Use Cases Employing a Machine Learning Network Architecture

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Abstract. 5G mobile networks will soon be available to handle all types of applications and to provide services to massive numbers of users. In this complex and dynamic network ecosystem, an end-to-end performance analysis and optimisation will be "key" features to effectively manage the diverse requirements imposed by multiple vertical industries over the same shared infrastructure. To enable such a challenging vision, the MARSAL EU-funded project [1] targets the development and evaluation of a complete framework for the management and orchestration of network resources in 5G and beyond by utilizing a converged optical-wireless network infrastructure in the access and fronthaul/midhaul segments. In this paper, we present the network architecture of the MARSAL, as well as how the experimentation scenarios are mapped to the considered architecture.

Keywords: 5G, Cell-free (CF); distributed cloud; network automation; machine learning (ML); secure multi-tenancy.

1 Introduction

Communication networks currently undergo a high number of structural and functional changes that are associated with the need to support current and future demands (e.g., mobile traffic is expected to grow three-fold within 2025, as a result of predicted 10 million devices per km^2 and 100 billion devices worldwide), and with the commitment for the provision of ultra-low latency and reliability [2]. With the advancement of technology, the communication nodes will be inseparable from human social activities. To truly realize the diverse connection and interaction needs “at any-time and anywhere”, future networks need to have specific characteristics, such as: Omnipresence (covering air, ground, space and sea); All-in-one (Internet of Everything); Omniscience (with the help of various sensors), and All-purpose (based on big data and deep learning). The same circumstances are also forecasted for other fields, such as Industry 4.0, health sectors, manufacturing industries, and autonomous industries, where revolutionary changes are underway. Another major challenge of the future 6G networks is to reach climate goals by reducing CO_2 emissions. This will be achieved through improved operational and management efficiency and energy consumption reduction [3-4].

To tackle these challenges, several steps should be taken from the perspective of network concepts and technological aspects, to ensure economic developments, reliability and increased energy efficiency [5]. Key advances are required both at the network design and network management levels, as well as at the network security level to accommodate highly dynamic traffic demand, achieve energy reduction and provide cost-effective multi-level resource pooling in a secured way. Specifically, the network should support multiple distributed edge nodes and a multitude of access points (APs) coordinated by entities in a low-cost and near-zero latency manner. A unified and hierarchical infrastructure is essential to provide intelligent management of communication, computation and storage resources. The incorporation of efficient Machine-Learning (ML) algorithms [6] can further improve network efficiency. Additionally, infrastructure sharing is a sustainable way of lowering the network’s capital and operating expenditures. Furthermore, support of multiple tenants is the key enabler of the new sharing economy business models in the telecommunication industry. Novel mechanisms for resourceful and efficient management of shared networks are necessary to enable a plethora of use-cases and industry verticals targeted in beyond-5G (B5G) and 6G systems [7-11].

In this context, MARSAL proposes a novel converged optical-wireless configuration based on the Cell-Free (CF) concept that targets flexible connectivity of a massive number of Radio Units (RUs) and aims to unlock the potential of user-centric CF deployments in 6G networks, while aligned with the O-RAN initiative [12]. The paper is organized as follows: In Section 2, we present the MARSAL overall architecture. Section 3 presents use cases enabling cell-free networking in dense and ultra-dense hotspot areas. Section 4 presents use cases for cognitive assistance, as well as security and privacy implications. Each experimentation scenario is mapped to the MARSAL architecture. We built on our previous paper [13], where we presented the main use cases and the involved stakeholders. Our innovation is focused on how these use cases are applied to our proposed ML network architecture.

2 Network Architecture

The proposed approach is illustrated in Fig.1 and consists of an evolved 3GPP NG-RAN [14-15] that is extended with emerging CF technologies, and of an innovative optical transport domain that deploys a distributed edge infrastructure with Data Centres (DCs) structured in 2 tiers, featuring Regional Edge and Radio Edge nodes.

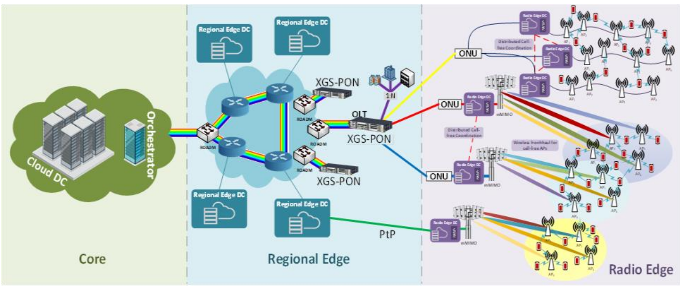

Figure 1: The MARSAL network architecture

At the radio edge, the proposed radio network configuration is based on two radio access solutions. The first solution is based on the interconnection of multiple RUs (Radio Units) with the DU (Distributed Unit) via a bus configuration (upper right part of Fig.1). This approach aims at addressing the most pressing CF limitations, as well as dealing with the fact that the clustering literature only considers disjoint RU clusters, even when multiple Central Processing Unit (CPU) nodes are assumed; thus, this novel approach will allow deployment of CF networks in beyond 5G RANs (Radio Access Networks) [16-18], based on the utilization of dynamic cluster-formation algorithms. The dynamic feature of such RU clustering algorithms is based on the CF CPU fragmentation in multiple DUs, a procedure that triggers the support of distributed computation and coordination between RUs and between DUs. Under this networking configuration, clusters of RUs, connected to multiple DUs, jointly address inter-DU and RU-DU coordination for the first time, while also considering fronthaul and midhaul constraints. The optimal cooperation levels between RUs and DUs and between DUs can be guaranteed through the application of dynamic adaptability algorithms of the involved entities' coordination levels.

The second solution for MARSAL's radio edge is based on a mmWave Hybrid Fronthaul for CF networks. Wireless CF Massive MIMO fronthauling solutions have been already proposed in the literature [19-21] targeting efficient interconnection of multiple APs to the CPU, by considering CF-based network configurations [22]. MARSAL's novel Hybrid MIMO fronthauling approach targets to provide support to CF networks through advanced beamforming solutions. In this way, the various RU topologies can be supported, where RUs can be reassigned to different DUs on demand. For the provision of this point-to-multipoint (PtMP) connectivity, MARSAL targets a new design of a mmWave radio node, by utilizing an RFIC (Radio Frequency Integrated Circuit) mmWave beamforming transceiver and phased-array antenna module [23]. In this way, diverse innovations can be provided by the MARSAL partners, related to new formulations of dynamic RU clustering and adaptive coordination problems, and studying the effect of functional splitting in the context of the CF fronthauling. As in the first radio-edge solution, MARSAL's mmWave Hybrid

Commented [RB1]: I think we should reword this but not sure how yet fronthaul approach also considers inter-DU coordination, targeting to introduce the interface for direct interconnection of DUs for the first time.

At the regional node, two SDN (Software Defined Network) controllers are considered, for managing the optical and wireless networking resources, respectively. The controllers at the edge are coordinated by the Network-Slicing-as-a-Service (NSaaS) subsystem at the core-tier Network Function Virtualization Orchestrator (NFVO), communicating via the OR-Vi interfaces [24]. Thus, intelligent traffic management and load balancing among PtP (Point to Point) and PtMP traffic via the appropriate scheduling of the two SDN controllers can be implemented, while improved power consumption can be achieved via traffic rerouting and shutting down individual SFP-OLTs (Small-Formfactor Pluggable – Optical Line Terminals[1]) during light loads. Additionally, the implementation of predictive slice reconfiguration that provides traffic fluctuations' prediction can trigger slice reconfiguration, thus increasing statistical multiplexing while minimizing the impact on Service Level Agreement (SLAs).

At the core, the orchestrator is integrated to the NFV infrastructure [25-26] and supports coordinated resource allocation for MEC (Multi-access Edge Computing) applications [27] and network functions by coordinating two diverse management and orchestration subsystems (i.e., the NFVO and the MEC Application Orchestrator (MEAO)) [24]. Moreover, MARSAL aims at achieving self-driven and closed-loop autonomy for the Virtual Elastic Infrastructure to enable dynamic orchestration and management of networking and computing resources. To this end, MARSAL incorporates a distributed approach that involves Analytic Engines (AEs) at all tiers of the Edge infrastructure, and Decision Engines (DEs) in the two Core-Tier orchestration subsystems, targeting to overcome the isolation and underutilization of resources deployed at Edge nodes, through resource sharing.

For the network security pillar of MARSAL, three main contributions are considered in the overall architecture. Firstly, the solution for private and secure exchange of data among tenants through decentralized framework for confidentiality and trust that is based on novel data privacy representation techniques that are integrated into a smart contract platform. Secondly, the solution for ensuring data security through different policies and distributed storage of the data. Finally, the solution for network security protection through two different technologies that allow the analysis of the data transferred by the network in real time. Thus, MARSAL do not limit itself to the typical network security (also covered using accelerated hardware ML), but it also aims at protecting the data stored in the cloud, allowing secure multi-party computation and distributed data storage, while also it allows the cooperation among tenants by allowing them to automatically sign smart contracts and share data in a privacy preserving way.

[1] An SFP is a compact, hot-pluggable network interface module format used for both telecommunication and data communications applications. An SFP interface on networking hardware is a modular slot for a media-specific transceiver, such as for a fiber-optic cable or a copper cable. A GPON (Gigabit Ethernet Passive Optical Network) SFP module transmits and receives signals of different wavelengths between the OLT at the "Central Office" side and the ONT at the end-users' side. GPON SFPs utilize both the upstream data and downstream data by means of Optical Wavelength Division Multiplexing (WDM).

3 Cell-free Networking in Dense and Ultra-Dense Hotspot Areas

During high-popularity events, both indoors and outdoors, a large number of users tend to stream high volumes of content from multiple handheld devices, thus creating a heavy burden to the network infrastructure both in the uplink and in the downlink. In Cell-Free massive MIMO (Multiple Input Multiple Output) [28-29], users are simultaneously served by multiple cooperating APs (with a low number of antennas) instead of associating each user terminal to a specific cell of a gNB (next generation NodeB) equipped with a large number of antenna elements. Thus eliminating cell boundaries, which can significantly reduce or even eliminate inter-cell interference and significantly improve user fairness. Therefore, the canonical cell-free mMIMO (massive MIMO) [30-31] shows 2.5X improvement over small cell in terms of per-user UL (Uplink) network throughput and it can achieve 95%-likely user throughputs of 4 Mbits/s and a mean throughputup to 8 Mbits/s on a 20 MHz bandwith [32-33]. This makes cell-free networking, an emerging 6G technology, extremely suitable for hotspot areas, as it can offer seemingly infinite capacity and fully mitigates the problem of cell-edge users having lower data rates. Like 5G the Small-Cell Network (SCN) with the concept of non-cooperative base stations (BSs) can only serve up to 200-meter cell-radius, reduce power in signal transmission up to 10 Watts, and achieve the mean spectral efficiency 3 Mbits/s. Network densification through small-cell deployments, even with cellular Massive MIMO, are outperformed by Cell-Free Massive MIMO [34]. This is because of the interference generated by the neighboring cells and increasing numbers of uncoordinated and lightly loaded small cells in the network; an in-depth analysis of small cell deployments is provided in [35]. We will overcome the Inter-Cell Interference (ICI) problem [36] and uncoordinated deployment of such SCN by the distributed cell-free RAN solution of MARSAL where the dynamic adaptability algorithm will enable RU-DU and DU-DU coordination. Such a coordinated solution can further improve the system capacity/spectral efficiency of future 6G networks.

3.1 Dense User-Generated Content Distribution with mmWave Fronthauling

The main objective of this scenario is to demonstrate and evaluate MARSAL's cell-free RAN in terms of increased sum capacity and user fairness gains, and the adaptivity of dynamic clustering and RRM (Radio Resource Management) mechanisms in managing connectivity resources in a dynamic environment with varying hotspots areas. Furthermore, an additional objective of this scenario is to evaluate the Hybrid MIMO Fronthaul [37] in terms of its ability to offer dynamic fronthaul connections.

This experimentation scenario shows the potential of deploying Cell-Free algorithms in 6G networks with massive AP deployments [38], named now RU under O-RAN architecture. Here the MARSAL innovations focus on distributed processing, with clusters of RUs and DUs coordinating via fronthaul links. In this experimentation scenario, we evaluate the performance of dynamic data driven clustering algorithm. This scenario will also explore and evaluate the effect of inter-DU cooperation on Spectral Efficiency [39] and propose dynamic adaptability of the coordination levels jointly addressing RU-DU and DU-DU coordination, for the first time. The Cell-Free vRAN (virtualised RAN) components in this experimentation scenario will validate the design of cell-free enabled vO-DU, Cell-Free MAC (Medium Access Control) scheduler, PHY (Physical layer)layer. Moreover, it will also validate the appropriate modification of the CP (Control Plane) protocols and O-RAN specified interfaces (i.e., E2, O1) ([12], [40]), to support practical cell-free operation [41] and fully distributed processing.

The investigated experimental scenario represents an event with a high density of users and APs. It can be an indoor venue (e.g., a concert) or an outdoor setting (e.g., a football stadium). During this kind of event, it is common for dense UGC (User Generated Content) to be streamed by spectators via their handheld devices and consumed locally in real-time (RT). Moreover, there may be users with very different requirements: for instance, a UAV (Unmanned Aerial Vehicle) controlled by law enforcement or security agent vs. a regular user/spectator. In general, this use case is characterized by high user density and the users generate much traffic.

In this scenario, RUs will be interconnected with O-DU (ORAN DU) [12] nodes serving the users in a coordinated manner. Furthermore, MARSAL's Hybrid MIMO fronthaul solution [42] will be leveraged for the interconnection of O-RUs (ORAN Radio Units) and O-DUs. The performance of the cell-free NG-RAN (Next Generation RAN) will be evaluated via pre-recorded video content that will be uploaded and downloaded by UEs (User Equipments) to/from a video streaming MEC application (app) deployed at the Regional Edge node, to emulate Dense UGC streaming both in the uplink and in the downlink (DL) direction. To support the abovementioned experimentation scenario, MARSAL CF NG-RAN will include cell-free clustering solutions, mmWave fronthauland a CF MAC scheduler as part of the vRAN to provide CF mMIMO support in the MARSAL architecture. The cell-free vRAN, especially the vO-DU and vO_CU-UP will be deployed as VNFs (Virtual Network Functions) at the radio edge data centre. The mmWave transport network will be providing distributed cell-free coordination amongst the VNFs deployed in radio edge DCs (data centers) and regional edge DCs. A MEC platform be deployed both at the regional and radio edge DCs and a pre-recorded video will be used during the PoC (Proof-of-Concept) evaluation. Moreover, Near-RT RIC (RAN Intelligent Controller) will be hosted at the regional edge DCs, and it will relate to the XGS-PON (10 Gigabit Symmetrical - Passive Optical Network) of the MARSAL architecture.

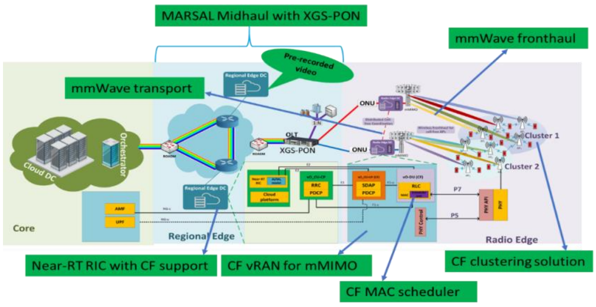

Figure 2: Overview of the dense UGC distribution with mmWave fronthauling scenario, mapped into the MARSAL architecture

Fig.2 depicts the mapping of this scenario into the MARSAL architecture. To deploy the cell-free vRAN solution on the radio edge data centre we can consider the higher and lower layer split suggested by 3GPP [43], O-RAN [12], and Small Cell Forum [44]. Such flexible split options together with the utilization of a converged optical wireless network will allow us to deploy the cell-free vRAN solution in a cost-effective manner for future 6G networks. Furthermore, the O-RAN Alliance [45] introduces a near Real-Time RAN Intelligent Controller (RT-RIC), which implements radio resource management, measurement, and telemetry.

The proposed configuration deploys the vO_CU-UP and vO-DU at the Radio Edge, while the vO_CU-CP near-RT RIC is deployed at the Regional Edge. The split inside the physical layer will simplify the data mapping by limiting the required associated control messages and it will also allow us to enable transport bandwidth scalability based allowing usage of a higher number of antennas without asking for extra transport bandwidth. The O-RAN compliant vO-CU and vO-DU components are incorporated in the form of RAN Virtual Network Functions, while the APs serve as the O-RUs [46].

3.2 Ultra-Dense Video Traffic Delivery in a Converged Fixed-Mobile Network

This scenario showcases MARSAL's solution towards Fixed-Mobile Convergence (FMC) in an ultra-dense indoors context like campus, stadium, malls, etc. Mobile clients served by a distributed Cell-Free RAN will be sharing the Optical Midhaul [47] with third party fixed clients. The Fixed-Mobile Convergence in an Ultra-dense indoors scenario will be operated based on two operation modes, that is Fixed operation (Passive Optical LAN (Local Area Network)) and Mobile operation (small/pico cell with optionally Distributed Antenna System - DAS), respectively. The mobile clients served by a distributed cell-free RAN will be sharing the Optical Midhaul with third party FTTH (Fiber-to-he-Home) clients. The optical fiber access equipment (Optical Line Terminal - OLT) will relate to PON and PtP interfaces where the Network urbanism organization, e.g., OLT and CU co-localized and DU at the end face of the optical termination.

Here we would like to highlight the motivation of this work by considering the 5G status and the 6G needs. So first, 5G carriers and equipment are emitted and localized at the regular antenna locations with previous generations (2G/3G/4G). The pressure of coverage based on the requirements of the regulator is the main reason to have such deployment engineering rules. Concerning the mobile backhaul, 5G deployment coincides with a massive use of optical fiber to achieve the required backhaul throughput up to 10GEth. The fixed access network is based on PtP topology to achieve the connectivity between antenna site and the first aggregation node (central office). Due to the fact that in parallel of 5G, FTTH is under deployment, we have more and more central offices equipped with OLT shelf. 5G backhauling could be addressed either by direct PtP connection to aggregation switch/router or through OLT PtP ports & cards. To address the increase of 6G cells, the preferred fixed technology to collect multiple spots is the PtMP also named PON based on "tree" fiber infrastructure. 6G transport challenges concern the coordination between RAN and FAN (Radio & Fixed Access networks) networks to address throughput, latency, availability issues.

MARSAL's distributed cell-free RAN Radio Unit is deployed based on a Serial Fronthaul topology [48-49]. The Serial Fronthaul allows a large number of cell-free APs to be interconnected in a bus topology, significantly increasing Spectral Efficiency, but with minimal cabling requirements. The technology of transmission considered to support serial fronthaul is Wavelength Division Multiplexing (WDM) [50]. A passive fiber network infrastructure is preferred using passive optical multiplexer. Serial Fronthauling is considered an ideal solution for indoor venues.

Secondly, in this scenario, Radio Edge nodes, that host the vRAN elements, are interconnected via PtP and PtMP (PON technology like G-PON (gigabit capable) and XGS-PON (10 gigabit capable)) midhaul links with the Regional Edge. The Regional Edge nodes, interconnected in a WDM ring topology, will host the Near-RT RIC and vCU_CP VNFs. The SDN-Transmission controller and Near-RT RIC SDN function will also be deployed at the Regional Edge nodes. The performance of this scenario will be evaluated via pre-recorded 4K/HDR (High Dynamic Range) video that will be uploaded and downloaded by UEs to/from a video streaming MEC application deployed at the Regional Edge node. Fixed clients will be included as well in this scenario that will be served by the same infrastructure via PtMP (PON) links sharing capacity with the Radio Edge node.

To support this experimentation scenario, we include an Optical Access Network to serve the connectivity between radio edge data centers and cell sites equipped with DUs and RUs. We also propose coordination between the controllers dedicated to Fixed and Radio access networks. Fig.3 depicts the mapping of the scenario into the MARSAL architecture. It must be noted that we also use existing and next-generation PON technologies, to take advantage of their lower CAPEX (due to higher reuse of commodity Fiber-to-the-x (FTTx) equipment) and shared OPEX options, to demonstrate 5G midhaul and backhaul traffic over PON [51]. The PON solution also provides a management interface to the network operators. When used for mobile networks, PONs already make use of a Dynamic Bandwidth Allocation (DBA) algorithm to prioritize certain flows [52]. The development of network slicing could be proposed by dynamic creation/edition/deletion of slice instances.

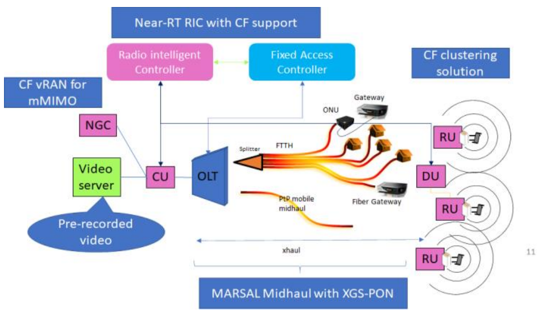

Figure 3: Overview of the ultra-dense video traffic delivery in a converged fixed-mobile network scenario, mapped into the MARSAL architecture

This scenario demonstrates an on-the-fly reconfiguration of the PON DBA parameters, to be managed from an SDN controller in coordination between fixed and radio networks, used for mid- and back-haul of 5G traffic with integrated RU/DU. We also consider PTPv2 (Precision Time Protocol v2) and SyncE (Synchronous Ethernet) protocols (transportation over the different transport domain mentioned above will be demonstrated. To support this demonstration, video services of various flavors (e.g., downstream HD/4K streams and/or conversational video) will been selected as representative vertical services that the Edge and Core DCs will also host the 5G NFs (e.g., the 5G Core VNFs) [53], while resource sharing will be accomplished via MARSAL's innovative MEO. This will allow disaggregating the AR (Augmented Reality), scene analysis, and activity recognition application functions in multiple tiers (i.e., Regional Edge, Radio Edge, on-device).

4 Cognitive Assistance and Security and Privacy Implications

The introduction of B5G/6G networks for cognitive assistance in a multi-tenant environment, without assuming trust, will raise security concerns that need to be addressed [52]. In fact, many security and privacy implications are inherent in applications that process personal data and Personally Identifiable Information (PII) as per the GDPR regulations [54], including video streams with users' field of view and tracked location. Hence, privacy and security mechanisms that guarantee the isolation of slices and ensure collaboration of participants in multi-tenant B5G/6G infrastructures without assuming trust, need to be developed and demonstrated. Hereof, to ensure the end-to-end security in 6G, AI techniques will also play a critical role in protecting the network, user equipment, and vertical industries from unauthorized access and threats [11], [55-57]. Besides, blockchain is envisioned as another key technology in 6G privacy/security given its decentralized operation, immutability, and enhanced security [58-59].

The effectiveness of the MARSAL solutions in B5G/6G Cognitive Assistance will be demonstrated as discussed in section 4.1, below. By bringing state-of-the-art technologies in a novel way, MARSAL aims to address security- and privacy-related issues in B5G/6G networks, while optimizing user experience and enhancing confidentiality and trustworthiness

4.1 Cognitive Assistance and Smart Connectivity for Next-Generation Sightseeing

5G introduced real-time, interactive, Next-Generation Internet (NGI) applications [60] that support human-centered interaction via novel interfaces (e.g., vision and haptics) including augmented reality applications. However, as it has been described in the previous section, current 5G networks do not have the capabilities to unleash the full potential of these applications due to, e.g., the required huge data throughputs and low latency for scene analysis and activity recognition. In this context, this experimentation scenario motivates the need for going beyond 5G through a high-level definition of two real-time, interactive, cloud-native applications for B5G/6G outdoors sightseeing. Through the use of AR – a technology that superimposes a computer-generated image on a user's view of the real world, thus providing a composite view – these types of applications will support cognitive-assistance and human-centered interaction features.

Before moving forward to the description of the scenario, let us briefly define the key concepts involved from a user perspective. First, cognitive assistance is "*a systematic approach to increasing human intellectual effectiveness*" [61] that assumes "*computational assists to human decision making are best when the human is thought of as a partner in solving problems and executing decision processes, where the strengths and benefits of machine and humans are treated as complementary co-systems*" [62]. Second, human-centered computing is a computer system engineering methodology that uses a combination of methods from computer science, social science, and management studies to understand and model work practice, technology use, and technology gaps. Its objective is developing computer systems that fit human capabilities and practices by exploiting/improving AI programming methods [63-64].

To support these applications while respecting the correct performance of others, operators must provide a flexible network architecture capable of adapting to the demand. So, this experimentation scenario puts the focus on how to cope with the challenging requirements imposed by the operation of the proposed applications while keeping the SLAs of the rest of applications running in parallel. Load balancing according to priority services will be implemented at the same time MEC approaches will be conducted to lighten the network burden of the AR applications and leverage the use of edge computing nodes.

In this scenario, the deployment of two real-time and interactive cloud-native applications for outdoors sightseeing supporting human-centered interaction via 3D cameras is envisioned in the MARSAL's multi-tenant Elastic Edge Infrastructure. These applications would be offered to users equipped with untethered AR glasses. Both applications would endure an enhanced strolling experience by showing overlaid information relevant to their surroundings (APP#1) and enabling virtual artifacts manipulation (APP#2), while considering background traffic from other applications and services.

To better showcase the scope of the proposed scenario, let us conceive a general use case consisting of a next-generation sightseeing tour enhanced with AR in the city of Barcelona [46], [65]. Throughout the tour, the user is provided with information of interest as she/he walks by the streets of the city (APP#1). The tour also proposes a predefined route where the user visits multiple points of interest (POI) empowered with artifact manipulation applications (APP #2).

The description of the above experimentation scenario would fit within the "Immersive smart city" use case under the category "Massive twinning" and also within the "Fully merged cyber-physical worlds" use case under the category "Immersive telepresence for enhanced interactions" as described in [52]. In our vision: (i) the sightseeing application (APP#1) could be part of the different services that would be managed under the Immersive smart city, e.g., under the ambience/environment (for example, climate, air quality) and cultural aspects, and; (ii) the virtual artifact manipulation (APP#2) would be linked with the enhanced interactions to be addressed by B5G/6G networks. As explained in [52], the use of B5G/6G networks are needed in these use cases as they improve some existing Key Performance Indicators (KPIs) of 5G networks (such as service availability, coverage and network energy efficiency), but also because B5G/6G networks bring new capabilities leading to new KPIs among which we highlight integrated sensing, local compute integration, integrated intelligence and flexibility (i.e., the ability of the system to be adapted and tailored to specific use cases and environments as a consequence of disaggregation, softwarization and automation/orchestration, which are concepts dealt with in MARSAL). The improvements in existing KPIs and the new KPIs that B5G/6G networks will bring are required in order to be able to guarantee the necessary quality of experience (QoE) brought by the respective MARSAL's experimentation scenario.

To support the abovementioned APPs, MARSAL Virtual Elastic Infrastructure will include a MEC platform be deployed both at the regional and radio edge Data Centers and centralized orchestrators (i.e., the MEO and the NFVO [53]) which will be deployed at a Core-tier Data Centre. Fig.4 depicts the mapping of the scenario into the MARSAL architecture. It must be noted that the Edge and Core DCs will also host the 5G NFs (e.g., the 5G Core VNFs), while resource sharing will be accomplished via MARSAL's innovative MEO. This will allow disaggregating the AR, scene analysis, and activity recognition application functions in multiple tiers (i.e., Regional Edge, Radio Edge, on-device).

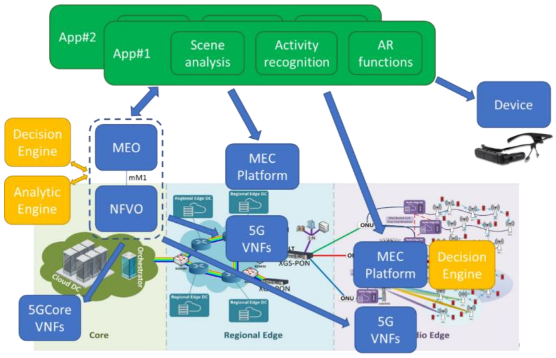

Figure 4: Overview of the cognitive assistance and smart connectivity for next-generation sightseeing scenario, mapped into the MARSAL architecture

Two novel key MARSAL components are highlighted in Fig.4. First, the Analytic Engine (AE) is the module in charge of creating the Context representation of the system. To this end it interprets the data collected from the different MARSAL architecture components in the form of knowledge graphs and creates vectors representations that, on the one hand avoid the sharing of private information and on the other hand make easy to downstream ML algorithms to understand the status of the system [66]. From an information flow perspective, the AE is placed between the data collection and the DE. It generates an embedding of each node in the context knowledge graph using dedicated tools [67]. The embeddings are used then by the DE to optimize the resource usage.

Second, MARSAL designs and implements DEs at the two Core-Tier orchestration subsystems (i.e., the NFVO, which manages end-to-end (E2E) slices via the NSaaS module [68] and the Multi-access edge orchestrator [69]) towards a Self-Driven Virtual Elastic Infrastructure. The DEs use as input the resulting embeddings of the AE that represent the current state of the MARSAL infrastructure in a highly compressed form and feed them to different multi-objective downstream ML algorithms that are implemented in the DEs. Through these mechanisms the DEs jointly orchestrate Network Slices, Network Services and MEC applications continuously and automatically evaluating the current context under the required policy [70], while also delegating data-driven local control decisions to the lower tiers of the hierarchy.

4.2 Data Security and Privacy in Multi-Tenant Infrastructures

The goal of this scenario is to demonstrate and evaluate MARSAL's privacy and security mechanisms [71]. These guarantee the isolation of slices and ensure collaboration of participants in multi-tenant 6G infrastructures without assuming trust. These mechanisms will also be evaluated in terms of their ability to mitigate the increased privacy risks of NGI applications that process Personally Identifiable Information (PII). To this end, this scenario aims to demonstrate the application of security and privacy mechanisms in four different layers, namely: *secure and private sharing of information among tenants*; *legal security using smart contracts*; *security of the data stored in the cloud*, and *security of the final users*. The development of each of the different layers presents different challenges ranging from the implementation of smart contracts among different tenants to the real time analysis of network data to allow the protection of the final users in a timely manner.

In MARSAL we approach the security and privacy in 6G networks in a holistic way. Contrary to the previous scenarios, offering a solution tailored for the MARSAL architecture, now we present a modular design to offer four different layers of security and privacy that could be applied in very different contexts. This scenario assumes a multi-tenant infrastructure with one MNO (Mobile Network Operator) and two MVNOs (Mobile Virtual Network Operators), each serving an OTT (Over-The-Top) application provider. MARSAL technology ensures the isolation of the different slices while offering the possibility of collaboration among different tenant [72]. To this end, the aim is to demonstrate how the usage of smart contracts can be paired with the private representation of data [73], allowing the sharing of information among different tenants and the owner of the infrastructure that can be interested in the optimization of different ML models.

Moreover, the scenario also covers the security (and privacy) at different levels of the MARSAL architecture. First, we consider how policies can be used to safely store data in the cloud (either at the core or the edge of the network), testing different allocation strategies that ensure the perpetual security of the data. Then, we move our focus to the network intending to investigate how the browsing patterns of users can be analysed in real time so that to alert final users against malicious behaviours they may have before they get in trouble.

The different components of the demonstrator provide security and privacy to many parts of the MARSAL architecture, as depicted in Fig.5. In the backend, we provide both, security to the data stored in the computing nodes and to the information shared among different tenants to improve the performance of the slicing infrastructure. Then, the Network Infrastructure Security is directly applied to the network equipment by using the SDN paradigm. Finally, a thread detection engine able to protect the final users will be demonstrated by collecting network data at the edge that can then be processed in the backend.

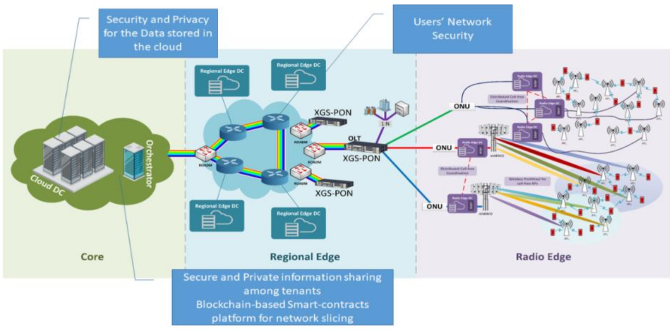

Figure 5: Overview of the data security and privacy in multi-tenant infrastructures scenario, mapped into the MARSAL architecture

The main components of the demonstrator are:

- *Secure and Private Information Sharing among tenants and Blockchain-based Smart-contracts platform for network slicing***:** The first two components are in charge of allowing secure information sharing among tenants. Both the algorithms for the secure and private information sharing and the smart-contract platform will be closely related and acting together with the Orchestrator to provide a better slicing with the collaboration of the different tenants.
- *Security and Privacy for the Data stored in the Cloud:* The third component defines the policies to ensure the data is stored in a secure and private way. As such, this component is an intrinsic part of cloud storage.
- *Users' Network Security:* Provide security to the final users from the network is a complex task that requires the collaboration of different parts of the network. In MARSAL, this security layer will involve the Data Centers on the regional edge and the network equipment placed on the regional edge.

4 Discussion

In this paper, we presented the main architectural components of MARSAL, as well as how the applied use cases are mapped into the proposed architecture.

In particular, the *first domain* is focused on *cell-free networking in dense and ultra-dense hotspot areas*. The first experimentation scenario considers *dense User-Generated Content (UGC) distribution with mmWave fronthauling*. The main objective of this scenario is to demonstrate and evaluate MARSAL distributed cell-free RAN in terms of increased capacity and spectral efficiency gains, and the adaptivity of dynamic clustering and RRM mechanisms in managing connectivity resources in a dynamic environment with varying hotspots areas. The second experimentation scenario investigates *ultra-dense video traffic delivery in a converged fixed-mobile network*. This showcases MARSAL's solution towards Fixed Mobile Convergence in an ultra-dense indoors context. Mobile clients served by a distributed Cell-Free RAN will be sharing the Optical Midhaul with third party FTTH clients.

The *second domain* is focused on *cognitive assistance and its security and privacy implications in 5G and Beyond*. The third experimentation scenario is about *cognitive assistance and smart connectivity for next-generation sightseeing*. In this scenario, the deployment of two real-time and interactive cloud-native applications for outdoors sightseeing supporting human-centered interaction via 3D cameras is envisioned in the MARSAL's multi-tenant elastic edge Infrastructure. These applications would be offered to users equipped with untethered AR glasses. Both applications would endure an enhanced strolling experience by showing overlaid information relevant to their surroundings and enabling virtual artifacts manipulation, while considering background traffic from other applications and services. The fourth experimentation scenario addresses *data security and privacy technical challenges in multi-tenant infrastructures*. We approach security and privacy in 6G networks in a holistic way. We present a modular design to offer four different layers of security and privacy that could be applied in very different contexts.

Our future work is focused on the evaluation process, as well as on a set of preliminary targeted KPIs. It should be noted here that these KPIs will be under continuous reconsideration. Furthermore, we will focus on the network architecture specifications, the requirements of management and security components, as well as the finalisation of MARSAL architecture.

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