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Abstract. 5G mobile networks will be soon available to handle all types of applications and to provide service to massive numbers of users. In this complex and dynamic network ecosystem, end-to-end performance analysis and optimization will be key features in order to effectively manage the diverse requirements imposed by multiple vertical industries over the same shared infrastructure. To enable such a vision, the MARSAL project 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. At the network design domain, MARSAL targets the development of novel cell-free-based solutions. Namely, scalable and cost-efficient wireless access points deployment will be achieved by exploiting the distributed cell-free concept combined with wireless and wired serial fronthaul approaches. We will target the inclusion of these innovative functionalities in the O-RAN project. In parallel, in the fronthaul/midhaul segments MARSAL aims to radically increase the flexibility of optical access architectures for Beyond-5G cell site connectivity via different levels of fixed-mobile convergence. In the network and service management domain, the design philosophy of MARSAL is to provide a comprehensive framework for the management of the entire set of communication and computational network resources by exploiting novel ML-based algorithms of both edge and midhaul data centers, by incorporating the Virtual Elastic Data Centers/Infrastructures paradigm. Finally, at the network security domain, MARSAL aims to introduce mechanisms that provide privacy and security to application workload and data, targeting to allow applications and users to maintain control over their data when relying on the deployed shared infrastructures, while AI and Blockchain technologies will be developed in order to guarantee a secured multi-tenant slicing environment.

Keywords: cell-free; distributed cloud; network automation; machine learning; secure multi-tenancy.

1 Introduction

The number of people living in megacities, (i.e., cities with a population greater than 10 million) has increased from 69.5 million in 1975 to a staggering 472.8 million in 2015 [2]. In parallel, the percentage of network traffic originating and terminating in a city is increasing [3] through the use of popular online services and smart city applications. It is expected that Smart Megacities will become the primary source of data, characterized by massive data growth and processing requirements. Today these requirements are served by a variety of optical and wireless networking and edge/fog/cloud computing technologies and infrastructures deployed in the cities and belonging to different providers, while smaller business owners (e.g., stadium operators) are also deploying their own infrastructures. In such an environment, 5G networks are set to address the demands of a fully connected and mobile society, enabling a wide variety of applications over the same infrastructure [3], while carrying 45% of the total mobile traffic and serving up to 65% of the world's population [4]. These numbers are expected to increase due to the urbanization of global population and the increase of the size and volume of megacities [2, 5].

5G changes the landscape of mobile networks profoundly, with an evolved architecture supporting unprecedented capacity, spectral efficiency, and increased flexibility. Moreover, 5G adopts Edge computing as a key paradigm, evolving from centralized architectures (e.g., based on Cloud-RAN (C-RAN)) towards multiple tiers of Edge nodes and a virtualized RAN (vRAN). Open RAN initiatives such as O-RAN have a key role in this evolution, complementing the 3GPP 5G standards with a foundation of vRAN network elements. However, these technologies have been in large developed in isolation between them, making difficult to fully exploit their capabilities in an integrated, end-to-end and secure manner. Algorithms do not only run in the cloud, and optical and wireless links cannot be abstracted in the same way. When going to cell-free networking concepts, more nodes and links will be interconnected, serving local and global secure applications. Thus, it is essential to rethink the architecture and algorithms running elastically at the scale of a city or building level.

In general, application traffic flows from and towards end-users and end-devices, served by multiple levels of storage and computing entities from the edge to the cloud, while utilizing a diverse set of wireless and optical technologies in the fronthaul, midhaul and backhaul network segments. These infrastructure resources belong to different administrative domains, operate in parallel in the same network areas and are usually shared between competing flows, computations and data in static and/or statically multiplexed manner. Thus, it is clear that targeted innovation activities need to take place to fully exploit key technological developments, towards a disaggregated infrastructure model, where technological infrastructure blocks can be transparently and flexibly replaced by others, while offering similar networking and/or computing offerings and control and monitoring capabilities. Specifically, key advances are required both in the network design and network/service orchestration levels:

- The network infrastructure should be able to support multiple distributed edge nodes and a huge number of Access Points (APs), which are coordinated and orchestrated 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, which can be further enhanced by incorporating efficient Machine-Learning (ML) algorithms;
- The support of multiple tenants should be followed by the application of mechanisms that are able to guarantee data and information security and integrity especially in multi-tenant environments, which would play a vital role in enabling various use-cases and industry verticals targeted in 5G and Beyond (B5G) systems.

This is where MARSAL steps in, proposing a new paradigm of elastic virtual infrastructures that integrate in a transparent manner a variety of novel radio access, networking, management and security technologies, which will be developed under the MARSAL framework in order to deliver end-to-end transfer, processing and storage services in an efficient and secured way.

To this end, MARSAL focuses on three pillars to enable a new generation of ultra-dense, cost-efficient, flexible and secure networks: (i) network design pillar; (ii) virtual elastic infrastructure pillar, and; (iii) network security pillar. For the network design pillar, MARSAL pushes cell-free networking towards the distributed processing cell-free concept. This will enable wireless mmWave fronthaul solutions, which will be implemented and integrated with existing vRAN elements while being in-line with the O-RAN Alliance. In parallel, MARSAL's second pillar is built based on the Elastic Edge Computing notion, targeting to optimize the functionality of the Multiple Access Edge Computing (MEC) and the network slicing management systems via a hierarchy of analytic and decision engines. Finally, under its third pillar, MARSAL will develop novel ML-based mechanisms that guarantee privacy and security in multi-tenancy environments, targeting both end users and tenants.

In this paper, we focus on a wide range of experimental scenarios that MARSAL will consider. The first domain includes a set of use cases focused on cell-free networking in dense and ultra-dense hotspot areas (Section 2). The second domain includes use cases related to cognitive assistance, as well as security and privacy implications in 5G and beyond (Section 3). We conclude our remarks in Section 4.

2 Cell-Free Networking in Dense and Ultra-Dense Hotspot Areas

During high-popularity events, both indoors (e.g., music concerts) and outdoors (e.g., a fair), 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 direction.

The current state-of-the-art (SoTA) solution is network densification that involves small cells with Massive MIMO (Multiple-Input, Multiple-Output) capabilities (i.e., a large number of transmitting and receiving antennas with beamforming and precoding techniques). In this case, users are bounded to the service area of a single cell. This solution is limited by inter-cell interference, with a performance at the cell edges being a particular concern. This makes cell-free networking [6], an emerging B5G technology, highly suitable to hotspot areas. Cell free concept can offer seemingly infinite capacity and it fully mitigates the cell edge challenges as the users are served by multiple rather than just one access point. Also, a massive number of distributed antennas exploit spatial diversity to mitigate the counter effect of large-scale fading, and consequently, the users will enjoy a higher quality of service [6-8].

Two deployment scenarios of MARSAL cell-free NG-RAN (Next Generation RAN) will be explored as the project proofs-of-concept (PoCs): That is, we will accommodate dense traffic via: (i) Hybrid MIMO fronthaul [9, 10] in an outdoor scenario, and; (ii) Serial Fronthaul [11, 12] in an indoor setting. The indoors scenario showcases MARSAL's Fixed-Mobile Convergence (FMC) solution, supporting integrated connectivity of mobile and fixed clients, that share the same Midhaul and Edge infrastructure (e.g., MEC hosts).

2.1. Dense User-Generated Content Distribution with mmWave Fronthauling

This scenario's main objective is to demonstrate and evaluate MARSAL's distributed cell-free NG-RAN in terms of increased capacity and spectral efficiency 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, we aim at evaluating the Hybrid MIMO Fronthaul in terms of its ability to offer a dynamic AP topology.

During outdoors events, such as fairs or festivals, it is common for dense user-generated content to be streamed by spectators via their handheld devices, and consumed locally in real-time. This puts very high stress on the radio interfaces. In this scenario, MARSAL's cell-free NG-RAN will be evaluated while supporting dense video traffic at the uplink and downlink direction. The cell-free vRAN components on dense user-generated content distribution with mmWave fronthauling experimental scenario will be consisting of the following layers: RLC, MAC, RRC, PDCP, SDAP. The layers are apportioned into two virtualized components, i.e., the distributed unit (vO-DU) and centralized unit (vO-CU). The vO-CU can be further splitted into vO-CU_UP (user plane) and vO-CU_CP (control plane). Even though each communication layer the components within the layer can be a separate as a software component for the purpose of this use case vO-DU and vO-CU can be treated as three monolithic, virtualized applications (so called Virtualized Network Functions -VNFs).

Specifically, APs from KU Leuven [13] will be interconnected with Radio Edge nodes, which host MARSAL's vRAN elements, while the Near-RT (Near Real-Time) RIC (RAN intelligent Controller) and vCU_CP VNF (Virtual Network Function) will be deployed at a Regional Edge node (REN). To deploy cell-free vRAN components on the RENs, we will consider higher and lower layers split options according to the specification of 3GPP, O-RAN and small cell forum. The choice of how to split RAN functions depends on factors related to radio network deployment scenarios, constraints and intended supported services, e.g., support of specific QoS per offered services (e.g., low latency, high throughput), support of specific user density and load demand per given geographical area, availability of transport networks with different performance levels, from ideal to non-ideal, and application type e.g., real-time or Non-Real Time, respectively. Furthermore, MARSAL's Hybrid MIMO fronthaul solution will be leveraged for the interconnection of RUs (Remote Units) and Radio Edge nodes, while point-to-point mmWave links will be established between neighbouring Radio Edge nodes, facilitating DU (Distributed Unit) cooperation without capacity constraints from the Midhaul and Fronthaul interfaces. The performance of the cell-free NG-RAN will be evaluated via pre-recorded video content that will be uploaded and downloaded by User Equipment (UE) to/from a video streaming MEC app deployed at the Regional Edge node, to emulate Dense User-Generated Content streaming both in the uplink and in the downlink direction. This scenario will demonstrate and evaluate the following sub-scenarios, showcasing numerous MARSAL innovations related to cell-free networking and Hybrid MIMO fronthauling:

- Demonstrate MARSAL's data-driven approaches for AP cluster formation and RRM, that consider per-user rate and estimated CSI (Channel State Information) as well as computational and fronthaul constraints. Evaluate their effect on channel capacity and spectral efficiency at the uplink and downlink, showcasing how they react to changes in hotspot areas.
- Demonstrate MARSAL's dynamic adaptability algorithms, showcasing their capabilities in selecting the optimal AP-DU and inter-DU cooperation levels and how these are affected by fronthaul capacity constraints, and evaluate the effect of the point-to-point (PtP) Xn-line interface in inter-DU cooperation.
- Demonstrate dynamic adaptability of the AP topology via beam-steering and beam-sharing, offered by the new Hybrid MIMO interface, and showcase optimized cluster formation leveraging on the adaptive topology.

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

This scenario will showcase MARSAL's solution towards Fixed-Mobile Convergence in an ultra-dense indoors scenario. Mobile clients served by a distributed Cell-Free RAN will be sharing the Optical Midhaul with third party FTTH (Fiber-to-the-Home) clients. The spectral efficiency and channel capacity gains of the distributed Cell-Free RAN in a Serial Fronthaul topology, and the load balancing and end-to-end slice reconfiguration mechanisms of the converged infrastructure will be demonstrated and evaluated.

In large concert venues, visual content which supplements the live event can be captured locally (e.g., from multiple fixed 4k cameras, as well as unmanned aerial vehicles (UAVs)), and distributed to a high number of spectators in real time, generating ultra-high-density video traffic. MARSAL's distributed cell-free RAN in a Serial Fronthaul topology will be deployed in this scenario. 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; hence Serial Fronthauling is considered an ideal solution for indoors venues.

Moreover, in this scenario, Radio Edge nodes, that host the vRAN elements, are interconnected via PtP and PtMP (Point-to-Multi-Point) Midhaul links with the Regional Edge. The Regional Edge nodes, interconnected in a WDM (Wavelength Division Multiplexing) ring topology, will host the Near-RT RIC and vCU_CP VNFs. The SDTN (Software-Defined Transport Network) controller and Near-RT RIC SDN (Software-Defined Network) 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 links sharing capacity with the Radio Edge node. In this scenario, a number of MARSAL innovations will be showcased and evaluated:

- Demonstrate load balancing between fixed and mobile traffic through the coordination of the two SDN controllers, leveraging unused capacity from the PtMP link to serve traffic from the mobile clients of the cell-free RAN. Evaluate the distributed control plane's capability to adapt to workload variations in near-real time.
- Demonstrate adaptive cooperation between multiple cell-free serial fronthaul, leveraging on the Midhaul links for information sharing. Showcase the effect of Midhaul capacity limitations on the levels of cooperation and achieved Spectral Efficiency.
- Evaluate the energy savings that can be achieved via traffic aggregation on a limited number of wavelengths and shutdown of unused SFP+ (enhanced small form-factor pluggable) modules in light load conditions, under the control of the SDTN controller.

3 Cognitive Assistance and its Security and Privacy Implications in 5G and Beyond

Future generations of 5G will bring support for hyper-connectivity, offering seemingly unlimited bandwidth and zero perceived latency, and facilitating disruptive PoCs that are not currently technically feasible. These include real-time, interactive Next-Generation Internet (NGI) applications that support human-centered interaction via novel interfaces (e.g., vision and haptics). One such application is Cognitive Assistance, which takes the concept of Augmented Reality (AR) one step further, relying on real-time video and scene analytics and activity recognition to provide personalized feedback for activities the user might be performing (e.g., recreational activities, furniture assembling, sightseeing, etc.). One of the main challenges is ensuring zero perceived latency to guarantee a satisfactory user experience, and also to send timely feedback, especially for time sensitive activities. Furthermore, the high computational load and massive data sets required for scene analysis and activity recognition makes on-device execution infeasible. This PoC will also address the many security and privacy implications inherent in applications that process personal data and Personally Identifiable Information (PII) as per the GDRP (General Data Protection Regulation) provisions [14]. Challenges related to multi-tenant infrastructures, such as policy-driven sharing of operational data and blockchain-based Network Slicing as a Service (NSaaS) will also be addressed.

3.1 Cognitive Assistance and Smart Connectivity for Next-Generation Sightseeing

The main objective of this scenario is to demonstrate and evaluate MARSAL's Virtual Elastic Infrastructure, showcasing its ability to ensure high reliability and quality of experience for Next-Generation human-centred applications with new terminal types, while sharing resources with high-priority 5G NFs (Network Functions).

In this scenario, two real-time and interactive Cloud-Native applications for outdoors sightseeing, supporting human-centered interaction via 3D cameras, will be deployed at MARSAL's multi-tenant Elastic Edge Infrastructure. The latter will include a MEC platform which will be deployed at Regional Edge and Radio Edge Data Centres (DCs) and Centralized orchestrators (i.e., the MEO (Mobile Edge Orchestrator) and NFVO (Network Functions Virtualization Orchestrator)) which will be deployed at a Core-tier Data Centre. It must be noted that the Edge and Core Data Centres will also host the 5G NFs (e.g., the 5G Core VNFs) while resource sharing will be accomplished via MARSAL's innovative MEO. In the targeted scenario an enhanced strolling experience with overlaid information relevant to their surroundings and activities (e.g., restaurant ratings, nearest ATMs (automated teller machines) or bus-stations, touristic information, etc.) is offered to users equipped with untethered, 5G-enabled AR glasses. Specifically, an AR sightseeing application will apply real-time video analytics on the user's field-of-view to detect user intent or activity and offer visual guidance in the form of relevant information that is optically super-imposed. Furthermore, at certain attraction points, IoT (Internet of Things) nodes equipped with novel interfaces (i.e., 3D cameras) and 5G connectivity will be deployed to facilitate interaction with the user. A Cognitive Assistance application will encourage the user to manipulate in real-time the virtual representation of an artefact, projected at their AR glasses. Gesture recognition will be implemented via real-time analysis of the 3D camera stream, while the application offers cognitive visual guidance, superimposing information at the users' field of view explaining how the exhibit (or artefact) is used in real time. Both applications will rely on MARSAL's Virtual Elastic Infrastructure to optimize and disaggregate their AR, scene analysis and activity recognition application functions in multiple tiers (i.e., Regional Edge, Radio Edge, on-device). The following MARSAL innovations will be demonstrated and evaluated:

- Demonstrate and evaluate the capabilities of the MEO to derive the optimal placement of the (containerized) application functions at the Radio Edge or Regional Edge DCs, achieving optimized distribution of latency budgets. The computational requirements and latency constraints of application functions will be derived from at the applications' manifest files. This will result in imperceptible latency of the untethered AR applications, comparable to tethered AR, which will be validated by user tests.
- Demonstrate the collaborative interaction of the MEC system with the 5G UPF for real-time inter-DC traffic steering for load balancing purposes, evaluating the effect on resource utilization. Unbalanced demand will be

emulated in the coverage area of certain Regional Edge nodes, and the ability of the MEC system to uniformly re-direct traffic will be showcased.

- Demonstrate the Analytic and Decision engines of MARSAL's Self-Driven infrastructure, and evaluate their ability derive accurate context representations and successfully drive the NFVO and MEO. Evaluate their effectiveness in achieving a set of objectives, related to SLA (Service Level Agreement) requirements (e.g., which of the two AR applications to prioritize) and cost considerations (e.g., related to OPEX, energy costs, etc.).

3.2 Data security and privacy in multi-tenant infrastructures

This scenario will demonstrate and evaluate MARSAL's privacy and security mechanisms that guarantee the isolation of slices and ensure collaboration of participants in multi-tenant 5G and Beyond 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).

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, while MARSAL's Threat Detection and Threat Analysis engines are leveraged to ensure the isolation of slices and prevent cross-slice attacks. The OTT applications that will be deployed in separate slices, process sensitive PII related to outdoors sightseeing, including video streams with users' field of view and tracked location. This information is stored for further processing at a multi-tenant Distributed Cloud Solution (or DCS) with Storage Nodes provided by multiple infrastructure owners. MARSAL's AONT (all or nothing transform) mechanism and NFS (Network File System) gateway, coupled with policy-driven storage resource allocation and anonymization will guarantee data security, and facilitate distributed computation on massive data sets (e.g., applying data analytics to build a user profile) while offering integrity guarantees. Furthermore, this scenario will demonstrate the ability of MVNOs to cooperate in a decentralized, blockchain-assisted scenario, leveraging smart contracts to negotiate slice resources and MARSAL's privacy-preserving representation learning algorithms to protect their sensitive operational data. More specifically, the following security and privacy MARSAL innovations will be demonstrated and evaluated:

- Demonstrate the ability of MARSAL to guarantee end-to-end slice security and isolation of OTT applications, even in the presence of compromised sub-slices in the shared infrastructure. Cross-slice attacks will be emulated based on real-world cyberattack datasets and the ability of the Threat Detection and Threat analysis engines to detect malicious flows will be evaluated.
- Demonstrate decentralized cooperation of NVNOs via smart contracts. Significant cost reductions will be demonstrated when MVNOs face peak demand at different times, and hence can share slice resources when they are not used. MVNOs further cooperate via sharing operational data regarding traffic profiles. Joint training of the NSaaS (Network Slicing as a Service) traffic prediction models without exposing sensitive information will also be

showcased via MARSAL's privacy-preserving representation learning algorithms.

- Evaluate MARSAL's perpetual data security guarantees in terms of the minimum number of nodes required to reconstruct a resource, assuming a varying number of compromised Storage Node providers, and applying different fragmentation and data allocation strategies. Demonstrate assurance of data protection and privacy requirements of all stakeholders (i.e., infrastructure owners, OTT application providers, and end users).
- Demonstrate Distributed Computation (e.g., to derive the user profile via data analytics) on data sets containing PII which are stored at the DCS by multiple tenants. The policy-driven NFS gateway and MARSAL's probabilistic integrity mechanisms will be evaluated in terms of their ability to offer privacy and integrity guarantees expressed in MARSAL's policy language.

4 Discussion

5G mobile networks will be soon 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 optimization will be key features, in order to effectively manage the diverse requirements imposed by multiple vertical industries over the same shared infrastructure.

To enable such a vision, the MARSAL project 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.

At the network design domain, MARSAL targets the development of novel cell-free based solutions that allows the significant scaling up of the wireless APs in a cost-effective manner by exploiting the application of the distributed cell-free concept and of the serial fronthaul approach, while contributing innovative functionalities to the O-RAN project. In parallel, in the fronthaul/midhaul segments MARSAL aims to radically increase the flexibility of optical access architectures for Beyond-5G Cell Site connectivity via different levels of fixed-mobile convergence.

At the network and service management domain, the design philosophy of MARSAL is to provide a comprehensive framework for the management of the entire set of communication and computational network resources by exploiting novel ML-based algorithms of both edge and midhaul DCs, by incorporating the Virtual Elastic Data Centers/Infrastructures paradigm.

Finally, at the network security domain, MARSAL aims to introduce mechanisms that provide privacy and security to application workload and data, targeting to allow applications and users to maintain control over their data when relying on the deployed shared infrastructures, while AI (Artificial Intelligence) and Blockchain technologies will be developed in order to guarantee a secured multi-tenant slicing environment.

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