Beyond 5G Multi-Tenant Private Networks Integrating Cellular, Wi-Fi, and LiFi, Powered by Artificial Intelligence and Intent Based Policy

5G-CLARITY Executive Summary

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1 Motivation

Private 5G networks have gathered a significant interest in the industry for their potential to disrupt vertical domains, such as Industry 4.0 [1]. 5G-CLARITY [2], [3], is a Horizon 2020 5GPPP project executed between 2019 and 2023, which gathered European Mobile Network Operators (MNOs), network vendors, Small and Medium Enterprises (SMEs), and academia, with the goal to design and validate a new platform for private 5G networks that addresses some of the challenges that today hinder the adoption of private 5G, namely:

1. Coexistence with IEEE 802.11: Private 5G networks target environments, such as factories, where the use of IEEE 802.11 is already well-established and will be preserved in the upcoming years. Thus, new solutions are needed to allow private 5G networks to complement the connectivity services offered through IEEE 802.11.
2. Custom vertical requirements: Private 5G networks in vertical domains must address custom requirements that are not relevant in public 5G networks. An example is the need for high precision localization in industrial environments.
3. Lack of skilled 5G personnel: While there is a wide knowledge in managing IEEE 802.11 technologies within the enterprise and industry domains, there is a lack of personnel skilled in 5G technologies.
4. Interaction between public and private 5G networks: Availability of private spectrum enables vertical users to either deploy standalone private networks or to deploy private networks that are supported by the public 5G network of an MNO. Novel solutions are required to enable flexible business models arising from the interaction between public and private 5G networks.

To address these challenges, the 5G-CLARITY platform adopts the following design principles:

- Multi-band and multi-technology: The 5G-CLARITY platform integrates three access technologies: i) 5GNR operating at midband spectrum, ii) IEEE 802.11ax at 5/6/60 GHz, and iii) IEEE 802.11bb, also known as Li-Fi, operating at visible light spectrum. These three access technologies are used to provide benefits in terms of capacity, low latency, and localization accuracy. It is noted that multi-band operation is also possible using only 3GPP technologies, e.g., aggregating 5GNR FR1 and FR2 cells. However, aggregating IEEE 802.11 and 3GPP 5GNR access networks under a common platform reduces time to market by leveraging already deployed IEEE 802.11 networks.
- Unifying localization and communication infrastructure: Today, separate infrastructures are used for communications, e.g., Wi-Fi access points (Aps), and for localization, e.g., ultra-wideband (UWB) anchors. 5G-CLARITY has developed positioning mechanisms that can be embedded into IEEE 802.11 and 3GPP 5GNR radios to unify communications and positioning infrastructure.
- Intent-based network management: To overcome the 5G knowledge gap in vertical information technology (IT) personnel, the 5G-CLARITY platform simplifies network operations by allowing a network operator to interact with the infrastructure using natural language.
- Enable “as-a-Service (aaS)” service models between public and private networks: The management plane of the 5G-CLARITY platform enables three service delivery models between private and public networks, namely, i) Wireless as a Service (WaaS), ii) NFV as a Service (NFVaaS), and iii) Slice as a Service (SlaaS).

2 5G-CLARITY System Design

Figure 1 depicts the 5G-CLARITY platform architecture that is composed of four different strata:

- The *infrastructure stratum* consists of the physical infrastructure including Wi-Fi and LiFi APs and

5GNR radio heads, as well as COTS servers to sustain the software-based 5G radio, core, and the application functions.

- The *network and application function stratum* consists of all the virtual network and application functions, in the RAN, Core and edge domains, required to instantiate a 5G-CLARITY network.
- The *management and orchestration stratum* includes a set of Managements Functions (MFs) used to configure network slices on top of the 5G-CLARITY physical and virtual infrastructure.
- Finally, the *intelligence stratum* contains additional functionality to expose a simplified intent-based interface towards the private network operator.

These four strata gather the required functionalities to deliver novel capabilities in terms of multi-connectivity, positioning, intent-based management, and private-public service delivery models, which are reviewed next.

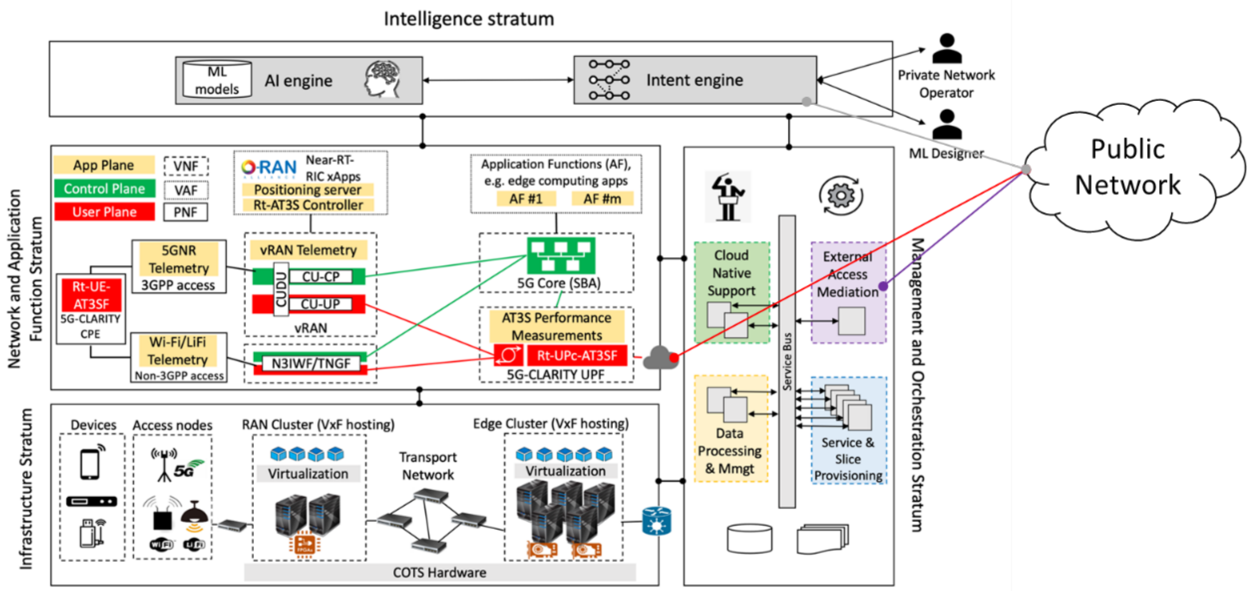


Figure 1 5G-CLARITY architecture [3]

2.1 Multi-connectivity

5G-CLARITY has developed a multi-connectivity framework that provides two new connectivity services:

- A multi-technology eMBB service, whereby a device that includes 5GNR, Wi-Fi and LiFi interfaces aggregates the capacity of all the wireless access networks into a single data pipe.
- A multi-technology URLLC service, whereby a device that includes 5GNR, Wi-Fi and LiFi interfaces may reduce latency and increase reliability by transmitting data in parallel through all the wireless technologies.

The 5G-CLARITY multi-connectivity framework is based on the 3GPP Access Traffic Steering, Switching and Splitting (ATSSS) framework [4], with a user plane function built upon multi-path transmission control protocol (MPTCP) [5]. MPTCP has been selected because of its capability to provide in-order delivery, and its modular design in Linux systems that allows to control the type of MPTCP scheduler, i.e., round-robin scheduler for the eMBB service, and redundant scheduler for the URLLC service. A challenge of using MPTCP to aggregate capacity of wireless technologies is that the differences in the relative wireless capacities of 5GNR, Wi-Fi and LiFi, decrease aggregation performance due to head of line blocking in the receiver. To mitigate this effect, 5G-CLARITY developed a weighted round robin MPTCP scheduler that is available open source [6].

2.2 Positioning

To address the challenge of providing high accuracy positioning in indoor environments, 5G-CLARITY has developed positioning techniques that can be embedded into 5GNR, Wi-Fi and LiFi. As depicted in Figure 2, three types of positioning technologies have been developed according to the target bands of operation:

- For Sub-6 GHz radios, namely 5GNR midband or IEEE 802.11 at 5 or 6 GHz band, a downlink time difference of arrival (TDOA) system was used, which allows devices to position themselves by passively listening for the beacon frames transmitted by the anchor nodes.
- For mm-wave radios, namely 5GNR at 26GHz or IEEE 802.11 at 60GHz, a two-way ranging protocol was designed. The use of TWR is due to the relaxed synchronization requirements in comparison to DL-TDOA, as the used 60 GHz radios do not support sub-nanosecond precision synchronization.
- For LiFi operating in visible light spectrum, proximity-based positioning is implemented based on received signal strength indicator (RSSI) measurements. The limited coverage of LiFi APs, typically below 5 m^2, favors this simple approach.

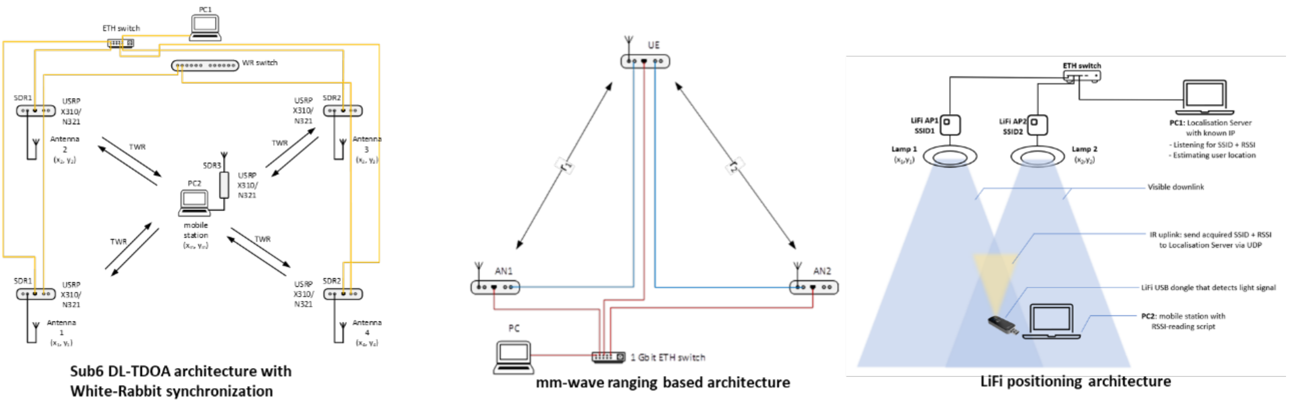
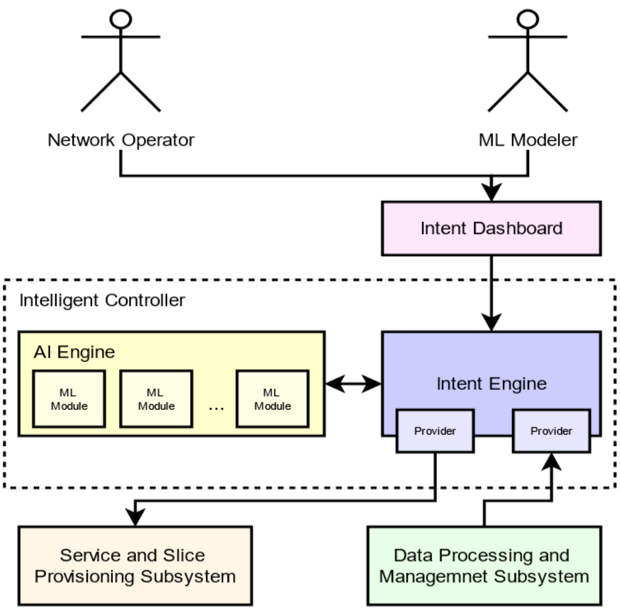


Figure 2 5G-CLARITY positioning technologies developed [7]

2.3 Intent based management

To simplify the operation of private 5G networks, 5G-CLARITY proposes the use of an intent-based interface using natural language. At the bottom of Figure 3 we can see an example intent definition, which consists of: i) an intent body using natural language, e.g., "*I want to create a slice*", and, ii) a set of intent parameters that are used to customize the intent, e.g., the GPS coordinates of the area where the slice should be active, the list of users that should be allowed to connect to that slice, or the type of access technologies that should be part of the slice.

To enforce the application of the user provided intent, the 5G-CLARITY platform includes two novel management entities depicted in Figure 3, namely the *Intent Engine* and the *AI Engine*. The goal of the Intent Engine is to map the user defined intent and parameters to a specific REST endpoint offered by a management function that has been previously registered in the Intent Engine. This matching operation is done using natural language processing techniques. The AI Engine is used to host machine learning (ML) models, which are used to provide the low-level details required to enforce the user defined intent. For example, in the slice creation example depicted in Figure 3 an ML model would be in charge of translating the target area where the slice should apply, provided by the user, to the concrete set of gNB and APs that should be configured to advertise the network slice.



Example: Intent based slice provisioning

Intent type:	Adding radio information
Intent body:	*I want to create a slice*
Parameters:	*Name: my-slice, user-list: {IMSI-list}, location: Coordinates, access technology: {wifi,5g,lifi,5g+wifi,5g+lifi,5g+wifi+lifi}*

Figure 3 Intent-based architecture and example intent [8, 9]

2.4 Private-public service delivery models

The 5G-CLARITY platform includes a management plane for private 5G networks that allows to configure infrastructure-based slices, consisting of: i) a set of wireless access nodes, i.e., gNB or APs, that are part of the slice where depending on the type of technology, specific wireless resources can be allocated to a slice, ii) an Ethernet transport layer service, e.g., VLAN, used to backhaul data from the slice, and iii) a compute service consisting of a resource quota allocation in the RAN, and edge clusters used to instantiate the virtual network functions (VNFs) and cloud-native network functions (CNFs) needed to provision the slice.

Using the capabilities of this management plane, a 5G-CLARITY private network can provide three novel types of on demand connectivity services:

- Wireless as a Service (WaaS), whereby a third party, e.g., a MNO or a Communication Service Provider (CSP), could use on demand the wireless resources, e.g., gNBs or APs, available in a private network. This service model is useful for example in stadiums or public hubs.
- NFV as a Service (NFVaaS), whereby a third party can manage the lifecycle of network services executed in the edge resources available in the private network.
- Slice as a Service (SLaaS), whereby a third party can request a network slice inside the private network, which comprises wireless, transport and network services.

3 Summary of the main results

The 5G-CLARITY platform was deployed and demonstrated in two different pilots:

- Industry 4.0 pilot implemented in the BOSCH factory, Aranjuez, Spain,

- Smart Tourism pilot implemented in the M-Shed Museum, Bristol, UK.

Figure 4 shows the 5G-CLARITY infrastructure deployed in these two pilots, highlighting the wireless access technologies, as well as the components of the infrastructure stratum (c.f. Figure 1). It is worth noting that in the BOSCH factory the 5G-CLARITY platform is deployed in a centralized manner, with all the platform components deployed on-site in the same rack, whereas in the M-Shed Museum a distributed deployment is adopted, with only the RAN elements located in the museum and the rest of components deployed in an edge node located at the University of Bristol.

The main results obtained in these two pilots in terms of: i) multi-connectivity, ii) localization, iii) intent-based management, and iv) Private-Public service delivery models are discussed next.

Figure 4 5G-CLARITY pilots: BOSCH factory, Aranjuez, Spain (left); M-Shed Museum in Bristol, UK (right)

3.1 Multi-connectivity

The 5G-CLARITY MPTCP-based multi-connectivity framework was deployed in the factory and museum environments, where a measurement campaign was carried out to evaluate the eMBB and the URLLC services offered by the multi-connectivity framework.

To evaluate the eMBB service, Figure 5 depicts downlink throughput measurements taken at different locations in the museum (top) and factory environments (bottom). The x axis represents the locations defined at an increasing distance from the gNB and AP locations. It is notable that different 5GNR and Wi-Fi configurations are used in museum and factory environments. In the museum a 100MHz 5GNR carrier and a 160 MHz WiFi6 carrier are used, whereas in the factory a 40 MHz 5GNR carrier and an 80 MHz Wi-Fi6 carrier were used. In the factory environment two different 5GNR configurations with a 6/3 and a 3/6 TDD pattern were tested. We can see how Wi-Fi6 excels in terms of data rate when being close to the AP location, but its performance quickly degrades with distance. For 5GNR, instead, a consistent, almost flat, performance across all locations in the museum and factory environments are observed with a capacity determined by the available carrier bandwidth and the used TDD pattern. For LiFi the capacity is spatially confined within the light cone, which demonstrates the potential of LiFi in terms of spatial reuse of light spectrum and hence area capacity (driving wireless network densification to new levels), as well as security. The available data rate in the implemented LiFi system in our pilots is limited because of the use of a pre-802.11bb product generation. With IEEE 802.11bb being fully ratified and approved, it is expected that LiFi APs will achieve downlink capacities of around 300 Mbps [9]. The column at the right side of Figure 5 depicts the results of aggregating all access networks using MPTCP, where we observe a downlink capacity roughly corresponding to the addition of the 5GNR and Wi-Fi6 capacities, which results in a strong eMBB service performance across the whole coverage area.

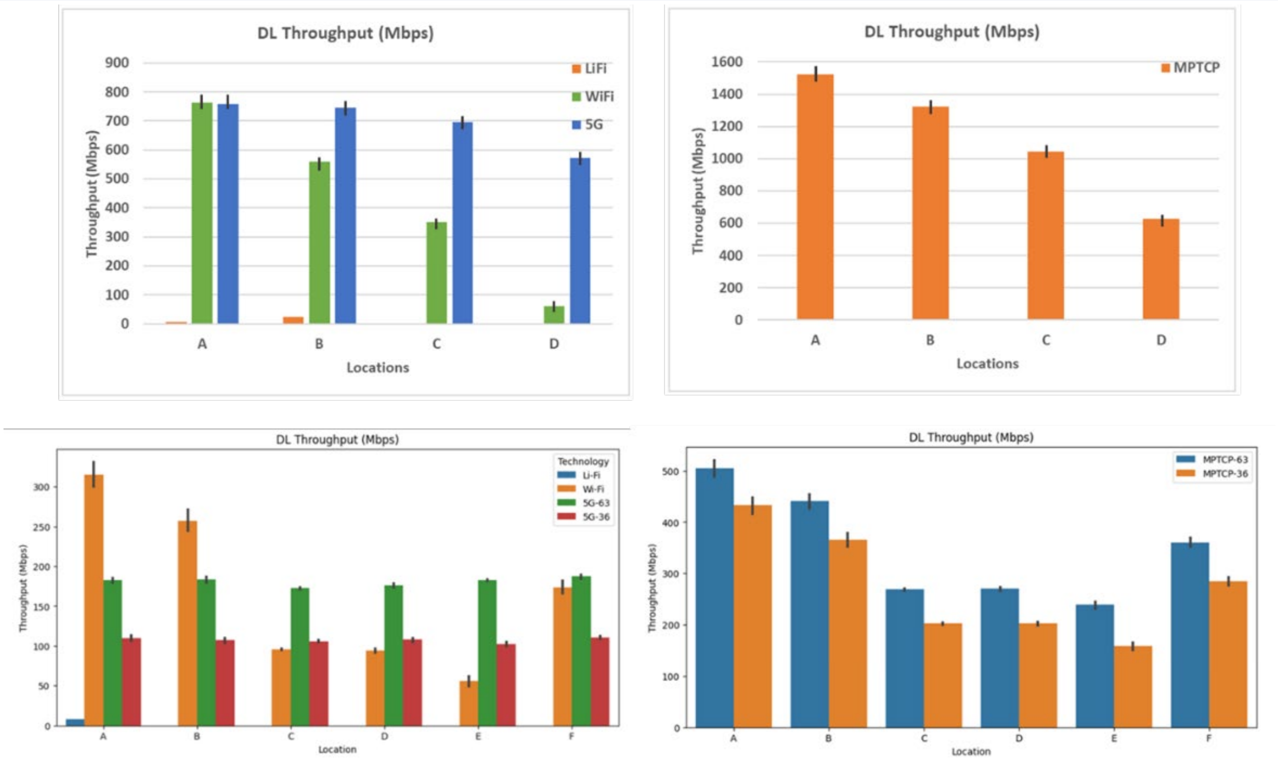


Figure 5 DL Throughput performance in the museum (top); and the factory (bottom). Graphs at the left side show per-RAT throughput, whereas those at the right side depict the MPTCP aggregation with a round-robin scheduler.

Looking now at the URLLC service, next the evaluation of the round-trip latency delivered by the 5G-CLARITY multi-connectivity framework is presented when packets are duplicated across the three access technologies. The key parameter to evaluate the reliability of the URLLC service is the amount of external interference, defined as additional devices that compete for the resources of each wireless access technology. Figure 6 depicts the round-trip latency under growing levels of interference, up to 80%, for the factory (left) and museum (right) environments, showing how parallel access through 5GNR, Wi-Fi and LiFi keeps round-trip latency below 15 ms even with 80% interference levels.

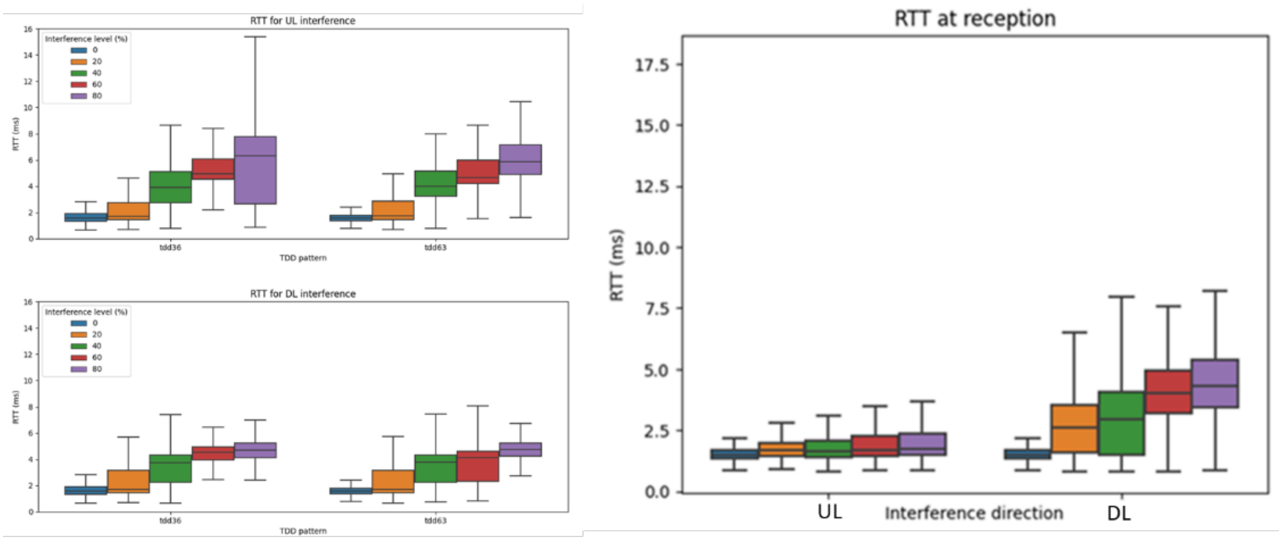


Figure 6 Round trip latency under interference and the MPTCP redundant scheduler in the factory (left) and museum (right). Measurements correspond to the location A in Figure 5

Based on the obtained results we conclude that combining 5GNR, Wi-Fi, and LiFi is a good approach to deliver consistent eMBB and URLLC connectivity services that can be of interest in manufacturing and museum environments.

For further details on the scenario and measurements, the interested reader is referred to [10] where we discuss how these connectivity services have been applied to a manufacturing execution system (MES) connected production line use case in the BOSCH factory, and to a humanoid robot use case in the M-Shed Museum, while providing a business case analysis for each use case.

3.2 Positioning

5G-CLARITY positioning mechanisms for Sub-6, mm-wave, and Li-Fi were evaluated in the BOSCH factory at Aranjuez, Madrid, in an automatic guided vehicle (AGV) positioning use case. Due to limitations in the available hardware the experimental evaluation was limited to an area of 260 m^2 with good line of sight visibility where the positioning anchors for Sub-6 and mm-wave bands were deployed using software defined radios, and two Li-Fi APs were installed at the height of 5 m in the factory for RSSI-based localization.

Figure 7 shows empirical CDFs obtained in the factory for the Sub-6 and mm-wave anchors, indicating positioning errors below 15 cm in the case of Sub-6 and below 3 cm for mm-wave. Even though this performance is expected to degrade in larger coverage scenarios and potential non-line of sight situations, the results obtained in this controlled environment demonstrate the potential of Sub-6 and mm-wave radios to provide high accuracy positioning services in indoor industrial environments. Regarding LiFi, the high-altitude ceilings available in the factory resulted in a decreased RSSI sensitivity in the LiFi receivers, which turned LiFi APs into on/off proximity beacons providing an approximate 3-meter accuracy corresponding to the per-AP LiFi coverage observed in the factory environment.

For an in-depth description of our measurement methodology and obtained results, the interested reader is referred to [10].

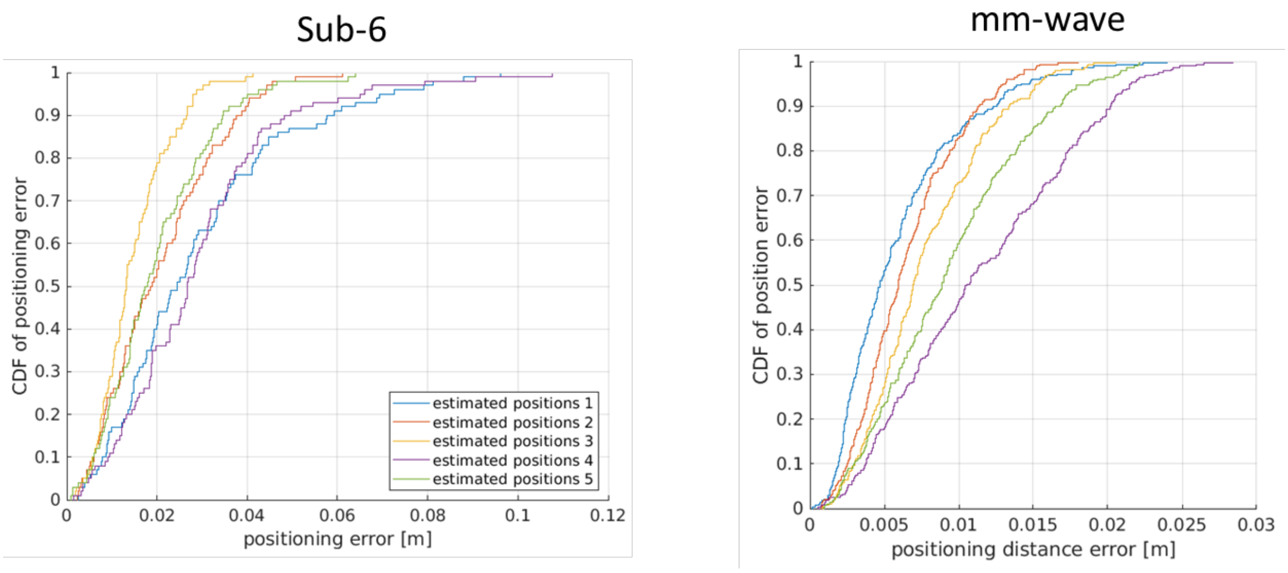


Figure 7 Empirical CDF of the positioning error in a static scenario in the factory

3.3 Intent-based management

A prototype of the 5G-CLARITY Intent and AI engines was developed as part of the 5G-CLARITY platform and demonstrated in the museum use case, as well as in two laboratory scenarios. These are the three intent-based management use cases demonstrated in 5G-CLARITY:

- Intent-based network service provisioning in the M-Shed Museum. In this use case, a public safety officer requests the museum IT admin to tap on to a camera stream transmitted by a humanoid robot available in the museum. The safety officer requests this video stream to be viewable on a mobile device. Realising this use case required the IT administrator to provision a VNF that would forward the requested video stream to the public safety officer device. The use case demonstration video, describing how the IT administrator executes the VNF provisioning by typing an intent in natural language into the Intent Engine dashboard, is available online [11].
- Intent-based slice provisioning. In this use case, a private network administrator uses natural language to express an intent to create a network slice. To execute this use case, the 5G-CLARITY Intent Engine was integrated with a slice manager component [12]. A demonstration of this use case is available online [13].
- Intent-based non-line of sight detection. In this use case, the intent is not generated by a human operator, but instead by another network management function, namely the location management function (LMF) defined in 3GPP. The LMF issues an intent to verify if a given ranging measurement provided by a user device has been obtained in line of sight or non-line of sight conditions. Upon this intent, the intent engine provisions an ML model in the AI Engine that can assess line of sight conditions from channel measurements. A demonstration of this use case is available online [14].

For further details on the 5G-CLARITY intent-based framework, the interested reader is referred to [8].

3.4 Private-public service delivery models

To demonstrate the concept of slice-as-a-service (SLaaS) between private and public networks, 5G-CLARITY liaised with the 5G-ZORRO project [15] to develop a joint proof of concept (PoC) submitted to the ETSI Zero Touch Network and Service Management (ZSM) group, which features an integration between the 5G-CLARITY private network management plane and a DLT-based marketplace developed in 5G-ZORRO.

The proposed PoC [16] illustrates the automated provisioning of an end-to-end slice combining resources inside a private network deployed in a factory, and resources provisioned within the edge cloud of an MNO. The provisioned end-to-end network slice provides connectivity to AGVs inside the factory, which are equipped with an onboard camera used to capture images of obstacles blocking the path of the AGV. The recorded images are transmitted to a video analytics function deployed in the MNO edge, which identifies the type of blocking object. The output of this service is information used to re-plan the AGV trajectories to enhance productivity within the factory. The video demonstration of this PoC is available online [17].

4 Conclusions and summary

Based on the results obtained in the two project pilots, we conclude that the aggregation of 5GNR, Wi-Fi and LiFi access networks within a common system for private networks can add significant value to vertical industries requiring novel eMBB, URLLC and positioning services. The highlight of some of the lessons learnt through the integration of the technologies considered in the project, as well as some of the open points that to be addressed in future are presented in the next sections.

4.1 Lessons learned

Some of the good practices learnt through the integration of the 5G-CLARITY technologies in the two project pilots are discussed here. These good practices can be helpful to other R&D projects that expand on the use of 5G in private networks:

- Stability of open source 5GSA core networks. 5G-CLARITY experimented with free5gc [18] and open5gs [19]. Although more features were available in free5gc, e.g., N3IWF, at the time of our testing open5gs was observed to be more stable and to be able to better cope with the available radio performance.
- Availability of 5GSA compatible devices. The project pilots required the development of custom customer premises equipment (CPE) that featured an MPTCP capable Linux kernel. This required to integrate USB connected 5G dongles, for which Quectel RM500Q were found to be the best model when tested with the NOKIA and Amarisoft radios available in the project. Some of the M2 to USB adapters used to connect the Quectel modules to the CPEs were found to degrade radio performance.
- ORAN interoperability problems: Due to lack of maturity in the ORAN ecosystem, the project developments encountered performance problems when integrating a multivendor ORAN stack considered for the pilots. Due to these problems, integrated 5G RAN solutions were used in the final trials. These issues are expected to be resolved in the near future.

4.2 Future Work

To conclude this executive summary, some proposed future works required to further develop the initial vision laid out in the 5G-CLARITY project are introduced:

- Based on the first PoC results obtained in 5G-CLARITY for the integration of LiFi in multi-RAT wireless networks, it is anticipated that scaling up networks using the newest IEEE 802.11bb compliant devices will transform future indoor private network environments. More research is needed to optimize mobility and multi-connectivity in these environments to fully exploit the potential of LiFi in multi-RAT environments.
- Further work is rquired to optimize the integration of LiFi in lighting products, such that greenfield private network venues consider deploying LiFi enabled lighting by default. This would provide a first layer of wireless communication and localization capabilities, which could later be enhanced by adding LiFi (with infrared downlink), 5GNR and Wi-Fi.
- To ease integration in factory environments, 5G-CLARITY CPEs should provide a native Ethernet service, which would ease the integration of the 5G-CLARITY platform in current Ethernet and Wi-Fi-based deployments.
- More work is needed to continue expose management operations as natural language based intent interfaces.

5 References

[1] 5G-ACIA, "5G Alliance for Connected Industries and Automation," [Online]. Available: http://5g-acia.org.

[2] 5G-CLARITY Project, [Online]. Available: www.5gclarity.com.

[3] T. Cogalan, et al., "5G-CLARITY: 5G-Advanced Private Networks Integrating 5GNR, WiFi, and LiFi," *IEEE Communications Magazine,* vol. 60, no. 2, pp. 73-79, 2022.

[4] 3GPP, "5G System Access Traffic Steering, Switching and Splitting (ATSSS); Stage 3," 3GPP Release 16,

TS 24.193., 2019.

[5] IETF RFC8684, "TCP Extensions for Multipath Operation with Multiple Addreses," March 2020. [Online]. Available: https://datatracker.ietf.org/doc/html/rfc8684.

[6] 5G-CLARITY, "5G-CLARITY Multi-Connectivity Testbed," [Online]. Available: https://github.com/jorgenavarroortiz/multitechnology_testbed_v0.

[7] 5G-CLARITY D3.3, "Complete Design and Final Evaluation of the Coexistence, Multi-Connectivity, Resource Management, and Positioning Frameworks," 2021.

[8] J. Macnamara, et al., "NLP Powered Intent Based Network Management for Private 5G Networks," *IEEE Access,* vol. 11, pp. 36642-36657, 2023.

[9] E. Khorov and I. Levitsky, "Current Status and Challenges of Li-Fi: IEEE 802.11bb," *IEEE Communications Standards Magazine,* vol. 6, no. 2, pp. 35-41, June 2022.

[10] 5G-CLARITY D5.3, "5G-CLARITY Use Cases: Demonstrations and Evaluations," 2023.

[11] "5G-CLARITY Smarrt Tourism Demonstration," [Online]. Available: https://www.youtube.com/watch?v=KiMVuBYJ7PA .

[12] 5G-CLARITY D4.3, "Evaluation of E2E 5G Infrastructure and Service Slices, and of the Developed Self-Learning ML Algorithms," 2022.

[13] "5G-CLARITY Intent Based Slice Management Demonstration," [Online]. Available: https://www.youtube.com/watch?v=5Jsc2ds-etI .

[14] "5G CLARITY Intelligent Stratum Demo v02," [Online]. Available: https://www.youtube.com/watch?v=-FgdyJBPiJQ .

[15] 5G-ZORRO Project, [Online]. Available: https://www.5gzorro.eu/ .

[16] ETSI ZSM, "PoC 5 On-demand Non-Public Networks (NPNs) for industry 4.0: zero-touch provisioning practices in public-private network environments," [Online]. Available: https://zsmwiki.etsi.org/index.php?title=PoC_5_On-demand_Non-Public_Networks_(NPNs)_for_indu.

[17] 5G CLARITY 5GZorro ETSI ZSM PoC Demo, [Online]. Available: https://www.youtube.com/watch?v=heU_ceO315s .

[18] free5gc, [Online]. Available: https://free5gc.org/.

[19] open5gs, [Online]. Available: https://open5gs.org/.