5G-CLARITY: 5G-Advanced Private Networks Integrating 5GNR, Wi-Fi and LiFi

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***Abstract*—The future of the manufacturing industry highly depends on digital systems that transform existing production and monitoring systems into autonomous systems fulfilling stringent requirements in terms of availability, reliability, security, low latency, and positioning with high accuracy. In order to meet such requirements, private 5G networks are considered a key enabling technology. In this paper, we introduce the 5G-CLARITY system that integrates 5G new radio (5GNR), Wi-Fi and light fidelity (LiFi) access networks, and develops novel management enablers to operate 5G-Advanced private networks. We describe three core features of 5G-CLARITY including a multi-connectivity framework, a high precision positioning server and a management system to orchestrate private network slices. These features are evaluated by means of packet level simulations and an experimental testbed demonstrating the ability of 5G-CLARITY to police access network traffic, to achieve cm-level positioning accuracy, and to provision private network slices in less than one minute.**

***Index Terms*—Private networks, NPN, SNPN, Industry 4.0, 5G-Advanced, 5GNR, Wi-Fi, LiFi, positioning, multi-connectivity**

I. INTRODUCTION

Fifth generation (5G) mobile communications in many private sectors hold great promises in terms of connectivity that will accelerate the digitalisation and enable emerging advanced use cases that today's wireless access technologies (WATs) cannot support. As concrete evidence, the service provider addressable 5G-enabled market in the most representative vertical industries is foreseen to be USD 700 billion in 2030 with a remarkable compound annual growth rate (CAGR) of 50 percent over 2020-2026 [1]. Candidate sectors that might leverage 5G connectivity for supporting breakthrough services include tourism, healthcare, retail industry, transport hubs, sport facilities, manufacturing, etc. These sectors will demand heterogeneous, disparate, and stringent wireless access requirements that, to date, only 5G can deliver. Focusing on Industry 4.0, one of the key benefits of adopting 5G in factories is the reduction of cables, which are costly and cumbersome, enable a low connection density of devices, and hinder the mobility of people and machines [2], [3].

Private 5G networks, named 5G non-public networks (NPNs) by 3rd Generation Partnership Project (3GPP), are 5G systems intended for the exclusive use of a private entity such as an enterprise, and might be deployed through various settings using both virtual and physical entities. 5G NPNs are categorized into: Stand-alone NPNs (SNPNs) which do not rely on network functions provided by a public land mobile network (PLMN), and public network integrated NPNs (PNI-NPNs) whose deployment is supported by a PLMN. The choice between the deployment options involves a trade-off between network costs, control, and deployment complexity. Although SNPNs ensure physical isolation and enable the private entity to retain full control of the NPN at the expense of high costs, PNI-NPNs present a lower entry barrier [3]. Some works have addressed the deployments options of 5G NPNs and several ongoing projects (e.g., 5GROWTH, FUDGE-5G, Affordable5G and TOUCAN) are designing 5G architectures to cover the different vertical industries' needs [2]–[4].

Industrial 5G NPNs impose stringent requirements in terms of throughput (500 Mbps/device), high connection density (100 devices/m^2), high positioning accuracy (cm-level), service availability/reliability (eight-9s), and security as specified in the 3GPP TS 22.104. These requirements impose the use of different technologies to increase available wireless resources in user-dense environments to provide required high data rates; to enable redundant transmission through disjoint paths to meet reliability constraint; and to utilize different sources to improve the positioning accuracy via fusion methods. Therefore, an integrated 5G new radio (5GNR) and wireless fidelity (Wi-Fi) network can be further enhanced by adding another non-3GPP technology, light fidelity (LiFi) [5]. LiFi can support high indoor connection density due to its narrow light beams and enable enhanced security thanks to the local confinement of light. Therefore, the non-3GPP technologies, Wi-Fi and LiFi [6], complement 5GNR to meet the aforementioned requirements.

Important use cases for industrial 5G NPNs in Industry 4.0 will require multi-tenancy support and service performance isolation between different operation technology domains within the factory floor to protect production lines. Examples of multi-tenancy use cases are remote monitoring of production lines by different product companies, or network equipment maintenance by different equipment vendors [7]. In this regard, the provision of infrastructure slices with dedicated and well-isolated resources is crucial. To the best of the authors' knowledge, multi-connectivity, multi-tenancy and service performance isolation in 5G NPNs have received little attention so far despite their potential benefits.

This article presents a new system for 5G-Advanced industrial networks, which is being developed in the H2020 5G-

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CLARITY project [8]. 5G-CLARITY includes three key novel features beyond 3GPP Release 16 that are crucial to meet the requirements of industrial NPNs. First, a multi-connectivity framework to enable smart access of not only 5GNR, but also Wi-Fi and LiFi for enhanced throughput, connection density and availability as previously discussed. Second, a positioning server that combines these WATs to achieve cm-level positioning accuracy. Third, a novel infrastructure-level slicing model to facilitate service isolation in industrial scenarios through the provision of well-secured and well-isolated multi-WAT slices to enable multi-tenancy support.

The article is organized as follows. Section II provides the 5G-CLARITY architecture description focusing on the multi-connectivity, positioning and slicing. Section III describes the Industry 4.0 scenario considered for assessing the performance offered by the 5G-CLARITY architecture. Then, the evaluation results are presented and discussed. Finally, Section IV concludes the paper.

II. 5G-CLARITY SYSTEM ARCHITECTURE

5G-CLARITY brings forward the design of a system that provides a rich set of capabilities in private industrial networks, NPNs, including high-precision positioning, delivery of critical services, integration with public 5G network infrastructures and network management with built-in slicing. These capabilities can be flexibly adapted, combined and extended to support variety of 5G services for non-public use, including infrastructure and communication/digital services. To address the design of such a complex system, the 5G-CLARITY architecture is structured into different strata, as depicted in Fig. 1. Each stratum encompasses a segregated scope and specific technological development cycle.

The *infrastructure stratum* is composed of all the on-premise hardware and software resources building up the 5G-CLARITY substrate, including multiple WAT nodes, user equipment (UE) and variety of compute, storage and networking fabric that enables virtualization of network and application functions.

The *network and application function stratum* includes 5G-CLARITY user, control and application plane functions. This stratum includes the virtualized network and application functions (VNFs/VAFs) that can be executed atop the infrastructure stratum. On the one hand, VNFs implement 3GPP functions such as virtual Radio Access Network (vRAN), 5G Core and user plane function (UPF); and provide means to support integration of non-3GPP access technologies and 5G-CLARITY multi-connectivity framework, detailed in Section II-A. On the other hand, VAFs allow providing domain-specific telemetry services such as vRAN telemetry, access network telemetry; and open RAN (O-RAN) xApps and service applications, i.e., access traffic steering (Section II-A) and positioning (Section II-B).

The *management and orchestration stratum* encompasses all the necessary functionality to deploy and operate the different 5G-CLARITY services and associated resources throughout their lifetime. This stratum is designed according to a service-based management architecture composed of multiple modular management services that can be flexibly combined into management functions targeting service/slice provisioning, cloud resource lifecycle management and assurance activities. Interactions between the noted strata are depicted in Fig. 2 and described in Section II-C. Further details on the design principles of individual strata and the architectural components can be found in 5G-CLARITY deliverable D2.2 [8].

It is worth noting that the 5G-CLARITY system provides means for public-private network integration, whereby 5G-CLARITY resources (on-premise infrastructure and functions) are combined with the mobile network operator (MNO)'s managed PLMN assets to create end-to-end (E2E) services. This integration allows the provisioning of PNI-NPN scenarios, with some workloads hosted by on-premise compute nodes and some others running in the telco edge nodes. The public-private network integration needs to be enforced at the connectivity layer and the management and orchestration layer (see Fig. 1). The first point refers to the need to set up a wide area network service between the private premises and the PLMN ingress node, typically a provider edge router connected to the MNO's central office to steer traffic across both domains. The second point refers to the need to make the management systems from the public and private network operators interact with each other to ensure a unified operation of the PNI-NPN and the E2E service atop. As seen in Fig. 1, this interaction can be done through external mediation fabric, integrated into the management and orchestration stratum. This fabric has a built-in access control and application programming interface gateway that allows the NPN operator to expose capabilities to the MNO in a secure, controlled and auditable way.

A. *Multi-Connectivity framework and eAT3S*

To integrate 5GNR, Wi-Fi and LiFi, 5G-CLARITY builds on two mechanisms defined in 3GPP Release 16: the integration of non-3GPP access networks in the 5G Core; and the use of access traffic steering, splitting and switching (AT3S) framework in 3GPP TR 23.793. In 5G-CLARITY, the 3GPP AT3S framework is extended into the enhanced AT3S (eAT3S) framework for 5G-Advanced networks.

Integration of non-3GPP access networks in the 5G Core is possible through non-3GPP interworking functions where the whole non-3GPP network appears like a single 5G base station (gNB) towards the 5G Core, connecting to the UPF through the interworking function. 5G-CLARITY uses this mechanism to integrate Wi-Fi and LiFi access networks with the 5G Core, where both networks connect to the same interworking function, but each network maps to a different IP subnetwork.

Without AT3S, a device with multiple wireless interfaces cannot transmit a single data flow simultaneously through the multiple access networks. This is overcome by 3GPP AT3S framework where steering functions in the UE and UPF aggregate the protocol data unit (PDU) sessions that a UE maintains through different access networks. Although 3GPP does not mandate the specific implementation of the AT3S steering function, it allows for different options such as Multi-Path TCP (MPTCP), which is also used in eAT3S [10]. MPTCP requires separate IP interfaces to manage different paths, which is possible in 5G-CLARITY. The choice of MPTCP is motivated

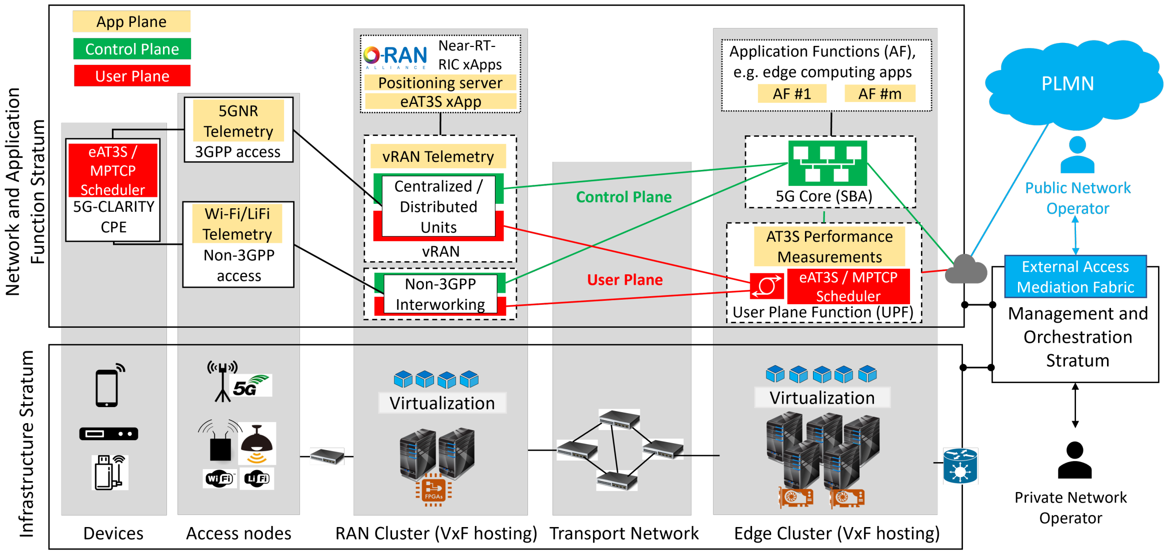

Fig. 1. 5G-CLARITY system architecture with the considered components/services for each stratum. Gray shaded boxes overlay on different strata are used to show mapping between components/services in different strata.

by the fact that TCP is the common protocol used by servers or data agents in industrial environments to communicate with applications [11].

In the control plane, AT3S supports different steering modes between 3GPP and non-3GPP access networks that can be defined on a per-flow basis, namely: *active-standby*, *smallest delay*, *static load balancing*, and *priority-based*. These steering behaviors are static (pre-defined factors) and can lead to a sub-optimal use of resources in industrial networks where signal conditions of the 5GNR, Wi-Fi and LiFi WATs can change at short timescales. Therefore, eAT3S introduces two new steering modes for 5G-Advanced networks. First, a *near-real-time (RT)* steering mode, where the percentage of traffic onto each access network is varied according to near-RT traffic statistics obtained in the RAN. This mode is based on a customized weighted round robin MPTCP scheduler available in [12]. Second, a *redundant* mode where packets are duplicated across all WATs to minimize delay and enhance reliability, which is critical in industrial networks. This mode is based on the standard MPTCP redundant scheduler [10].

The key to the *near-RT* steering mode in eAT3S is the availability of near-RT RAN telemetry. For this purpose, 5G-CLARITY leverages the O-RAN architecture [9], where the RAN intelligent controller (RIC) exposes a data bus with per-UE and per-cell 5GNR telemetry. The basic O-RAN architecture is extended in 5G-CLARITY to allow a custom controller to publish near-RT telemetry of Wi-Fi and LiFi to the RIC data bus. Based on the available near-RT telemetry, a custom control plane application, implemented as an O-RAN *xApp* [9], can be developed to configure the weights in the MPTCP schedulers located in the UE and the UPF. We refer to this as the 5G-CLARITY eAT3S *xApp*.

Notice that for the eAT3S *xApp* to be effective, a low latency is required between the RIC component and the MPTCP scheduler collocated within the *UPF*. This is a common assumption in industrial scenarios where the *UPF* can be deployed inside the customer premises to have a direct access to industrial applications.

An example implementation of the 5G-CLARITY eAT3S *xApp* is as follows. Assume that RAN telemetry, a pre-defined (by operator) weight factor per access network and a threshold, e.g. a minimum received signal strength (RSS) level, are available in the *xApp*. The regular 3GPP AT3S framework assigns the pre-defined weight factors as long as the given threshold is satisfied, regardless of congestion in the access network. Instead, the 5G-CLARITY eAT3S *xApp* uses near-RT RAN telemetry to detect congestion and temporarily overwrites the pre-defined weight factors to enhance performance. For example, if the LiFi RSS is above the availability threshold but the LiFi network is congested, the eAT3S *xApp* implements the following policy: (i) moves the LiFi load towards Wi-Fi, if this is not congested; (ii) moves the remaining LiFi load towards 5GNR, if the Wi-Fi network is also congested. Once the LiFi network load returns to an acceptable level, the eAT3S *xApp* increases the weight factors for the LiFi network to converge to the operator-defined weight factors in the long term. In Section III-B, we provide an evaluation of the 5G-CLARITY eAT3S framework and the described *xApp*.

B. Enhanced Positioning combining 5GNR, Wi-Fi and LiFi

Precise positioning is a key enabler for many industrial applications including mobile robots, augmented/virtual reality-based visualization or user safety. Currently, all of these applications use proprietary, standalone positioning technologies that cannot be reused by other applications. Additionally, 5GNR in Release 16 is not offering high precision positioning solutions that can be used in such applications.

To address the above-mentioned use cases, the 5G-CLARITY system includes a novel localization server for 5G-Advanced networks that achieves cm-level accuracy by combining positioning signals obtained from different WATs. In particular: (i) Sub-6 GHz positioning, which can be implemented in Wi-Fi bands at 2.4/5 GHz or in 5GNR bands at 3.5 GHz and deliver meter-level accuracy using time difference of arrival or two-way ranging/positioning methods; (ii) millimeter-wave (mmWave) positioning, which can be implemented in the 60 GHz Wi-Fi band, IEEE 802.11ad, or in the 5GNR band at 26/28 GHz, and in these bands, a cm-level accuracy can be achieved in line of sight (LOS) scenarios; and (iii) LiFi, which uses densely deployed light-emitting diodes (LEDs) to deliver a sub-meter positioning accuracy using RSS.

The scenarios of interest in 5G-CLARITY involve complex indoor environments covered by different WATs, where each technology alone delivers an uneven positioning accuracy within the area of interest. Therefore, the 5G-CLARITY localization server intelligently combines the position parameter estimates (RSS, time-of-flight, etc.) stemming from all considered WATs to enhance the localization accuracy and precision.

The 5G-CLARITY localization server uses Bayesian recursive filtering (BRF) data fusion to enhance position estimates stemming from different WATs. Although multiple special cases of BRFs exist (Kalman Filtering), we stick to the most general case for the purpose of this work. In particular, BRF updates the estimation of the position based on the following relation:

$$\text{posterior dist.} \propto \text{prior dist.} \times \text{measurement likelihood}$$

where dist. stands for “distribution”. In each estimation round, the device position is estimated using the posterior distribution computed by the above-mentioned relation. Here, we rely on the previous estimation and motion equations to obtain the prior distribution. Moreover, the noisy distance measurements (received from the WATs) and the velocity measured by the device sensors are employed to compute the likelihood distribution. Adopting such a general approach enables us to deal with the measurements coming from different positioning technologies, whose likelihood may not always follow a well-established distribution function. It also allows for a wide coverage by simultaneously receiving inputs from multiple technologies. A high-accuracy position estimation is facilitated when employing such a fusion approach.

Finally, the 5G-CLARITY localization server also implements a universal positioning interface, which can be used by operation technology business systems to obtain user device positions. This interface makes the enhanced positioning functionalities independent of the underlying WATs. The 5G-CLARITY localization server is evaluated in Section III-C.

C. Service and Slice Provisioning

3GPP defines a network slice as a set of network functions that are tailored (in terms of capacity and features) to satisfy a set of service requirements. The current 3GPP slicing information model (3GPP TS 28.541) specifies how slices are built out of network functions to support service requirements; however, it does not describe how to isolate slices at the infrastructure layer. This gap prevents using slicing to enforce service performance isolation, or even multi-tenancy, (the ability to deliver separate resource chunks for different tenants, so that they can deploy their own services atop), as there is no way to guarantee performance for a given slice if the underlying infrastructure resources are not isolated.

To cover this gap, 5G-CLARITY proposes to use slicing at the infrastructure layer (infrastructure slicing) for 5G-Advanced networks, with a 5G-CLARITY slice defined as a logical partition of the infrastructure that provides an isolated execution environment for a particular service or tenant. The 5G-CLARITY management and orchestration stratum (Fig. 1) allows to provision 5G-CLARITY slices on top of the infrastructure stratum.

To provide isolation, 5G-CLARITY introduces the concept of resource chunks, which are a set of network resources of the same type supporting the customer-facing services of a given 5G-CLARITY slice. Three types of resource chunks are considered: compute, transport and wireless chunks. A compute chunk consists of compute, storage and memory resources allocated to a given slice. Isolation in the Ethernet transport domain is achieved using virtual local area networks (VLANs), whereas in the wireless domain isolation is achieved through technology-specific quotas consisting of physical resource blocks (PRBs) for 5GNR, airtime for Wi-Fi, and a combination of airtime and wavelength for LiFi. Once resource chunks are allocated to a 5G-CLARITY slice, one or more ETSI network function virtualization (NFV) network services, or 3GPP slices, can be instantiated to provide customer-facing services over such slice.

Fig. 2 depicts a deployment example of two 5G-CLARITY slices, each delivered to Tenant 1 and Tenant 2. Tenant 1 has three network services (*NS0*, *NS1* and *NS2*) instantiated over the blue compute chunk, whereas Tenant 2 has two network services (*NS3* and *NS4*) instantiated over the red compute chunk. Tenant 1 features a 5G Core entirely deployed within the edge cluster, with two 3GPP slices that provide access to the red application function included in *NS1*, and the green one included in *NS2*. Each 3GPP slice for Tenant 1 uses the same PLMN identifier (PLMNID), *PLMNID-1*, but a specific slice service type - slice differentiator (SSTSD), *SSTSD-1* for *NS1*, and is made available through a particular subset of 5GNR nodes. Similarly, each slice uses a specific service set identifier (SSID) that is made available from a subset of the Wi-Fi and LiFi nodes. Connectivity between the radio services and the corresponding core network functions is achieved through dedicated VLANs in the transport network. Unlike Tenant 1, *NS3* for Tenant 2 includes only the user plane functions (interworking gateway and UPF), whereas the remaining 5G core functionalities are deployed in the public network (not explicitly depicted in Fig. 2), thus supporting a distributed 5G Core deployment. The red compute chunk for Tenant 2 also embeds *NS4*, which sustains the application function depicted in pink. This service is advertised using a different PLMNID, *PLMNID-2*, and specific *SSTSD* and *SSID* in the 5GNR, Wi-Fi and LiFi nodes, respectively.

The upper part of Fig. 2 depicts the interfaces used to manage the lifecycle of 5G-CLARITY slices. First, NETCONF is used to manage the 5GNR, Wi-Fi and LiFi access devices, to configure the required PLMNID, SSTSD and SSID values. Standard transport software defined networking (SDN)

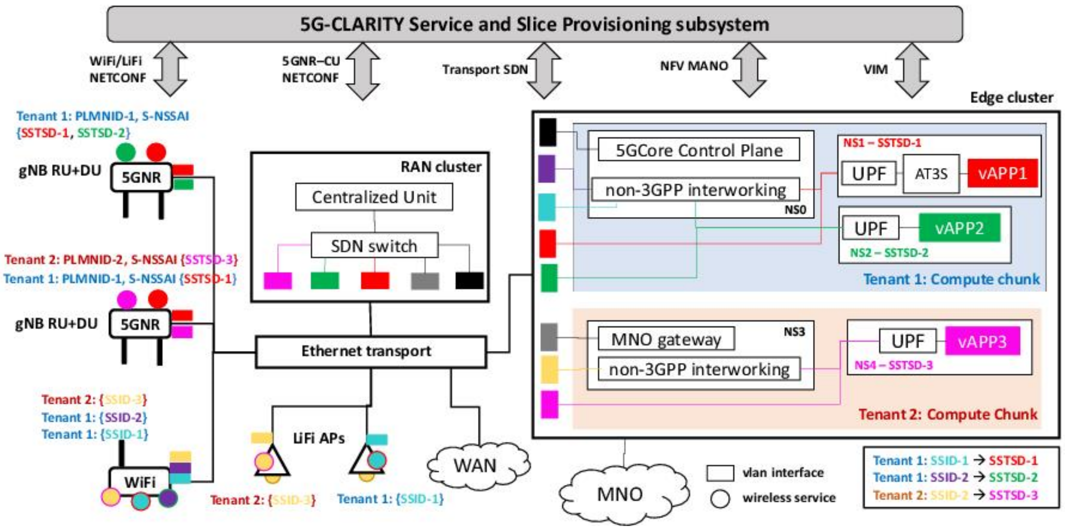

Fig. 2. Example of two 5G-CLARITY slices serving two different tenants deployed in a private premise. Each slice supports multiple network services providing access to VAFs.

interfaces are used to control the provisioning of VLANs in the transport domain. Finally, NFV virtual infrastructure manager (VIM) and NFV management and network orchestration (MANO) interfaces, SOL005 [13], are used to configure compute chunks across tenants and to manage network services.

To ensure slice performance isolation over a shared infrastructure layer, it is essential that 5G-CLARITY slices can be quickly provisioned and reconfigured. Thus, a machine learning function could dynamically adjust NFV network services, or tune compute, transport and wireless quotas to enforce performance guarantees across slices. In Section III-D, we evaluate the time required to provision a 5G-CLARITY slice using a laboratory testbed.

III. PERFORMANCE EVALUATION

A. Scenario description

In order to evaluate the performance of two of the proposed key features, namely multi-connectivity and positioning, an Industry 4.0 scenario based on a real factory layout, depicted in Fig. 3 is chosen. The scenario includes the deployment of three different WATs; Wi-Fi at 5 GHz, LiFi at 337 THz, 5GNR at 3.5 GHz and Wi-Fi at 60 GHz, where the latter is only used for positioning. The Wi-Fi, LiFi and 5GNR systems use the channel bandwidth values of 80, 20 and 80 MHz, respectively. The scenario considers a moving automated guided vehicle (AGV) along the path illustrated in Fig. 3; and 100 randomly located users which represent programmable logic controllers (PLCs) and factory workers. With the aid of mobility of the AGV (with a speed of 0.7 m/s) and 100 other users that are modeled with full-buffer traffic, both the adaptability of the proposed eAT3S *near-RT* steering mode to provide service continuity and the localization accuracy of the proposed positioning algorithms are evaluated.

In simulations, all users are equipped with a 5G-CLARITY customer-premises equipment (CPE) that provides network connectivity to the WATs. A total of 70 LiFi access points (APs) with a 4 meters inter-AP distance, 4 Wi-Fi APs, 2 mmWave Wi-Fi APs, and a 5GNR gNB are deployed. All the APs and the gNB are located at a height of 4 meters. The number of APs and their positions are chosen such that good coverage of the area of interest is achieved, while sufficient link budget needed for the required communication and localization services is attained.

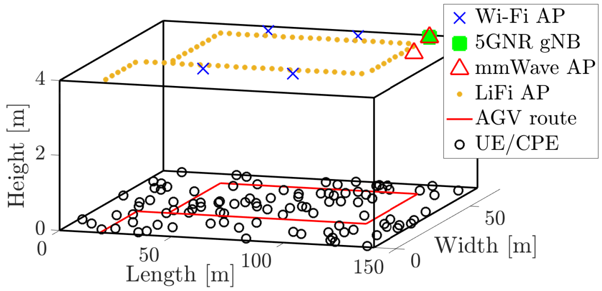

Fig. 3. Simulated factory environment. UE/CPE x–y axis coordinates are uniformly distributed.

B. Multi-connectivity evaluation

The main goal of our simulations is to validate the ability of the 5G-CLARITY eAT3S *near-RT steering mode* to enforce traffic distribution policies while providing service continuity for the mobile AGV. Hence, the performance is evaluated in terms of achieved data rate of the AGV and assigned load percentage to each WAT. To evaluate the key value proposition of 5G-CLARITY, namely integrated 5GNR, Wi-Fi and LiFi, we compare eAT3S with a similar algorithm applied to a network that only integrates 5GNR and Wi-Fi. In this work, two different operator-defined AT3S rules are considered. The first rule (R1) assigns 70% of the traffic onto 3GPP and 30% onto non-3GPP networks. Whereas, the second rule (R2) assigns 30% onto 3GPP and 70% onto non-3GPP networks.

Fig. 4 shows that LiFi plays a crucial role on complementing 5GNR and Wi-Fi networks where it raises the average rate of the AGV from 5 Mbps to 17 Mbps, and with the eAT3S

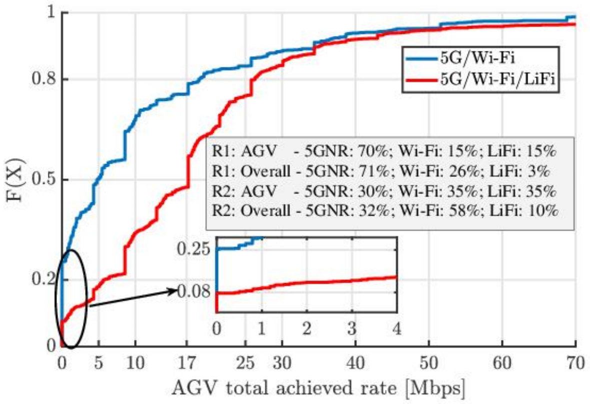

Fig. 4. Total achieved rate performance of a mobile AGV when 100 other users exist in the system. $F(X)$ refers to the CDF of a random variable X.

near-RT steering mode, the service continuity is improved by 17%. Also, the *near-RT steering mode* successfully applies the operator-defined load assignments. As most of the users are not in coverage area of an LiFi AP, (Fig. 3), the load on non-3GPP network is mostly served by Wi-Fi. However, when the users are in the coverage of all WATs, the *near-RT steering mode* precisely achieves the given load assignments.

C. Enhanced positioning evaluation

The localization server retrieves AGV distance measurements from each WAT with an uncertainty modelled as folded normal distribution. Furthermore, we assume that inertial sensors on the AGV estimate the velocity with an uncertainty modelled as normal distribution. All the received measurements are supplied to the BRF to estimate the AGV's position. One critical parameter for BRF is the process noise covariance matrix which prevents the filter to be overconfident about either prior distribution or measurement likelihood. We set this matrix to be $\mathbf{Q} = \text{diag}(\sigma_x^2, \sigma_y^2) = \text{diag}(5, 5)$ in order to account for any possible change in any direction. A total of 1000 independent simulations are performed and the position is estimated with the aid of the posterior distribution computed by the BRF (explained in Section II-B). Fig. 5 shows a CDF of the positioning error for each WAT and the position error for the data fusion approach. Such CDFs are computed by obtaining the empirical histogram of the estimation error, which represent the empirical PDF, and performing integration over it. The position estimates obtained using the data fusion approach outperform those computed individually by each WAT. Such behavior is expected as BRF outweighs the measurements with higher certainty (lower error variance). Hence the location estimation after fusion is always equal to or greater than the best performance among the WATs. The achievable positioning precision is in the order of a few tens of centimetres. A better precision can be achieved by denser deployment of APs.

D. Benchmarking slice provisioning time

To evaluate the time required to provision 5G-CLARITY slices, we deploy a testbed featuring NETCONF enabled wireless nodes including: a custom Wi-Fi AP, based on a Gateworks Ventana 5410 single board computer, a PureLiFi LiFi AP, and an Accelleran E1000 4G small cell. 5GNR small cells were not available in our testbed but no significant differences are expected regarding provisioning times. The testbed also includes an OpenStack based edge cluster, featuring a DELL PowerEdge server with 64 GB RAM, and an NFV orchestrator based on open source MANO (OSM) [14]. We characterize the slice provisioning time by looking separately at the time required to advertise new PLMNID and SSID services in the WATs, and to provision the VNFs required to support the slices. In particular, we define:

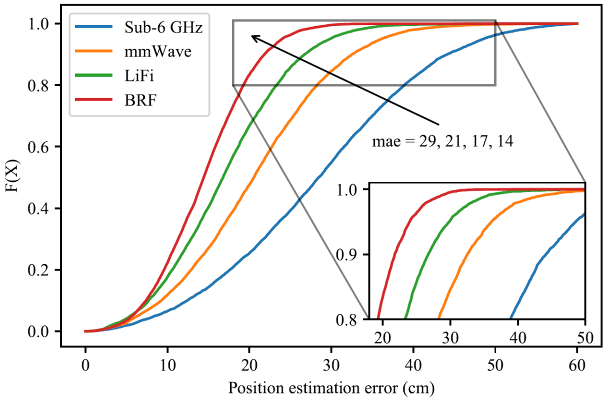

Fig. 5. CDF of the positioning error for different WATs and the BRF fusion approach with mean absolute error (mae) of the position estimation error.

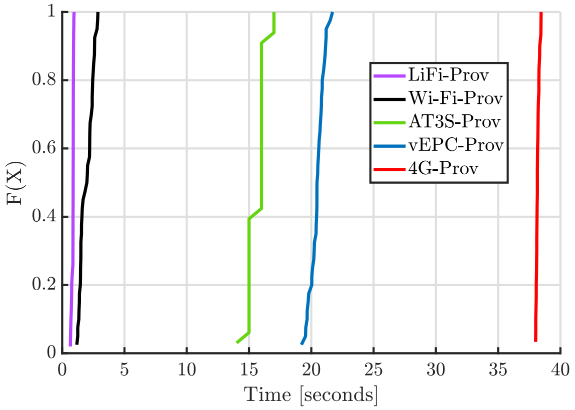

Fig. 6. Empirical times required to provision the various components of a 5G-CLARITY slice.

- LiFi/Wi-Fi-Prov: The time required to configure an *SSID* and a *VLAN* in the LiFi/Wi-Fi nodes using NETCONF;
- 4G-Prov: The time required to add a *PLMNID* to the 4G cell using NETCONF;
- vEPC-Prov: The time required to instantiate a virtual evolved packet core (vEPC) based on open5gs [15] to support the traffic of the slice. The vEPC is provisioned directly on top of the OpenStack;
- AT3S-Prov: The time required to provision a virtual AT3S proxy used to support the multi-connectivity framework introduced in Section II-A. This virtual function is deployed as a VNF using the NFV MANO orchestrator.

Fig. 6 depicts CDF of the provisioning times obtained from 50 experiments. Accordingly, configuring a new SSID service in Wi-Fi and LiFi using NETCONF can be performed in less than 3 seconds, while configuring a PLMNID in 4G cell requires ∼40 seconds, which is due to a hardware limitation in the small cell that cannot update the list of radiated PLMNIDs without a reboot. This limitation is expected to be resolved in future 5GNR small cells resulting in reduced slice provisioning times. Deploying the vEPC and AT3S functions in the edge cluster involves booting virtual machines which requires between 15 and 20 seconds in our OpenStack based edge cluster deployment. The overall slice provisioning time can be extracted from the previous measurements as follows. First, vEPC needs to be provisioned (takes ∼20 seconds). Then, the AT3S function and all WATs can be configured in parallel, dominated by 4G-Prov time of ∼40 seconds. Thus, we can conclude that an E2E 5G-CLARITY slice including wireless, transport and compute services can be deployed in ∼60 seconds.

IV. CONCLUSIONS

Enabling the fourth industrial revolution is not only subject to stringent connectivity-related requirements but also on operational cost, flexibility and ease of network deployment/management. In this paper, we introduced the 5G-CLARITY system which integrates 5GNR, Wi-Fi and LiFi access technologies with an advanced 5G management system for NPNs. It is reported that the 5G-CLARITY system improves the average throughput of a mobile AGV by 240% compared to an integrated 5G/Wi-Fi system; improves the positioning precision by 48% and 27% compared to Wi-Fi or mmWave positioning, respectively; and deploys an E2E slice composed of wireless, transport and compute services with a provisioning time less than a minute. We believe that the features enabled by 5G-CLARITY are key to address the diverse requirements for 5G-Advanced NPNs/SNPNs.

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