Multi-RAT enhanced Private Wireless Networks with Intent-Based Network Management Automation

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***Abstract*—Private wireless networks have become essential enablers for network use cases in enterprises. The emerged enterprise applications push private networks to be more complex in terms of operation and management. However, current private network managers are contending with the challenge of finding a strategy for a network solution that adequately fulfils the service Key Performance Indicators (KPIs) for the growing innovative applications, which are increasingly uplink hungry. They also confront the need to optimise the management of networks without the cost implications associated with hiring onsite experts. In addressing these two key challenges, we demonstrate a multi-connectivity framework that utilises multi-radio access technologies, namely 5GNR, WiFi-6, and LiFi, to enhance private 5G network capacity with intent-based network automation in a museum. Our framework employs MP-TCP link aggregation strategy that combines multiple network connections to ensure a minimum throughput capacity to meet the maximum uplink requirement for a Smart Tourism pilot use case.**

We also implement an intent-based platform that uses a Natural Language Processing (NLP) interface as a management enabler to simplify the deployment of network services for the Smart Tourism use case. The integration of these two implementations within a private 5G network offers significant advantages for strategic research and innovation aimed at advancing future-generation wireless private networks.

***Index Terms*—Multi-RAT, multi-connectivity, intent-based networking, private 5G networks, MPTCP, smart tourism, uplink.**

INTRODUCTION

Private wireless networks, especially 5G networks, have emerged as promising solutions to build private enterprise networks by leveraging the advanced capabilities of 5G to enhance wireless connectivity. The interest in deploying private 5G networks has been sparked by the gradual deployment of public 5G networks and the maturation of new network features and functions within these networks.

The straightforward solution is to deploy the available pubic 5G networks to support enterprise applications. However, industries encounter various challenges while attempting to utilize public 5G networks. Some of the obstacles include coverage, security, and network control, which prohibit the adoption of public 5G networks.

Firstly, most industries suffer from inadequate network coverage provided by public network operators. This is because most industries are sited away from residential neighbourhoods, which are the primary targets for subscription by public operators [1]. It is unrealistic to expect the public network operator to provide customized service for small industries.

Secondly, security and privacy is another concern for private networks. As the awareness of safeguarding against privacy breaches and exploiting vulnerabilities in the complex public 5G networks grows, enterprises are increasingly challenged to prioritize security against potential malicious exploitation.

Furthermore, there is a growing necessity to exert greater network control due to increasing demands from industrial applications for stringent KPI requirements especially in the uplink, as public networks tend to prioritise downlink applications [15]. These requirements include throughput, latency, reliability, availability, and security [1], which public 5G networks are unable to adequately satisfy.

Given these situations, public 5G networks face various constraints, leading to the rise of private 5G networks, also known as Non-Public Networks (NPNs) by the 3rd Generation Partnership Project (3GPP). However, private 5G networks, despite being more suitable for enterprise use cases, still face certain challenges. For instance, emerging industry vertical applications demand higher performance standards [2], particularly in areas such as video streaming, IoT data upload, and other similar platforms that involve multicast and broadcast scenarios [14], which rely heavily on uplink capacity.

The British Broadcasting Corporation (BBC) has been driven to explore the implementation of standalone private 5G networks for live coverage during the last Commonwealth Games in Birmingham, recognizing that guaranteeing a robust uplink signal on public networks is not always possible [15]. However, In the context of private networks, a notable challenge arises when dealing with traffic patterns that involve substantial uplink traffic. In such scenarios, it becomes difficult for a single radio access technology to efficiently deliver high data rates and reliable connectivity [3], [4].

Also the effective management of private 5G networks by enterprise operators is problematic. Small industries often struggle with managing networks efficiently due to a lack of technical expertise and limited budget. [5]. To address these challenges, careful consideration of the various private 5G network deployment options is essential. Also, an innovative deployment approach becomes imperative to meet the expected service requirements.

A. Main contribution

In this paper, we detailed the implementation of the multi-connectivity testbed supporting two networking functions: i)

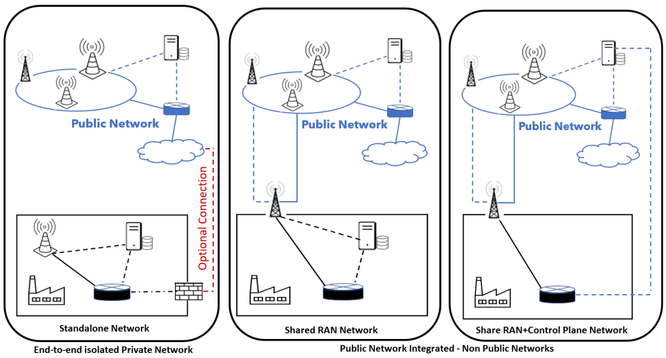

Fig. 1. The primary deployment models of Private 5G Network.

multi-radio access technologies namely 5G, WiFi-6 and LiFi with enhanced link capacity and improved connection reliability, and ii) intent-based network management automation, as a management enabler to simplify network operations.

With a standalone private 5G network, the Smart Tourism pilot is demonstrated using the multi-connectivity testbed deployed at the University of Bristol's Smart Internet Lab and the M-Shed Museum. The demonstration highlights key benefits, including enhanced throughput performance using link aggregation and a user-friendly intent engine strategy for deploying network services.

In the remaining sections of this paper, we provide a description of the main requirements driving private 5G networks, and a portrayal of the different deployment options. This is followed by an introduction of our Multi-RAT solution, comprising a multi-connectivity framework and intent-based network management automation. We then present the use case, measurements, and results from our experimental platform before concluding.

I. Overview of Private 5G Networks

Private 5G networks are a type of cellular network that are being deployed by organizations to provide dedicated, secure, and high-speed connectivity for their operations. It leverages the features of 5G networks and supports a wide range of use cases and network scenarios, including enhanced Mobile Broadband (eMBB), Massive Machine-Type Communications (mMTC), and Ultra-Reliable Low-Latency Communications (URLLC) [9].

A. Requirements

Private 5G networks require specific characteristics to fulfill their core requirements for diverse applications. These requirements include reliability, interconnection with public networks, high availability, network control, security, and customization [6], [7], [8].

These features ensure private 5G networks have the capabilities for adequate capacity, network coverage, and resilient service switching functionality. They also allow seamless integration with public networks, constant access to maximum network availability, decision-making control over configurations, network functions, and traffic flow policies. Furthermore, these features provide end-to-end security and privacy to protect infrastructure, data, and employees from threats, while also enabling the ability to configure and add features for enhanced functionality and performance.

B. Deployment options

The options to deploy private 5G networks are based broadly on two architecture types:

(i) Standalone Non Public Network (SNPN) which is an end-to-end isolated network from the public land mobile network (PLMN); and

(ii) Public Network Integrated-Non Public Network (PNI-NPN), which is deployed based on Service Level Agreement (SLA) reached between the public PLMN and the enterprise operator [9]. Figure 1 illustrates the basic deployment models for private 5G networks.

There can be further subdivisions of the PNI-NPN which is not within the scope of this paper. Our experimentation is based on a standalone NPN.

C. Main challenges

High data rate and link reliability are performance requirements, especially in the uplink, that pose obstacles to private 5G networks.

As observed by the authors in [2], [8], and [10], the implementation of an integrated multi-RAT method, application of intent-based/artificial intelligence approaches, utilization of network slicing and deployment of 5G-capable devices are potential solutions to overcome the challenges faced by enterprise network operators.

Specifically, [8] calls for affordable improvement to private 5G network performance through the integration of WiFi and 5G technologies, as specified by 3GPP in Release 15 and 16 with the introduction of the Non-3GPP Interworking Function (N3IWF). They also point in the direction of "Zero-touch practice" for private 5G network management.

II. Our deployment solution

Our solution to these challenges addresses the above-mentioned problems in two fronts - the utilization of a multi-connectivity framework and intent engine deployment.

First, we designed and built a Customer Premises Equipment (CPE), a 5G-enabled device that uses Multi-Path Transmission Control Protocol (MPTCP) to aggregate link capacities of 5GNR, WiFi-6 and LiFi. It provides enhanced bandwidth and link reliability throughout a given coverage area.

We also implement an intent-based service deployment, as a network management enabler. This platform allows non-technical personnel to manage request of intents and deployment of related network services.

A. Multi-connectivity framework

The framework incorporates 5GNR, WiFi-6, and LiFi, within a standalone private network deployment scenario. The objective is to aggregate these multiple network links to provide high data rate with link reliability. The aggregated link will offer sufficient throughput performance to support the required uplink capacity for a Smart Tourism use case.

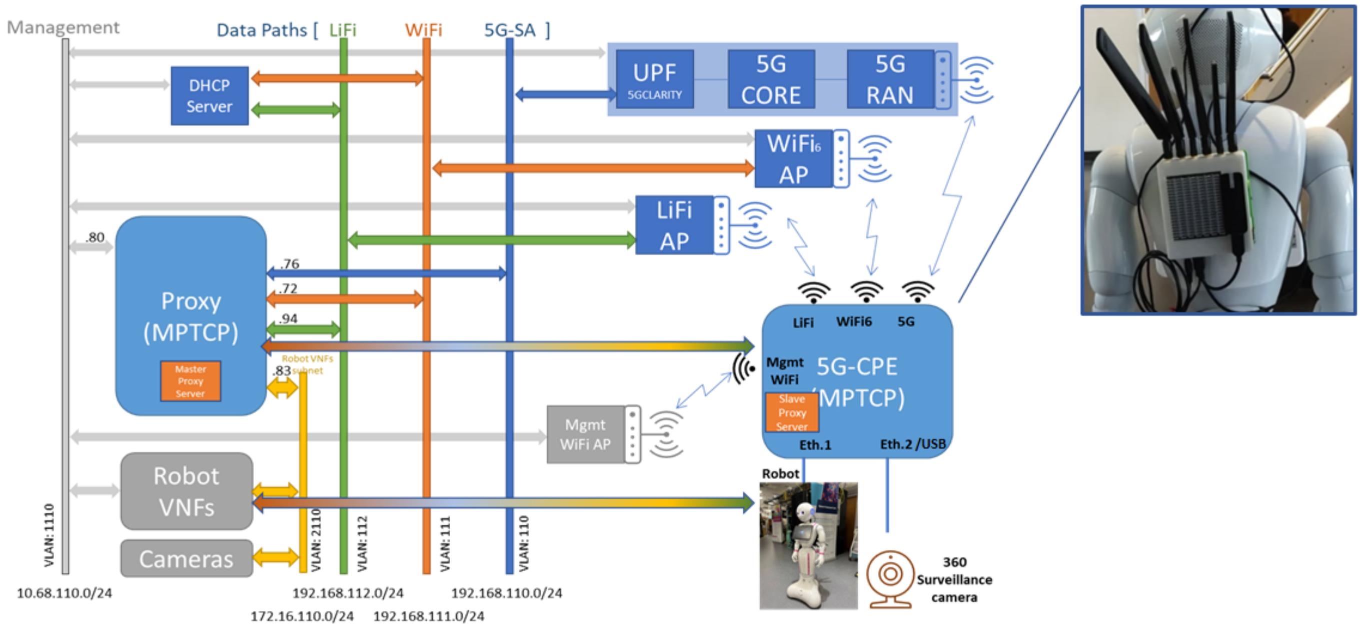

Fig. 2. MPTCP supported multi-connectivity testbed.

1) Multi-connectivity testbed setup: Figure 2 presents the multi-connectivity testbed setup, which comprise of a multi-WAT CPE, a 5G modem, a WiFi-6 module, and a LiFi dongle. All these components are integrated into a single computer board that operates on an MPTCP-enabled Linux kernel [11].

To enable multi-connectivity, each wireless access technology is linked through an individual VLAN and IP subnet configuration. And to establish this connectivity, the MPTCP-enabled CPE is connected to an MPTCP proxy, which is installed in a Virtual Machine (VM) hosted on an edge server, as shown in the figure. The VM, responsible for serving as the MPTCP proxy, possesses an interface that connects to the VLANs and subnetworks associated with 5GNR, WiFi-6, and LiFi. A robot's VNFs establish an indirect connection to the CPE through the MPTCP proxy.

Each of the three access technologies, the CPE, MPTCP proxy and robot VNFs are all connected directly to a management plane responsible for control and management of the framework.

2) Multi-WAT CPE: The CPE was built at the University of Bristol Smart Internet Lab. It serves as the central hub of the multi-connectivity framework. The device consists of hardware and software components, designed with capability to measure signals of 5G, WiFi-6 and LiFi, and connect to the best available signal, switch between them and perform throughput link aggregation.

The use of MPTCP improves the system's reliability by enabling traffic to be routed across three chosen radio access networks (RANs) through multiple paths.

The CPE, installed on a mobile robot, dynamically switches between 5G, WiFi-6, and/or LiFi wireless access networks as the robot moves. The key functions of the CPE include providing multi-access connectivity using 5GNR, WiFi, and LiFi between the guide robot and the Edge Server, performing multi-connectivity throughput aggregation using MPTCP, conducting handover between different access technologies, and monitoring and measuring key radio parameters and network KPIs.

B. *Key infrastructure components*

The main components deployed in the Smart Tourism pilot demonstration are captured in figure 3. The equipment include 5G radio, WiFi-6 and LiFi Access Points (APs). The configurations of these equipment are available in [12]. Other components include a humanoid Pepper robot, on whose body the CPE, the 360-degree camera and a LiFi dongle are attached. The mobility of the robot enables testing of network KPIs at different locations within the coverage area. The CPE performs the measurements, while the 360-degree camera captures surveillance videos for remote monitoring.

The components are integrated in the infrastructure deployed in figure 5. It shows the link between the M-shed museum and Smart Internet Lab sites, each hosting the RAN and Edge clusters respectively. Within the RAN cluster, the multi-RAT access nodes, gNB-CU, DU, and Radio Intelligent Controller (RIC) are situated. While the Edge cluster houses several compute resources, Virtual Network Functions (VNFs) and the 5G core.

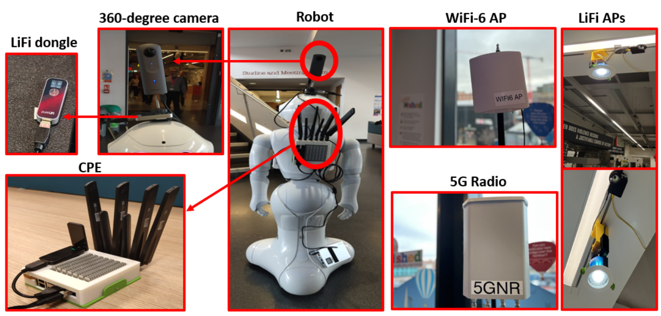

Fig. 3. Key elements of the smart tourism experimentation infrastructure.

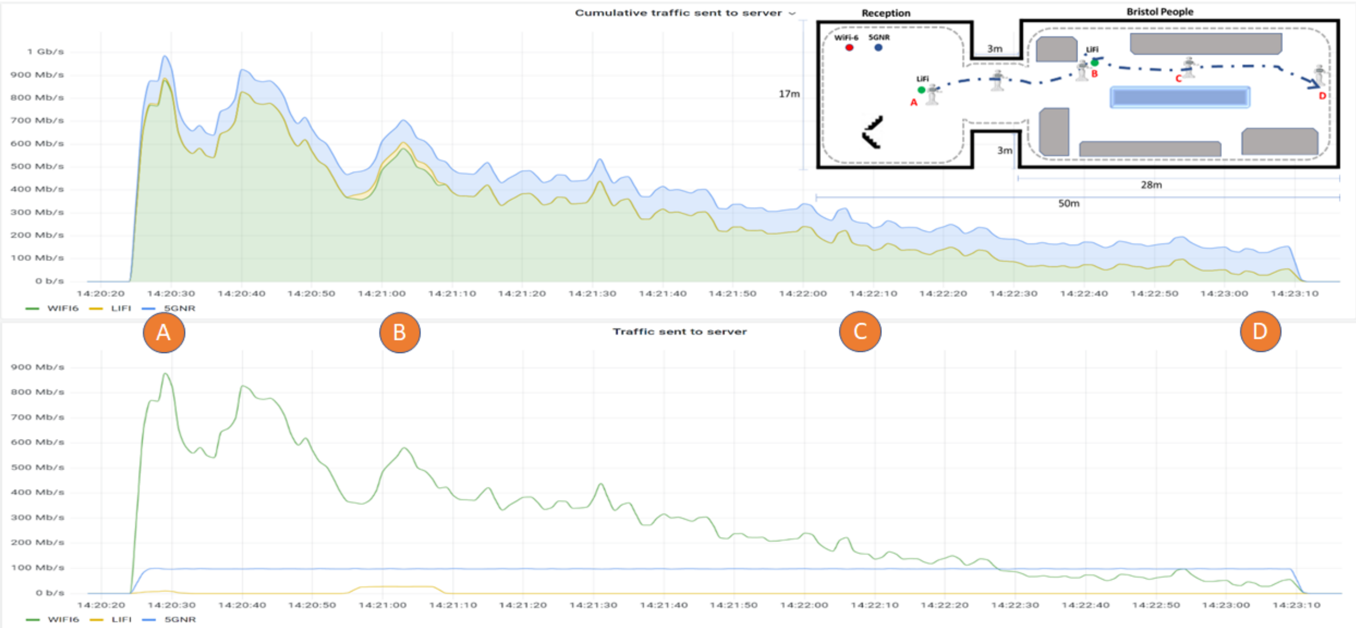

Fig. 4. Multi-RAT Uplink traffic for the cumulative and individual access networks.

C. Testbed integration and deployment

The full deployment stack of our Smart Tourism experimentation platform consist of the 5G-enabled CPE integrated with MPTCP. Nokia's AWHQM radio unit was employed to implement 5G, utilizing a Band 77 configuration equipped with 4 x 2 antennas. For this setup, a subcarrier spacing of 30 KHz was chosen, and the frame structure type was configured as semi-static. Additionally, the guard period length was set to 2 symbols. The TDD configuration followed the 7DS2U pattern, commonly known as the 7/4 Nokia configuration.

The WiFi-6 specification consist of Ruckus R850 model, which operates on the 5.180 GHz frequency. The signal strength for this AP is -40 dBm, and the RX and TX bitrates are both set to 1200.9 MBit/s with an 80MHz HE-MCS 11 HE-NSS 2 HE-GI 0 HE-DCM 0 configuration.

The LiFi network, takes the form of a pureLiFi-X device, and a LiFi Client, which is a pureLiFi USB dongle. The integration and deployment of the various technologies create a multi-connectivity experimentation platform for our Smart Tourism pilot.

III. Use case description

This section describes the Smart Tourism pilot use case that utilizes our multi-connectivity framework and the scenario that enables its deployment. The use case has been demonstrated at the Bristol M-shed museum in the UK.

The Smart Tourism pilot comprises two distinct objectives: the implementation of guide robot services in a human-robot interaction scenario, and the remote deployment of surveillance video for public safety monitoring.

The concept introduces a guide robot service that assists visitors to various exhibitions within the museum. This human-robot interaction holds the potential of improving visitor's museum experience and to attract an increased number of tourists to the museum.

Additionally, the prospect of increased museum visitor numbers raises concern for adequate public safety monitoring. To address this, we integrate a 360-degree camera on the robot to enhance surveillance within the museum environment.

Using the intent engine, a museum safety officer can remotely access on-demand, surveillance video captured by a 360-degree camera mounted on the robot. Remote access to this footage enhances monitoring and enables prompt intervention when necessary. This ensures a proactive approach to public safety management.

However implementing these advanced functionalities poses some challenges. First, is the demand for high UL bandwidth due to resource intensive applications. Since a single access network has limitations in meeting the required UL capacity while maintaining network reliability [12], we deployed the CPE. It aggregates the multiple links using MPTCP to achieve the required throughput and network reliability.

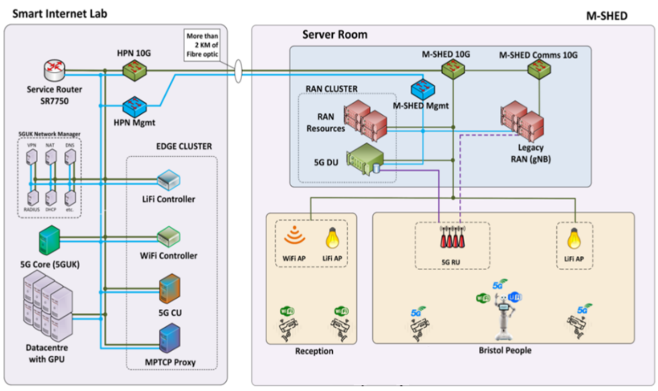

Fig. 5. Connections between the various network infrastructure.

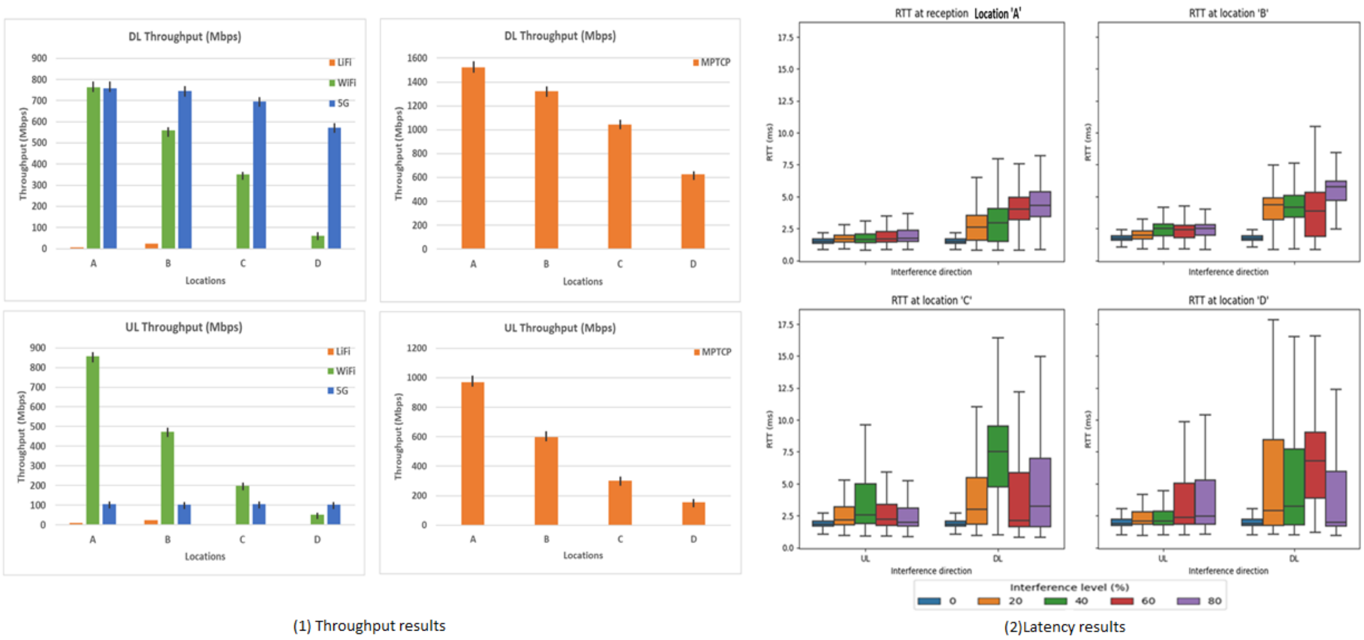

Fig. 6. Throughput and Latency network KPIs measurement results.

IV. Experimental Demonstration

In this section, we describe the experimental demonstration and the methods used to validate the network KPIs.

A. Methodology

To determine what wireless capacity would guarantee consistent and reliable coverage for the Smart Tourism pilot, we performed multiple throughput and latency measurements.

Each round of measurements involved moving the robot from a starting location in the museum called location A to the end of the coverage area called location D. This measures a total distance of 50 metres. The photo inserted in figure 4 illustrates this scenario.

B. Intent-Based Networking

Through the intent-based networking, the 360-degree footage is streamed to a monitoring device. To achieve this, a streaming server is required to connect the monitoring device. As the safety officer may not possess technical expertise in managing and orchestrating virtualised network functions and services, the intent engine simplifies this network management process by using natural language processing. The safety officer sends an intent request via a web interface specifying the display of video feeds from the 360-degree camera. As a consequence, the service for the intent request is instantiated by description. To deploy this service, a virtual media forwarding unit is set up at the edge of the network.

C. Network KPI Measurements

To measure the throughput and latency using the CPE, we collect measurements at various distances from the access points while the robot travels with the CPE. The reference positions for these measurements are marked in metres (m) as follows: A (0-5m), B (13-15m), C (35-36m), and D (45-50m).

LiFi APs are only at locations A and B. Between both LiFi APs, a signal level discrepancy exists due to the varying heights at which they are installed. Location A has an elevated AP at 4.2 metres, while location B has a lower AP at 2.9 metres, reflecting the different ceiling heights in the building.

The experiment is aimed at benchmarking the UL capacity and investigate the effectiveness of the multi-connectivity framework in meeting the total (126 Mbps) UL requirement across the coverage area. By saturating the channel, we test the framework's ability to maintain consistent and reliable UL throughput under heavy network traffic conditions. The MPTCP scheduler is set to RoundRobin mode.

V. Results and Analysis

In this section, we discuss the various results from our demonstration, which validates the experiments on intent engine deployment and successfully fulfilled the KPIs for visitor assistance service.

1) Intent Engine Implementation: To implement the service, the museum's safety officer uses natural language to submit an intent request. This request triggers the intent engine to instantiate the service, providing a description and requesting the network service (NS) catalogue from the orchestrator (OpenSource MANO). The intent engine then compares the intent description with the catalogue details and returns the identification of the appropriate NS.

The process can be summarized as follows:

(i) The safety officer's monitoring device initiates an intent request using natural language.

(ii) The intent engine generates call logs and creates a network service instance.

(iii) The orchestrator's (OpenSource MANO) GUI dashboard displays an orange tick to confirm the initialization of the NS instance.

(iv) The OpenStack GUI dashboard indicates the successful instantiation of the Virtual Network Functions (VNFs).

(v) The OSM dashboard validates and verifies the NS instance, changing the ticks to green to indicate its operational status.

(vi) Finally, the requested 360-degree video service is deployed on the safety officer's device.

The visual implementation of the Smart Tourism pilot, including the intent engine deployment is available on YouTube in [13].

A. Throughput Measurements

Figure 4 presents the cumulative and individual throughput of 5G, WiFi-6 and LiFi networks, and the four reference points for measurements.

The upper graph represents the cumulative performance. LiFi and 5G graphs adds on top of WiFi-6 to yield a cumulative performance of about 1 Gbps at location A and 150 Mbps at location D. The yellow contours indicate the contribution of LiFi at locations A and B.

In the lower graph, the individual contributions of 5G, WiFi-6, and LiFi are displayed, showing their respective signal levels across the museum's coverage area. The WiFi-6 signal exhibits fluctuations and its quality diminishes with increasing distance from the AP. Starting at around 890 Mbps, the signal deteriorates and reaches approximately 50 Mbps at location D. For the LiFi, the difference in signal levels between the two APs can be observed, which is due to the disparity in their respective AP height.

The performance of 5GNR remains consistent across the coverage area, maintaining an average throughput of around 100 Mbps. Overall, from locations A to D, we successfully achieved UL throughput above the maximum requirement of 126 Mbps.

Figure 6 (1) Throughput results: The graphs explain the impact of MPTCP on throughput aggregation by showcasing the average throughput performance at locations A, B, C, and D for both UL and DL. A comparison is made between scenarios without MPTCP and those with MPTCP implemented, highlighting the differences in performance. For instance in the UL traffic at location D for both scenarios, the case of MPTCP implementation surpasses the required 126 Mbps. Without MPTCP this would be a struggle. The results from this experiment, highlight the aggregated throughput benefits that multi-RAT implementation can bring to emerging private wireless networks.

B. Latency Measurements

Figure 6 (2) presents the latency results. At all four locations, the UL traffic encountered lower latency interference compared to the DL traffic. As anticipated, the latency generally rises with increasing distance for both traffic types.

The results confirms that the round-trip time (RTT) stayed below 18 ms for both the UL and DL. This latency level is deemed sufficient for remote control and offloading operations, demonstrating that the network can effectively support these remote video monitoring activities with further prospects for other live streaming broadcast activities without significant delays or interference.

VI. CONCLUSION

Our multi-connectivity framework demonstrates how Multi-RAT can enhance uplink capacity of private 5G network, while ensuring consistent and reliable connectivity.

The use of Intent Engine not only simplifies the management of private 5G networks but helps to reduce the operational cost for enterprises operators. This demonstrates the significance of network management automation in facilitating future network service deployments and cost saving for enterprises.

The implementation of both solutions in private wireless networks addresses current challenges of the network and offers a promising experimentation platform for future beyond-5G networks.

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