (for example at trains or cars), co-located with the RAN, at the transport network or linked with the core. Furthermore, a single MEC instance can serve different scales of regions, e.g., at single- or multiple cell level, or at metropolitan regions and counties. In this paper we consider the MEC host

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co-located with the RAN node, integrated in the 3D-Network, which means the MEC host is either on-board a satellite, an aerial vehicle or close to a terrestrial base station.

The main difference between 3D-Networks and today's mobile communication networks is the flexibility of the access and transport part. RAN and transport network components are fixed in the terrestrial domain; in 6G 3D-Networks they are moving. In the space domain, as already subject of 3GPP Release 19, the RAN will be hosted on satellites moving around the Earth which can be in low, medium or geostationary Earth orbit (LEO, MEO, GEO). The difference in altitude characterizes also the transmission parameters and the duration a single satellite can service a UE, i.e. the duration the base station is in the line of sight. Low orbiting satellites provide lower latency services but have a smaller coverage area, hence, multiple satellites are required for continuous services leading to LEO mega-constellations. A service handover between the satellites is required to continuously provide communications services to users in a given area. Communication thereby benefits from the use of Inter-Satellite Links (ISL), which can also be used to connect satellites in other orbits. GEO systems offer a wide area coverage by means of a single satellite but the latency is high due to the long distance from Earth to satellite (~0.5s round trip time). LEO satellites instead exhibit an end-to-end latency quite close to that of terrestrial links, depending on the actual altitude of the satellites. In satellite communication the link performance at higher frequencies is sensitive to weather conditions due to atmospheric effects. The main idea of the inclusion of satellites in the 3D-architecture is to provide ubiquitous services, as they can cover areas where terrestrial coverage cannot be provided cost-effectively. Also, they can be used complementary to other networks for higher capacity, or in case of disasters where terrestrial infrastructure can be disrupted. Furthermore, the ability to cover a wide area is also interesting for Internet of Things (IoT) applications where a vast amount of potentially wide-spread devices and sensors send sporadically short messages.

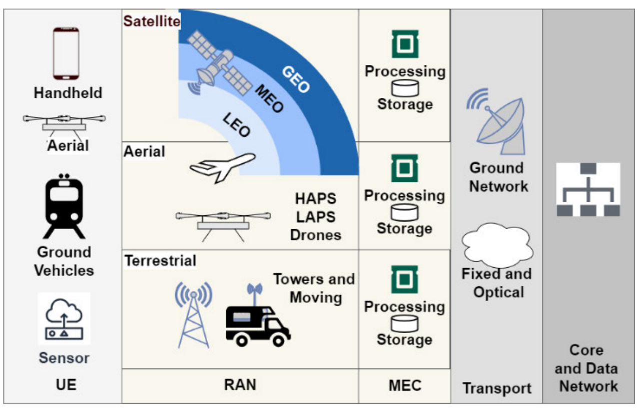

FIGURE 1. 3D-network with MEC Co-located at RAN.

In the aerial domain the RAN can be hosted on Uncrewed aerial Vehicles (UAVs), which are separated into High Altitude Platforms and Low Altitude Platforms (HAPs, LAPs), though low flying drones can be considered as well. The main idea of aerial domain is to provide temporary services and additional capacity which might be necessary either in case of large-scale events, disasters or time-limited provision for remote locations. They provide a rapidly deployable solution.

Terrestrial nodes are the backbone of today's mobile communication and will keep this role in the 6G-architecture providing high-throughput, ultra-reliable and low latency services as well as connecting IoT devices. Generally, terrestrial RAN is considered to be on a fixed location, however within the 6G 3D-architecture they can also be set up temporarily, e.g. in the case of bigger events, disasters, or they can be general moveable in case of RAN mounted on rovers, trucks or similar.

Summarizing, 3D-Networks have a complex topology that is time varying. Therefore, having background information available on dedicated Application Programmable Interfaces (APIs) of a MEC system is important for the development of low-latency applications, which is however not offered by current standards. Introducing MEC into this architecture, the MEC-platform in this paper is considered to be connected to the transport network and located at different topological positions across the 3D-Network (see Figure 1), while we put special emphasis on having it close to RAN network, i.e. hosted on satellites, or aerial vehicles together with a gNB, following the idea that the closer the MEC platform is to the UE the lower is the latency for the service.

Integrating MEC within the 3D-architecture fulfills the usage scenarios planned by the ITU IMT-2030 vision [2], especially with respect to AI and communication, and ubiquitous connectivity to eventually support overarching aspects such as "connecting the unconnected" and "ubiquitous intelligence". Furthermore, the integration of a MEC concept into 3D-systems can address several Key Performance Indicators, as those currently introduced still in ITU IMT-2030 and also in the early 3GPP technical reports [3] towards the specification of 6G Systems [4]. Some of the most notable advantages are:

- Ubiquitous coverage: satellites and aerial nodes are complementing the area traffic capacity due to larger coverage areas. If MEC is hosted on satellites, low latency MEC services can be provided also to remote locations. Furthermore, MEC services can be provided from different domains at the same time. While demands with very low latency requirements can use the shortest paths, services with less strict demands can use other paths offloading the low latency links.
- Broadcast capabilities: due to the bigger coverage of NTNs and HAPs/LAPs, broadcast capabilities are beyond those of terrestrial systems and can be used if more users need to be reached at the same time by a MEC service.
- Latency: in NTNs the latency is strongly dependent on the link distance which is mainly influenced by the altitude of the nodes. The orbit selection depends on latency

requirements. MEC on 3D-nodes would at a minimum save half of the RTT of the over the air link.
- Resilience and availability: having MEC services and data storage capabilities placed in different parts of the network is increasing the capability of the system to counteract failures. This includes both, having copies of services and user data in different domains and the capability to migrate MEC data to other domains in case of failures. A concrete use case is a disaster event in which the terrestrial domain is destroyed or overloaded. Mission critical communication from first responders has very demanding requirements in terms of data rate, reliability and latency and as such would benefits for 3D-MEC services. Generally, the network gets more robust with a 3D-Network, including the services provided by MEC.
- Local autonomy: when taking into account the concept of ''network-of-networks'' discussed e.g. in [5] the gNB and MEC node, along with the UEs served locally, can be seen as a subnet. This subnet could work in a temporarily autonomous way, even if it loses connection to the parent network – thus maximizing service availability and limiting the dataflow to the shortest paths needed in the network.
- Load balancing: by the use of different domains and in interlinking of the different nodes, idle processing capacities can be used to balance the computing demand. In LEO constellations satellites orbiting the Earth are mostly above the ocean and in areas with low demands. Using ISLs processing tasks from satellites or terrestrial nodes which are in areas of high processing demand can be distributed within the network. Concepts for multi-orbit processing distribution already exist in the literature (refer to section III).
- Generally, MEC allows for flexible resource assignment and optimization which supports green requirements. Being able to decide in which part of the edge-cloud continuum a task is processed allows for this. For instance, processing tasks in space nodes is beneficial since they have almost a constant power from the solar panels but are without load during most of the time. Moving the processing task to space can save energy that might come from other sources, but the energy for transmission needs to be considered.

On the other hand, adding MEC to NTN and Arial nodes bears also some disadvantages and challenges:

- Cost of terminal: the general idea is to have unified air interfaces, but in SatCom case the link budget is challenging due to the high path loss. Considering higher frequency bands (e.g. 3GPP FR2 and wider bandwidths directive antennas are needed, which can lead to more expensive terminals).
- Latency: as mentioned the latency for LEO is comparable with those of terrestrial domains. Nevertheless, the latency introduced by GEO and MEO satellites is much higher, hence contradicting the actual idea of MEC to provide low latency services at the edge. However, it might be the case that GEOs and MEOs are the only services available, e.g. because of political restrictions, in which case the requirements must be carefully traded-off per applications to see whether a service should favor continuity or low latency from some boundary. In order to consider this, the edge application developer must be aware of it. But it should be noted even in GEO half of the wave travelling time can be saved if the service is directly provided by the satellite. In the literature, satellites in GEO are considered as data centers [6], but also, they could be used for service orchestration and synchronization.
- It needs to be considered that satellites are power limited systems and offer limited processing and storage capabilities.
- Similar considerations also hold for the aerial domain. Here, specifically for drones, the battery limitations are challenging. Additional to gNB services, the processing and storage capacities for MEC services would need to be hosted onboard, hence further increasing power and weight demands. On the other hand, for HAPs and LAPs with proper dimensioning it is not expected to be a problem.

In general, the support of the MEC requirements on-board needs to be considered, while we assume it is feasible and provide a concept for MEC networking and service provisioning for the 3D-Network architecture. At this point, it needs to be mentioned that the requirements on processing power and storage depend on the offered service. As a consequence, it is likely that first stateless services not requiring big storage capacities nor necessitating user data migration between nodes (e.g. between satellites) during their movement. With improved hardware capabilities in future more services can be provided.

The rest of the document is organized as follows: section II presents the MEC architecture for 3D-Networks. Section III provides a state-of-the-art review of MEC in 3D-Networks. In Section IV we provide an overview of possible use cases, by dedicating special attention on 3D-Network combination of coverage in remote areas, rapidly coverage extension, and low latency services. In particular, the case of optimized QoS for video distribution for Smart Agriculture application is presented in detail. Section V outlines possible extension of standard APIs to the 3D-Network, and section VI discusses mobility implications. Finally, Section VII summarizes the main findings and the lessons learnt.

II. MEC IN 3D-NETWORKS ARCHITECTURE

For MEC we are following the general MEC architecture specified by ETSI illustrated in Figure 2, [7]. We assume that the MEC platform and the MEC apps are hosted on satellites, UAVs, close to terrestrial base stations. The Mp1 is the interface between the MEC platform and the MEC apps, Mp2 is the one between MEC platform and data plane. Via Mp1 apps register their services at the MEC platform which provides these services, e.g., to device apps on UEs. If data plane information is needed the MEC platform uses the Mp2 to provide Radio Network Information Services (RNIS). The underlying data plane needs to be able to provide measurement and configuration data to the services. For 3GPP systems this includes for example L2 Measurements, radio access block information and general UE and load information, as specified in [8] and [9].

Control functions of device apps running on UEs can connect to the MEC platform and the MEC app hosted there. This is managed by the MEC orchestrator and the Operation Support System (OSS). Via the MEC Platform Manager the MEC platform itself can be controlled and managed. For mobility within the MEC framework, the MEC platform can be connected to other MEC hosts. All is based on virtualized infrastructure managed by the virtualization infrastructure manager.

For the application of 3D-Networks, the federated architecture work by ETSI [10] can be a starting point where MEC systems of provider A are interlinked with MEC systems of provider B and service information is exchanged. If MEC systems at each domain are managed by separate operators this function can be used. However, for a unified approach in 6G this can be a very flexible setup with different operators spanning multiple domains, or multiple operators combining various systems on different domains. The capabilities of the federated functions do not cover such cases.

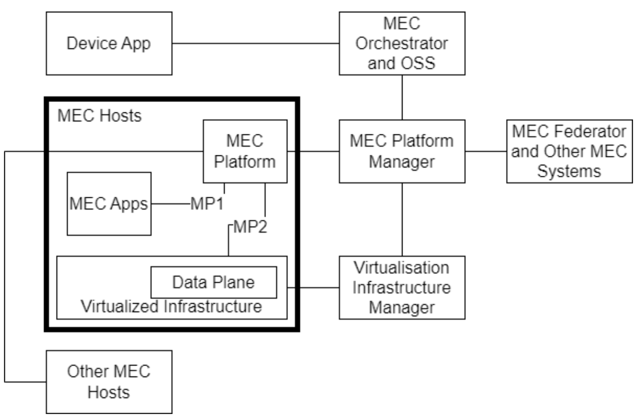

FIGURE 2. MEC management rchitecture [7].

In Release 19 of 3GPP, regenerative satellites payloads have been introduced, implying the deployment of base stations (i.e. gNBs) onboard satellites. Additionally, accommodating a User Plane Function (UPF) would enable hosting MEC functionalities directly on-board the satellite providing a Local Area Data Networks (LADN) reducing latency compared to transparent satellite setups. The architecture of such a RAN and MEC node is depicted in Figure 3. The UE connects to such a RAN and MEC node, while the UPF is routing the user service request either via the 5G core to a data network or to the MEC platform processing the request closer to the UE. At the 5G Core an anchor UPF is included for the general communication. Additionally, Figure 3 depicts the typical NTN system and the used nodes. Mapping between the two, the UE is typically refered as User Terminal, the RAN and MEC node is hosted as payload on the satellite (marked in blue), and finally, the 5G core is connected to or is part of the ground network. At the end the system is connected to the data network.

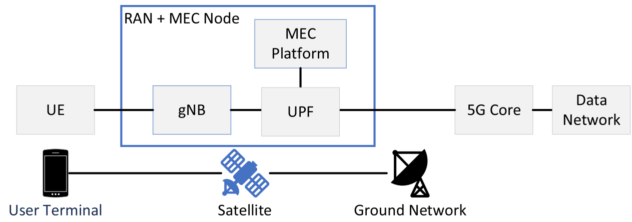

FIGURE 3. Single node architecture.

III. MEC IN 3D-NETWORKS STATE OF THE ART REVIEW

The integration of edge computing into 3D-Networks—comprising space, air, and ground layers has introduced novel research avenues focusing on its application in areas such as 6G systems, energy-efficient multi-layer integration, and AI-driven optimization.

In the literature, this topic has been investigated from different angles: introducing MEC on space nodes, integrated terrestrial and non-terrestrial systems, and 3D-Networks. Mostly, the focus is on algorithms for optimization of resources, while in this paper we are focusing on the practical setup of a MEC system following standardization and the necessary adaptations for 3D systems.

Reference [6] applies satellite mobile edge computing to reduce data transmission overhead, save bandwidth resources, and enable rapid task responses for both space and ground users. A two-layer architecture is proposed consisting of a low-orbit satellite MEC cluster and a high-orbit satellite cloud computing layer for coordination and management. The core of the paper lies in addressing the task scheduling problem considering the dynamically changing network topology and inter-satellite link loads.

In [11] the authors developed and evaluated an Orbital Edge Computing Task Allocation algorithm for LEO satellite networks, which utilizes a greedy strategy to efficiently allocate computing tasks to satellites within a Walker Delta constellation. The algorithm differentiates between Delay-Sensitive Tasks (DST) and Delay-Tolerant Tasks (DTT), employing different optimization goals for each task type: minimizing delay for DSTs and minimizing energy consumption for DTTs, all while considering the limited computing and memory resources of the satellites.

Reference [12] introduces the concept of Satellite MEC, which aims to enhance the QoS in high-speed satellite-terrestrial networks by extending MEC capabilities to satellite environments. The authors aim to address the increasing demand for high data rates, low energy consumption, and the limitations of cloud computing due to transport network delays, i.e. high latency. A dynamic Network Functions Virtualization (NFV) technique is proposed to integrate the distributed computing resources within the satellite network, addressing the mobility of LEO satellites. Furthermore, a cooperative computation offloading model was developed.

Reference [13] introduces the concept of applying Federated Learning (FL) to satellite MEC to address the growing demands of beyond 5G communications while ensuring data privacy. Recognizing the wide coverage of satellite communication and the computational capabilities offered by MEC, the paper proposes a FL-based satellite MEC architecture where edge devices such as LEO satellites and UAVs perform local model training on their data, and a central MEO satellite aggregates these model updates. The paper highlights that the characteristics of satellite MEC systems, particularly their wide coverage and the need for efficiency and security, make them well-suited for FL. They explore key techniques within this FL-based satellite MEC framework, focusing on resource management, multi-modal data fusion, and privacy and security protection.

Reference [14] proposes the integration of Space Edge Computing (SEC) with terrestrial networks through a satellite-cloud architecture. The paper explores the feasibility of SEC and showcases its potential through quantitative experiments, ultimately outlining the practical challenges and future research directions. The authors mention the challenges related to the dynamics of LEO satellites, scarce space resources, and limited power budgets, suggesting future research to overcome these hurdles.

In [15] the authors propose to move beyond the traditional view of satellites as mere relay networks and to enable direct task processing on satellites equipped with MEC platforms, alongside terrestrial MEC platforms and edge computing clusters. This way the paper shows how the limitations of terrestrial networks can be overcome in achieving global seamless coverage and resilience to disasters, while also addressing limitations due to increasing demands of emerging applications for high bandwidth, low latency, and ubiquitous access.

Also, in [16] the main concept is to integrate MEC functionalities with satellite and terrestrial networks to enhance computation performance, reduce network congestion and transmission latency, and improve the quality of Internet of Things (IoTs) services. This architecture involves a three-tier structure comprising LEO constellations, a GEO backbone network, and terrestrial stations, where MEC servers can be deployed. The paper also discusses open issues related to energy and computation limitations in LEO satellites, the complexity of scheduling and energy cost modeling in MEC due to the integration of terrestrial and satellite links.

By considering different satellite edge computing scenarios, including those with and without terrestrial network involvement, [17] establishes a framework for efficient resource management in space-ground heterogeneous multi-layer networks. The authors formulate the resource allocation problem as a mixed-integer programming problem aiming to minimize the weighted sum of application latency across multiple UEs.

In [18], a hybrid terrestrial-satellite backhauling network to improve the efficiency of placing popular content in 5G edge nodes is introduced. The main concept is to offload conventional point-to-point optical terrestrial links by using LEO and GEO satellites to multi-cast popular content to multiple 5G edge nodes simultaneously. This approach aims to significantly reduce the time required to distribute frequently requested files to the edge nodes during off-peak hours, addressing the increasing data demand from services like video streaming. The paper considers a pan-European Content Delivery Network (CDN) and analyzes the performance of a GEO satellite for continuous coverage versus a small constellation of LEO satellites acting as data mules with sporadic connectivity. The study focuses on the resource allocation strategy within this hybrid network to minimize the content placing time.

Reference [19] introduces the concept of "6G in the Sky," providing on-demand intelligence to 3D-Networks. This innovation aims to deliver communication, computation, and caching services seamlessly and ubiquitously across 3D spaces. This shall be achieved by the integration of AI-driven algorithms that dynamically orchestrate virtualized network functions across both terrestrial and non-terrestrial networks.

Reference [20] addresses the challenges of providing seamless communication and computing services for Power Internet of Things devices with stringent QoS requirements in future 6G wireless communication networks by proposing an AI-based cloud-edge-device collaboration framework for 3D-Networks. They utilize cloud-edge-device collaboration to enable intelligent resource management, including communication, computation, and energy, across these heterogeneous layers to cope with multi-dimensional resource heterogeneity and network dynamics. The authors develop a hybrid and hierarchical cloud-edge-device architecture and a task offloading algorithm considering queue backlogs, energy consumption, and delay constraints.

Generally, the 3D-architecture, as presented in this article, can further be extended using meta-surfaces which provide additional options for optimization [21].

Reference [22] addresses optimization of computation offloading decisions to minimize the sum energy consumption of ground users, while adhering to the coverage time and computation capability constraints of each LEO satellite.

Furthermore, in [23] fine-grained joint offloading and caching scheme based on orbit-ground collaboration have been investigated.

For vehicular users, [24] proposes an integrated terrestrial and NTN that incorporates edge computing facilities onboard various platforms such as LEO satellites, HAPs, LAPs, and road side units. The paper further designs a partial computation offloading process allowing vehicles to offload a portion of their tasks to selected edge nodes while processing the rest locally, aiming to minimize the overall latency and energy requirements.

Reference [25] states that UAV-enabled MEC networks offer transformative potential by integrating UAVs as UEs, MEC servers, or relays to address computational challenges in diverse environments. These networks utilize optimized UAV trajectories and short-distance line-of-sight communication to ensure seamless service delivery in hotspots, disaster zones, and remote areas lacking terrestrial infrastructure. However, the paper highlights persistent challenges such as efficient resource allocation within UAV constraints, secure and reliable offloading techniques, and coordination in multi-UAV scenarios. Additionally, the application of machine learning for intelligent UAV control and advanced energy optimization strategies is identified as critical for realizing the practical deployment of UAV-enabled MEC systems.

A. MEC IN STANDARDIZATION FROM 3D-NETWORK PERSPECTIVE

Standards for MEC have been elaborated by the ETSI MEC ISG and 3GPP. Starting with the focus on Mobile Edge Computing, to which the abbreviation MEC initially was referring to, ETSI broadened the scope and included Fixed and WLAN Communication in the standards changing MEC from Mobile to Multi-access Edge Computing, making it independent on the underlying access technology. Although in scope of the ETSI MEC standard, NTN technology and the use of aerial vehicles, such as drones, have not been considered so far. As mentioned, satellites became part of the standard as NTN in 3GPP from Releases 17 and will introduce the regenerative setup with full gNB as satellite payload in Release 19 which would be the enabler for MEC in space.

Generally, the possible implementation of MEC at a satellite system depends on the underlying communication system standard that is used to build the system and the services that need to be provided. For the provision of RNI services a coupling with the data plane is needed, i.e. the Mp2 interface. Nowadays, most satellite systems are based on proprietary technology, not necessarily providing this interface. One open standard for lower and higher layers of SatCom systems that is widely applied for internet connectivity is the DVB-S suite of standards (e.g., the most recent DVB-S2x). However, they are not considering any interface to MEC for accessing and controlling radio layer information. On the other hand, MEC is a native part of the 3GPP system and the necessary interactions and enablers of MEC with the 3GPP system are already specified, whereby a necessary effort towards the inclusion of NTN into the MEC picture has been started with a dedicated study item [26]. In more detail, this study addresses some key issues arising from the inclusion of MEC in NTN and provides some architecture updates and related solution implementations that might later mature to a normative work. In [27] the general architecture for enabling edge applications is presented and includes in Release 19 enablers for satellite access and describes in the (informative) annex deployment options for GEO/MEO/LEO satellites. It should be differentiated between a dynamic service area (MEO/LEO) or not dynamic (GEO).

In standardization, drones are a major use case as UE and are also investigated to host gNBs but are not referred so far to host MEC.

Considering the 3D-Network, in particular, it provides the option to connect to multiple MEC platforms at the same time or open multiple paths towards these. This means that space, aerial, and terrestrial domains can communicate and exchange user and app information of the MEC platforms. In 3D-Networks not only the UEs are mobile, but also the moving base stations make it necessary to transfer MEC state information among the nodes. Although ETSI is looking at federated architectures, i.e. transferring services from a MEC system of provider A to a MEC system of provider B, all this is not supported by the standards at the moment. For multi-connectivity 3GPP specifically excludes MEC by not allowing LADNs together with multi-access PDUs on transport layer using Access Traffic Steering, Switching and Splitting (ATSSS) [28]. Consequently, techniques for placing MEC services, offering them on multiple domains, flexibly perform user data migration and routing of application data needs to be elaborated.

IV. USE CASES OVERVIEW

MEC addresses a multitude of use cases and services, starting from IoT applications, V2X communications, logistics, optimized video and audio distribution to Augmented/Virtual Reality solutions and private networks. Due to the ability to merge ubiquitous coverage with low latency and the ability to rapidly deploy services, MEC in 3D-Networks is considered an enabler for new services that were not possible before. Considering IoT, MEC can be used to process and fuse data before it's transmitted to the next hop. One example would be the triggering of any event by a sensor which might exceed a specific threshold. MEC apps can read the sensor data and trigger further actions preventing high frequency data distributions. Similar holds for fleet management in logistics, facility management, and AI/ML applications. The algorithms can directly run at the edge and only if an event of interest occurs, data is forwarded saving transmission bandwidth and energy.

The ability to process the uplink data on the MEC nodes in 3D-Network strongly reduces latencies for producers and consumers of services if they both are in the same local subnetwork served by the base station. Especially for local machine steering use cases like for the smart agriculture this creates a strong advantage as outlined in the following.

A. USE CASES IN AGRICULTURE

The field of agriculture is constantly utilizing a variety of technological concepts aiming to enhance productivity, efficiency, sustainability and cost efficiency. This led to an increasing demand for ubiquitous connectivity, higher data rates requirement, and lower latency to be able to handle the increased amount of shared data between the agricultural machinery. It is important to acknowledge the connectivity challenges in rural areas with the connectivity being completely absent or of inadequate quality compared to connectivity in urban areas. This lack of connectivity is blocking innovation in smart agriculture and hindering further improvement of the services. Edge computing is currently being considered for agricultural applications due to its ability to enhance the performance within which the data is being processed. Hence, MEC with the improved processing time for the shared data among machinery is enabling advanced services of smart agriculture, also being referred to as precision agriculture [29]. Some applications of MEC in smart agriculture are for example, video based remote support in which data is preprocessed to generate alarms or identify objects, sharing data and analytical results of field work of agricultural machinery to the cloud, or among cooperatively working agricultural machinery through machine-to-machine- communication approaches. MEC, hereby, is improving with close to field communication, reducing the time until a service is distributed which allows for lower safety margins, which might serve as an enabler for safer and more precise steering of a machinery fleet/convoys. In addition, few examples are listed below on the significant benefit that 3D-MEC brings to agricultural use cases:

- Adaptive QoS management: The ability to dynamically adjust data rates and QoS according to the available network performance is a significant benefit of 3D-MEC in agricultural settings. For instance, if the network experiences congestion or limited bandwidth, MEC can reduce the video resolution or frame rate to maintain a continuous stream without interruption. This adaptability is particularly important in agricultural environments where connectivity may fluctuate due to geographical challenges or infrastructure limitations. By ensuring a steady flow of information, farmers can continue to monitor their operations effectively, even under less-than-ideal network conditions, where continuity of service is more valuable.
- Data prioritization: In scenarios where immediate decisions are required, such as responding to equipment malfunction, 3D-MEC can prioritize video data transmission over less critical streams. By ensuring that high priority streams receive the necessary bandwidth, farmers can react swiftly to changing conditions, thus minimizing potential losses. This prioritization is especially relevant during critical phases of crop production when timely information can significantly impact outcomes.
- Efficient resource utilization: By efficiently managing varying data rates, 3D-MEC helps optimize the use of network resources. This efficiency is particularly important in rural agriculture settings, where connectivity may be limited. Instead of overloading the network with high bandwidth demands at all times, MEC allows for a more balanced approach that adapts to the operational context and prevents unnecessary strain on the network.

Technologies that are utilized by smart agriculture are many, namely, positioning, remote sensing, telemetry & data analytics, and automation & robotics, among others. Given the increasing reliance on these technologies, it is essential to explore specific use cases that illustrate how MEC enhances the operational efficiency and responsiveness in agricultural practices.

B. TELEMETRY & INFIELD DATA SHARING

The objective of telemetry systems is to give the user more control over the farming processes by analyzing and visualizing telemetry data in a timely manner. Some examples of the data collected with telemetry equipment are operating hours, fuel consumption, diagnostics of machines, machine settings and productivity [29]. Dedicated sensors and cameras are used and combined with satellite positioning services. It is important for the machine operator in the field to have low latency access to the data to be able to benefit from data observation in real-time.

1) REMOTE CONTROL & MONITORING

The increased productivity enabled by increasing autonomy has led to very complex machines which require expertise to be maintained and repaired. Human Machine Interfaces (HMI) based on the previously mentioned sensor data can be utilized here to remotely control and monitor the situation. A close to the field access is also beneficial for cooperation of involved parties, e.g. the farmer in the field and closed by technicians to provide guidance. Sending dedicated expert technicians can be minimized, saving both cost and time, which both are essential for farmers while harvesting and throughout the seasons. A specialist with MEC access could provide support close to a group of farmers of a bigger area and decide based on the situation whether it is still essential to physical approach and provide support. This can even be combined with pre-checking a machine remotely which improves efficiency of repairs [30].

Another use case for remote support and monitoring is tuning of the machinery. Farmers need to tune their machine settings and adapt it to the current conditions of the field and plants growing before planting or harvesting, which might also trigger the need for remote support. Such remote support and monitoring systems have been developed and are offered by a variety of manufacturers of mobile agricultural equipment [31]. With MEC the capabilities of those systems can be advanced. Additionally, in the case where remote support would not be sufficient on its own. Considering that the support provider is keeping a database with the specialty and location of their technicians. The user having a close connection would allow to match to the closest and most relevant support personnel.

Nevertheless, such scenarios can suffer from the challenging environment of rural areas and the poor connectivity that can be an obstacle against initiating a seamless connection with a remote support center. Hence, in this case edge computing technology can enable efficient remote support experience on both ends and contribute to preventing exhaustive repairs and increasing productivity [30].

2) MACHINE-TO-MACHINE COMMUNICATION

Driving agriculture towards automation calls for more precise and effective coordination between the agricultural machinery or vehicles in the field. Machine-to-machine communication refers to the ability of machines to communicate among each other through direct links between them. This enables working machines to share various types of data among each other such as, coverage maps, guidance trajectories increase the efficiency or work through coordination between multiple agricultural machineries. Operations like seeding, spraying or unloading harvested grains can highly benefit from an efficient machine-to-machine communication solution, not only through enhancing the efficiency and coordination of machine work, but also through minimizing costs of wasted resources during the operation [32]. Taking unloading as an example, which involves coordinated transfer of materials such as grains from harvesting equipment, e.g., combines, into transport vehicles, e.g., grain trucks. Such operation utilizes wireless communication to transfer data including telemetry data and camera imagery while also enabling decision-making processes that facilitate real-time coordination between different agricultural machines. Considering the amount of data generated by modern agricultural machinery -ranging from GPS positioning and telemetry to real-time sensor outputs- the need for reliable and responsive connected systems becomes paramount for ensuring seamless coordination among machines. The integration of MEC addresses these challenges effectively. On the one hand, MEC can help offload some of the resource-intensive tasks that are typically performed on-board the machine, such as data processing and analysis, hence freeing up computational resources for more time-critical operations. On the other hand, MEC also facilitates secure and efficient data distribution. By fusing sensor data close to the field, MEC can deliver the required information to the farmers with low latency and enable them to monitor the situation and make informed decisions timely whenever required.

3) THE FUTURE OF AGRICULTURE

As the industry moves towards smart farming, the use of Augmented Reality (AR) in agriculture becomes increasingly relevant, offering innovative solutions for real-time data visualization, decision-making, remote assistance, and remote autonomous driving. MEC plays a critical role in this evolution by providing the low-latency data processing ad high-bandwidth connectivity necessary for seamless AR experiences. Additionally, MEC's ability to dynamically adjust QoS ensures that AR applications remain responsive and enable farmers to make informed decisions quickly, despite the challenging connectivity conditions often found in rural areas.

C. VIDEO ORCHESTRATION AT THE EDGE ENABLING APPLICATION CONTROLLED QOS

Generally, one application that can benefit from MEC infrastructure, as also motivated by the smart agriculture use case, is critical video distribution. For instance, video applications that facilitate interactive interworking with real-world objects. This includes remote operation of machines or other interactive activities (e.g. remote assistance). This is not only in smart agriculture, video and telemetry data streaming is in general crucial for different verticals and industry use cases involving the remote control or supervision of machines due to its ability to provide real-time visual feedback and monitoring. In this case, low latency and continuous service availability are more important than high data rates. We expect that the application adapting the produced video (or telemetry) bandwidth based on network information makes such services much more reliable and keeps the latency as low as possible.

For video application we see the following requirements that might limit the network node used, i.e. the satellite altitude:

- teleoperation: overall glass-to-glass latency must be lower than 100ms for moderately fast-moving machines. 50ms for fast moving machines
- slow moving machines (around 7 km/h) - 300 ms is doable but not optimal
- interactive conference calls - the lower the latency the better but 300ms seems max. for an acceptable experience

The possible QoS aware MEC app functions for video distribution are:

- As mentioned, adapting the data rate produced by the application and thus reducing network load which in turn reduces jitter and latency. One special case is to switch off the production of streams which are not retrieved by any clients. Especially when resources are limited, MEC apps can allocate more resources to critical tasks and reduce the performance slightly for less critical tasks without affecting the user experience. Reorganizing data streams by reassociation clients to other instances of the application (in case of multiple available connections.
- Distribution of video streams to many clients located in different geographically distinct locations of the network. MEC helps to limit the overall network costs if MEC apps send only one copy of streams to each of the locations. Local MEC instances can then fan out the data locally – thus limiting overall network cost and lowering latency by avoiding congestion. In contrast to IP multicast, this leaves the control of the video stream distribution on application level which, again, is interesting for QoS management with focus on low latency and high reliability.
- Removing a fraction of clients by signaling that the capacity of the system has been reached.

- Using dynamic instantiation methods to create new MEC service instances resulting in minimal network cost or allowing for temporary autonomous operation

The flexibility offered by these MEC functions allows to manage network resources effectively and maintain the required level of service for all users. In the following we are focusing on the first since in most MEC uses cases main goal is on low latency. An example is transmitting a video stream from a source, e.g. in a tractor as shown in Figure 4. On the tractor a client app is operating and on the access nodes (the satellite and the terrestrial gNB in this case) a MEC platform hosts the dedicated MEC-app that monitors the RNI and provides this feedback to the device app. The video stream is forwarded from the access nodes to a provisioning server which provides it to its destination. If network conditions change, and with this the QoS performance, the feedback from MEC RNI service will be used to change the source data rate, i.e., at the tractor. In the case of video, the encoder can be instructed to produce the allowed data rate. For telemetry data, the pre-aggregation (e.g. averaging period) will be adapted to the bandwidth requirements. Network buffering, packet retransmissions or losses are minimized by ensuring that the video stream aggregated data rate is not exceeding the current network's capacity, and hence, optimizing latency.

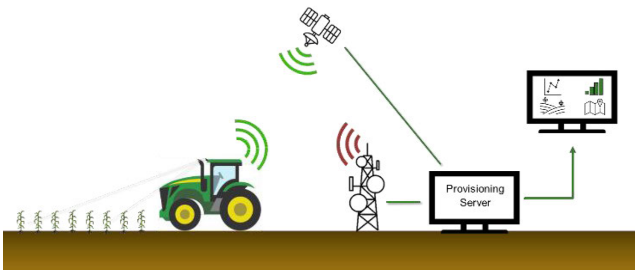

FIGURE 4. Use case for application controlled QoS.

This capability enhances operational efficiency, safety, and accuracy by allowing operators to oversee and control machinery from remote locations. High-quality video streams facilitate immediate detection and response to anomalies, reducing downtime and maintenance costs.

Considering the 3D-Network, in most cases more than a single link for transmission might be available which needs to be taken into account to optimally provide low latency services, which can be achieved by managing topology changes on MEC app level again, for avoiding packet retransmissions. This means, that a video orchestrating MEC app can select a domain that fulfills the requirements of a stream, and by using the knowledge of the current performance of the underlying network, consuming the RNI service of the selected domain.

In order to outline alternatives to the MEC approach for this case, there are several standardized technologies to convey information about the network state to the applications. User plane technologies like L4S [33] is an in-band approach (IP header fields) in the payload PDUs to signal network congestion information. The advantage of this approach is that reactions at the millisecond level are achievable. With MEC it is a control plane approach which result in reaction times in the order of seconds. We do this to pave the path to take more information into account for the data rate adaptation algorithm in the future. Examples for this can be packet loss counts signaled by stream receivers attainable only in the order of seconds.

V. EXTENDING ETSI APIs TO 3D-NETWORKS

The MEC platform itself is providing services via a REST-HTTP interface as well as making accessible services offered by MEC-apps. MEC apps on their side, may also consume services from the MEC platform. This relation and the MEC platform components on the MEC host are presented in Figure 5. It shows two exemplary MEC-apps providing their services and the MEC platform providing service registry, traffic rules and DNS handling necessary to make these services available. Last, the platform can include the MEC platform services described in the following. ETSI ISG MEC specifies and provides open source APIs for MEC application developers or management functions [34]. The aim of these APIs is not to provide a complete set of functions and cover all possible MEC services but to provide for some main services APIs for interoperability. Apps can use these APIs for interacting with the MEC platform, e.g. to de- or register services, get UE information or RNI.

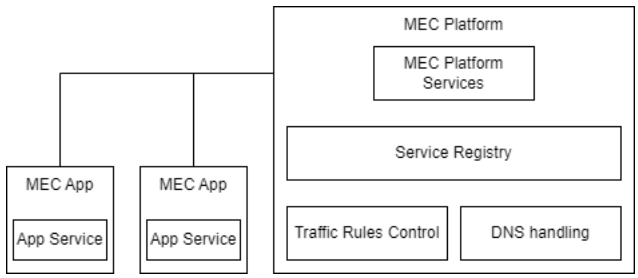

FIGURE 5. MEC platform architecture and services [35].

For an overview we classified the standardized APIs into groups:

MEC App Management: in this we include APIs offering services for app lifecycle and generals app management

- Application Mobility Service API: is enabling relocation of user context or MEC app instances, between MEC hosts or between MEC and cloud. It allows to query neighboring app instances.
- Application Package & Lifecycle API: used for app lifecycle management between orchestrator and platform manager, event handling and service availability tracking.
- Operation Granting API: creates and manages applications instances from orchestrator to platform manager.
- MEC Platform Application Enablement: divided into MEC Application Support API and MEC Service Management API. This API is the framework for the service

registry, traffic rules and DNS handling services illustrated in Figure 5.

- Device Application Interface API: allows to manage device application context and location constraints.
- MEC Federation Enablement API: allows to retrieve information about the MEC system, (i.e. ID, name, and provider), discover other MEC systems, and enable information exchange between different MEC systems.

Network Management: these APIS categories all that are offering data plane (RNI) services towards MEC apps.

- Radio Network Information API: get information form mobile networks, e.g. layer 2 measurements, radio access information.
- Traffic Management API: divided into Bandwidth Management API to manage bandwidth allocations, and Multi-Access Traffic Steering API to handle QoS requirements for multiple access links.
- MEC WLAN Information API: WLAN information, i.e. access point information, station information, and measurements.
- Fixed Access Information API: fixed connection information, e.g., device information, last mile technology, cable line, and optical network information.
- V2X Information Service API: allow to query information from V2X networks. Furthermore, request the predicted QoS correspondent to potential routes of a vehicular UE and to publish V2X messages.
- IoT API: allows to register and manage IoT platforms, including IDs, position, meta data, and dedicated traffic rules.

User Management: The apps provide user related information additionally to RNI services.

- Location API: UE location management, organized in zones and areas. Event handling.
- UE Identity API: allows to manage user identity tags, i.e. retrieve register and de-register resources.

An QoS Measurement API, an Enablement for Costumer Self-Service, and a Sensor Sharing API are currently under development.

Analyzing the available APIs, due to the virtualized architecture, which decouples the MEC platform from the infrastructure, most MEC App Management a MEC Platform Management APIs will work in other domains and in 3D-networks. But multi-domain operators can benefit from extending the current APIs with domain information. This way they can tune apps and platforms for different domains. Overall, we see the following APIs that require adaptations to enable the benefits of a 3D-Network:

- **The Application Mobility Service API** could be advanced into a 3D Mobility API that provides additional features for moving to another domain, see adjacent app instances in other domains or select preferred domains. Also, location-based switching shall be supported e.g. to consider white spots in terrestrial infrastructure. Functions for synchronization between domains as we introduce them in the next section could be managed via such API. The mobility service must be aware that the network topology is changing, updates cycles must be adapted.
- The ETSI federated concept with the **MEC Federation Enablement API**can be used to connect to MEC platforms of other operators. For MEC app developers an extension with a system info field with the domain information of and expected QoS characteristics of this domain would be beneficial.
- Also, the M**ulti-Access Traffic Steering API** is a good baseline for the 3D integration, it provides all methods necessary for QoS management via multiple access technologies. The preferences used to register an app at the service and the link information could be extended by the domain to allow developers to select or de-select certain domains or networks with dedicated characteristics.
- **The Location API** in principle provides already all features necessary for app developers, but considering NTNs and HAPs, zones could have different sizes, cells also covering a wider area and potentially more users. For app developers it might be better to introduce different layers of zones.
- **The UE Identity API** must consider that a UE connected to different domains can have several identities within the network or can be reached via multiple IP addresses.
- Another aspect is that the **Device Application Interface** can provide the MEC app location in terms of an area as coordinates. Given that the MEC platforms can move together with the gNB requires some adaptations.

For the network management APIs there are two options for adding additional domains and making the application aware of this for QoS management, (1) either they are seen as part of one mobile network (e.g. a joint 3GPP NTN and terrestrial system) in which case the RNI API would need to be extended and should at least include a flag to indicate the currently used domain, or (2) dedicated APIs are used for the domains which is in line with the current ETSI approach and simplifies parallel connections via different domains. In such case we propose to introduce the following new APIs and features:

- **SatCom RNI API:** Providing the same information as the RNIS API, additionally information about the orbit shall be provided, which can be high level (LEO, MEO, GEO), but also deterministic parameters of the satellite system can be provided such as trajectory of satellites, current position, expected hand-over timing. A prediction of the channel conditions could be provided (based on AI/ML) on two scales: short to medium time to cover channel related or general fading effects (e.g., due to weather conditions) and long term to cover daily traffic load distribution patterns.
- **Aerial RNI API:** Providing same information as the RNI API, and similar to the SatCom API, the location and trajectory, expected hand-over time. Device

information such as battery status, expected flight time can be helpful.

- **Topology API:** in order to support the 3D Mobility API or the app directly, the topology API provides information of the 3D-Network topology which is changing over time. In case of satellites this is deterministic and could be provided by the SatCom RNIS, in aerial case this must be manually introduced by an operator. It should include positions and availabilities for each domain allowing a network wide operation. Furthermore, the topology could be based on Location API, e.g. by abstracting a zone to a subnet which has a backhaul link characteristics information element. This offers also the capability to the app developer to decide which domains are fulfilling the requirements of the services and which to exclude, e.g. not using a GEO satellite for ultra-low latency applications.

VI. 3D-MEC MOBILITY

ETSI defines stateful and stateless services which can be treated differently for mobility. Generally, with mobility in MEC means that the user leaves the area served by one MEC instance and moves to the next. This is not necessarily linked to a single base station. If the service is sate full, i.e., it builds on user context data, the state data of the user must be migrated to ensure service continuity. If it is a stateless application still the MEC-app instance itself must be reallocated or at least be available on the second MEC node. Following [35], for migration the following steps need to be performed:

- Mobility enablement and registration: allowing to register the application for mobility services
- User context transfer initiation: various triggering and detection procedures
- Transfer preparation: optional step to prepare data
- Transfer execution: actual transfer and synchronization
- Application traffic path update: reconfiguring of the data plane to reach the new MEC instance
- Completion: clean up procedure on initial host system

The reallocation of both, stateful and -less, in 3D-Networks can be within a single domain, e.g. space, or in between the domains, from space to terrestrial. In first case, it could be handled as independent systems, so that follow MEC federation procedures where MEC data is transferred from provider A to provider B or only within provider A's network. For instance, provider A would be the terrestrial domain MEC provider, provider B the space-based. In case of fully integrated 3D-Network, all domains would be (at least in parts) fully inter-connected, i.e., a transfer is possible between almost any node at any time. In this case, it must be pointed out that a decision to migrate from terrestrial MEC instances to NTN instances can be done based on availability of the terrestrial network, i.e. at a certain power threshold a hand-over to NTN occurs including the MEC migration. But to move from NTN nodes to terrestrial needs another trigger is needed as one of the characteristics is the large coverage

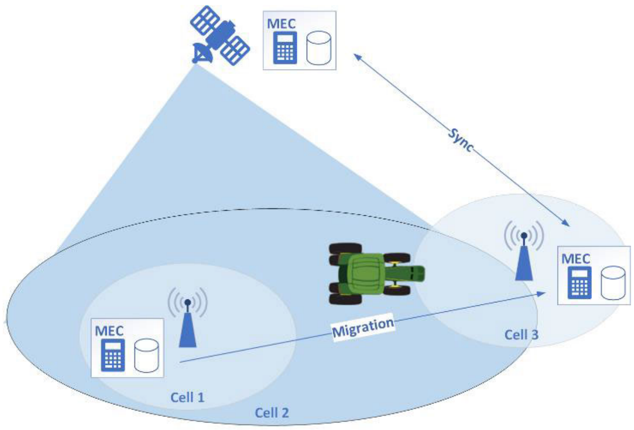

FIGURE 6. MEC migration in 3D-networks using synchronization.

area that is potentially available although the user might move back to terrestrial coverage. As example, if a user moves out of a terrestrial cell (e.g. cell 1 in Figure 6) into NTN coverage (cell 2), the loss of signal can trigger the migration. If the user enters the next terrestrial cell (cell 3), an NTN connection is still available.

A general overview of MEC user data migration strategies can be found in [36]. It should be mentioned that, especially when connecting a 3D-Network the possibility to synchronize app instances between the domains is given. Copies of the user context can be synchronized among the domains, while intra domain migration can be performed as done in non 3D case. Figure 6 illustrates ne example for this. A farmer in the field is connected to two domains, e.g., a LEO NTN and a terrestrial base station, both are linked with a MEC platform that synchronizes user data in background. If the user moves to another terrestrial base station the MEC migration will be triggered in terrestrial domain (from cell 1 to cell 3), and if a LEO hand-over in space domain occurs MEC data is migrated from one satellite to the other. State data from terrestrial domain is synchronized with the NTN domain and the other way around. If the UE on the tractor disconnects from one domain, e.g. by moving out of terrestrial coverage, the necessary user data for continuous low latency service is already present at other domains, as illustrated between cell 3 and the NTN node in Figure 6. Assuming the farmer moves out of the terrestrial coverage the system switches entirely to the NTN and the NTN-MEC platform starts taking over the low latency services. User context data and MEC apps are already available at the platform and operation can seamlessly continue. If the farmer returns into an area with terrestrial coverage, a new MEC instance with the user data is created in this domain from the NTN domain. This increases availability and resilience. A loss of connection without the NTN back-up might otherwise lead to a loss of data and to a stop of operation. The loss of data and services are mitigated by using parallel domains.

The 3D Mobility API together with the Topology API can be used to implement the handling of multiple instances for each domain. For synchronization the NTN broadcast capability could be used. Synchronization could be done directly between the MEC platforms if direct links exist or via a central platform which, however, might introduce additional delay.

In order to support the migration within the domains, hub-nodes (e.g. the ground station in SatCom, or a pilot center in Aerial case) with some higher storage and processing capabilities can be utilized, which are also synchronized with the edge nodes.

VII. CONCLUSION AND OPEN POINTS

We have elaborated on MEC in 3D-Networks. by focusing on smart-agriculture use cases and video distribution, an approach for QoS control from the application using the RNI from the MEC platform has been presented. The dedicated algorithm and inputs for such a controller is the next step. We discussed that awareness of the used domain (space, aerial, terrestrial) for the MEC-app and its developer is beneficial and that the MEC framework should support it. The biggest benefits can be achieved by letting MEC applications estimate the currently available bandwidth and related updates using the collected RNI. User and base station location information can help the applications to dynamically adapt the data flow to the topology, which is especially interesting for NTN with moving base stations. But also, the MEC system itself could provide predictions on link performance. This could be enabled by AI/ML algorithms monitoring the link behavior.

For 6G a deeper integration of terrestrial and NTNs is expected and as such MEC needs to consider these updates which would mean moving from a federated architecture with a terrestrial and non-terrestrial MEC provider to direct migration and service hand-over between the nodes of different domains. We have pointed out potential gaps and updates on the ETSI APIs. Furthermore, we have proposed new APIs to support MEC in 3D. Main challenges is the selection of the right domain and the time varying topology of the network, since in this case also base stations move. Although MEC is a research topic in its application at the space domain and within a 3D-afrchitecture, mainly with the focus on efficient task distribution, many new research topics and open points appear. Some examples are as follows:

- Considering the hardware constraints of future satellite setups and optimize the resource usage. The feasibility of certain applicable apps and services will strongly depend on this.
- User data migration between MEC nodes on satellites in various orbits.
- Related to the previous, as pointed out, the migration between domain including the problem on overlapping cells, for NTN/terrestrial migration. This will strongly depend on the level of integration of the domains.
- Last, also, security is an issue to be considered. The data storage location might raise security constraints which can be an additional point to be considered also for MEC app developers.

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