Demo: 5G NR, Wi-Fi and LiFi multi-connectivity for Industry 4.0

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***Abstract*—The 5G-CLARITY project proposes a novel architecture for private 5G networks that converges Wi-Fi 6, 5G NR and LiFi under a common service platform for Industry 4.0. In this demonstration, we deploy the 5G-CLARITY system in a real factory setup and showcase its multi-connectivity framework, which allows to customize aggregation behavior for different devices. We demonstrate two different aggregation modes. First, a capacity aggregation mode that delivers between 200 Mbps and 600 Mbps to mobile devices throughout the factory floor. Second, a latency-sensitive aggregation mode that is used to replace Ethernet connectivity for a production line achieving end-to-end delays below 10 ms.**

***Index Terms*—5G NR, Wi-Fi, LiFi, ATSSS, Industry 4.0**

I. INTRODUCTION

Industry 4.0 is one of the sectors aiming to adopt private 5G technologies [1]. In these environments Ethernet and Wi-Fi are well established communication technologies. Ethernet is used to connect Programmable Logic Controllers (PLCs) in production lines to Manufacturing Execution Servers (MES), which control each step of the manufacturing process. However, maintaining complex deployments of Ethernet cables in factory environments is costly. Wi-Fi is used to provide communication services to mobile workers and Automated Guided Vehicles (AGVs), and also requires complex multi-AP deployments to cover typical factory setups. The promise of private 5G is to disrupt these environments by reducing the need of Ethernet cabling and multi-AP deployments.

In [2] we propose 5G-CLARITY, a novel architecture for private 5G networks that integrates Wi-Fi 6, 5G NR and LiFi under a common system platform. 5G-CLARITY defines a multi-connectivity framework, based on the Access Traffic Steering, Switching and Splitting (ATSSS) framework specified by 3GPP [4]. In this paper, we describe a demonstration of the 5G-CLARITY multi-connectivity framework that uses MultiPath TCP (MPTCP) as the ATSSS user plane function. Our demonstration highlights two aggregation modes, namely a capacity aggregation mode and a latency-aware mode, which are showcased simultaneously in a real production environment provided by BOSCH in Aranjuez (Madrid).

A large body of work exists in the literature on the use of MPTCP to aggregate different type of access technologies, e.g. Wi-Fi and cellular [3]. However, to the best of our knowledge, this is the first work that illustrates the benefits of aggregating 5G NR, Wi-Fi 6 and LiFi for Industry 4.0 services in a real factory environment.

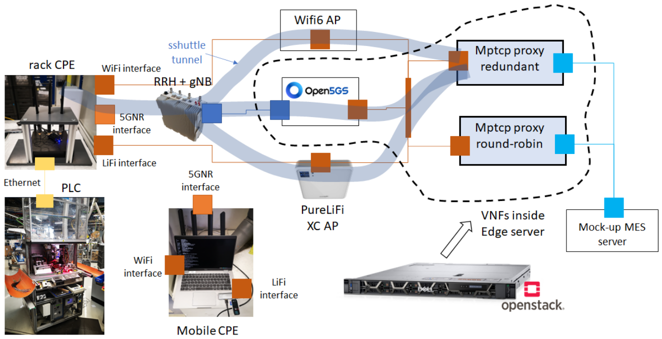

Fig. 1. Demonstration architecture

II. SYSTEM ARCHITECTURE

Figure 1 depicts the logical architecture of our demonstrator, and Figure 4 our physical deployment in the factory floor. The physical infrastructure consists of one LiFi AP operating with a 16.6 MHz carrier, one Wi-Fi 6 AP operating with 80 MHz at 5.7 GHz, and a 5G NR cell operating with 40 MHz at 3.9 GHz. The radio access nodes are connected to an Ethernet switch deployed in a portable rack, including one server to host the gNB protocol stack and one server with an Openstack Victoria installation to support the deployment of Virtualized Network Functions (VNFs).

Figure 1 also depicts the VNFs used in our demonstrator, which include an open5gs[1] based 5G core, and two MPTCP proxy functions, one configured with a *round-robin* scheduler to provide the capacity aggregation service, and one configured with a *redundant* scheduler to provide the latency-aware service. The round-robin scheduler transmits each TCP segment through a different access technology, whereas the redundant scheduler duplicates each TCP segment through all access technologies, delivering to the receive socket only the segment that arrives first.

Finally, Figure 1 depicts the two Customer Premises Equipment (CPE) devices used in our demonstrator, which feature a customized MPTCP kernel[2]. We refer to the first device as the *rack CPE*, used to connect an unmodified PLC to a mock-up MES server that replaces the real production MES

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[1] open5gs, available at: https://open5gs.org/

[2] https://www.multipath-tcp.org/

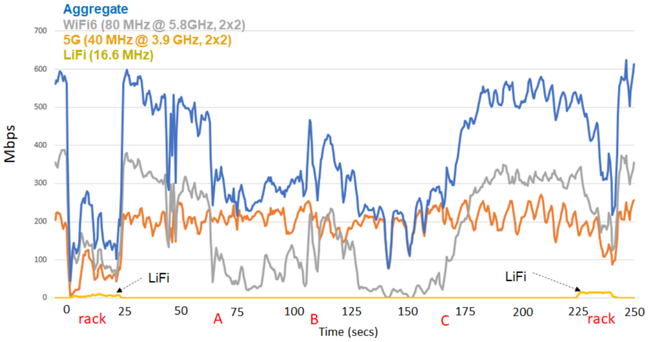

Fig. 2. Performance of the capacity aggregation service

server used in the factory. Note that the PLC is not MPTCP capable, hence an SSH tunnel based on *sshuttle*[3] is used in the rack CPE to proxy the TCP frames generated by the PLC through an MPTCP tunnel towards the redundant MPTCP proxy. We refer to the second device as the *mobile CPE*, which is also MPTCP capable and allows us to move throughout the factory to measure the throughput delivered by the capacity aggregation service.

III. DEMONSTRATION

To evaluate the performance of our demonstration we are interested in measuring the aggregated downlink capacity throughout the factory delivered by the capacity aggregation service to the mobile CPE, and the latency delivered by the latency aware service to the PLC. Figure 2 depicts the available capacity received through each access technology by the mobile CPE when moving across the factory. The letters in the x-axis of Figure 2 correspond to the points marked in the factory layout included in Figure 5, where we can see how we circle around the factory starting and finishing near the portable rack. The first aspect to highlight in Figure 2 is that the single 40 MHz 5G NR cell included in our setup delivers a uniform coverage of around 200 Mbps throughout the whole factory floor. Instead, the Wi-Fi 6 AP delivers a much more choppy coverage, with peaks of up to 400 Mbps when moving slightly away from the rack[4], but dropping very sharply at point A due to metallic structures blocking the AP line of sight, and recovering performance again at point C when walking back towards the rack. This result illustrates how Wi-Fi 6 and 5G NR are complementary in factory environments, where Wi-Fi may enjoy higher peak data rates due to its greater carrier bandwidths[5] but suffers from worse coverage. Indeed, our capacity aggregation service delivers the sum of the Wi-Fi 6 and 5G NR capacities, delivering peaks of up to 600 Mbps when being close to the Wi-Fi 6 AP and a baseline performance of around 200 Mbps throughout the factory. Looking at LiFi, we can see that in terms of capacity its performance is severely limited due to its reduced carrier bandwidth, the lack of MIMO and the high ceilings available in the factory, delivering only around 10 Mbps in an area of 5 meters from the LiFi AP.

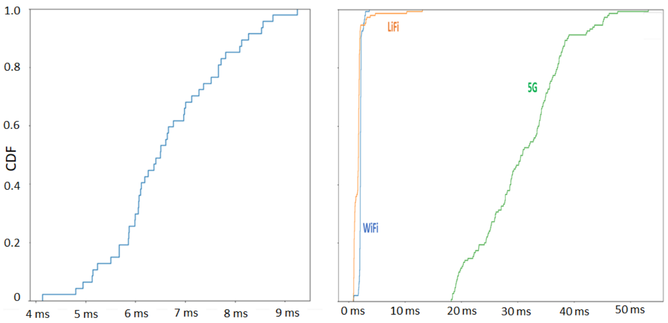

Fig. 3. Performance of the latency aware service

Figure 3 depicts the CDF of the uplink delay between the PLC and the MES server when going through the MPTCP tunnel in redundant mode (c.f. Figure 1). The left subplot depicts the resulting CDF after aggregating the three access networks showcasing a worst case latency below 10 ms, which sets a limit on the cycle time of the manufacturing processes that could be wirelessly connected through our architecture. The right subplot depicts the individual per technology latency CDFs, showcasing how in this case, due to not being based on Time Division Multiple Access (TDMA), LiFi and Wi-Fi 6 provide a significantly lower latency than 5G NR. The reason for the higher latency of 5G NR is that the used Time Division Duplex (TDD) pattern is not optimized for uplink latency, and the virtualized core adds an additional latency penalty not present in the other technologies. Thus, we can see that while LiFi lacks in throughput performance, it delivers good latency results. Considering that its limited coverage makes it robust to interference, we posit that LiFi can enhance application latency and reliability in deployments where line of sight can be guaranteed.

ACKNOWLEDGMENT

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[2] Cogalan, Tezcan, et al. "5G-CLARITY: 5G-advanced private networks integrating 5G NR, Wi-Fi, and LiFi." IEEE Communications Magazine 60.2 (2022): 73-79.
[3] Deng, S., Netravali, R., Sivaraman, A., and Balakrishnan, H. (2014, November). Wi-Fi, LTE, or both? Measuring multi-homed wireless internet performance. In Proceedings of the 2014 Conference on Internet Measurement Conference (pp. 181-194).
[4] Study on Access Traffic Steering Switch and Splitting Support in the 5G System Architecture(R16), vol. TR 23.793.

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[3] https://github.com/sshuttle/sshuttle

[4] Performance right below the rack when there is LiFi coverage is limited due to the radiation pattern of the 5G NR and Wi-Fi antennas.

[5] Note that 100 MHz carriers in private 5G are possible in some countries, but Wi-Fi 6 bandwidth can go up to 160 MHz.

DEMO PROPOSAL

The demonstration will be showcased by means of a video recorded using the factory setup described in this section.

A. *Testbed Configuration*

Figure 4 depicts our demonstration setup in the BOSCH factory. We can observe a portable rack hosting the servers for the gNB, the Openstack enabled edge and the mock-up MES server used to connect the PLC[6]. In the upper part of the figure we observe the three wireless access nodes: i) the 5G NR 3.9 GHz radio head, ii) the LiFi AP, and iii) the Wi-Fi 6 AP. The gNB software stack is provided by Amarisoft, the radio head by AW2S, the LiFi AP is provided by PureLiFi, and the Wi-Fi 6 AP is custom made based on the QCA6391 module and a Gateworks Venice GW7300 board. Table I describes the detailed configuration of each radio technology. Note that the LiFi AP is pointing towards the rack, so that the rack CPE used for the latency aware evaluation has continuous LiFi coverage. The mobile CPE though, only has LiFi coverage when staying close to the rack location. We can see from the figure the abundance of metallic structures in the factory that hinders the performance of the Wi-Fi 6 and 5G NR radios.

	5G NR	Wi-Fi	LiFi
Band	3.9 GHz	5.745 GHz	DL:450nm, UL:850nm
Bandwidth	40 MHz	80 MHz	16,6 MHz
MIMO	2x2	2x2	SISO
Subcarrier spac.	30 KHz	312.5 KHz	319 KHz
TDD pattern	5ms, 6DL/2UL	N/A	N/A

TABLE I
WIRELESS CONFIGURATION

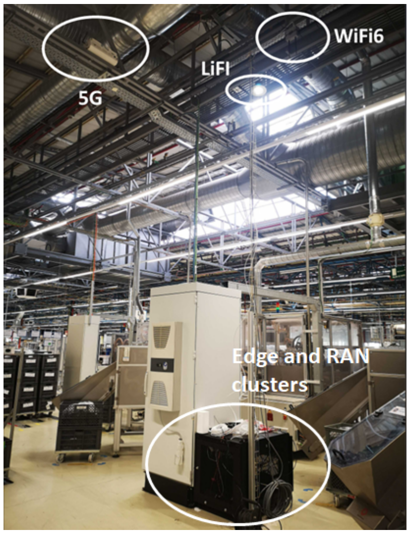

Fig. 4. Physical testbed setup.

Figure 5 depicts the factory layout, which is the physical space used for the capacity aggregation measurements shown in Figure 2. Red stars indicate the location of the portable rack and the factory locations discussed in Figure 2.

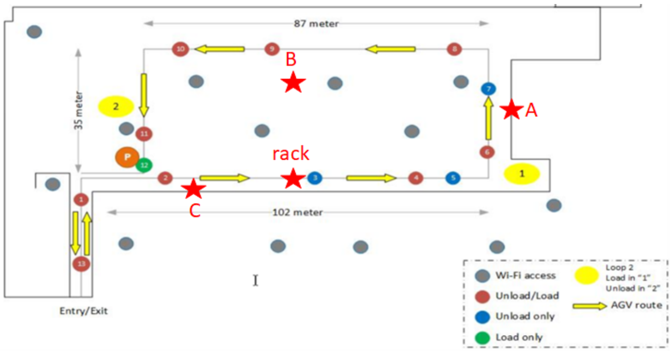

Fig. 5. Factory layout and measurement points highlighted in Figure 2

The two CPEs used in our demonstration are custom made featuring MPTCP kernel 5.5. For the rack CPE, we use a Gateworks Venice GW7300 board, with an Intel AX200 Wi-Fi 6 module, a USB powered Quectel RM500QGL 5G NR modem, and a USB LiFi dongle provided by PureLiFi. For the mobile CPE, we use a Dell Latitude 5420 laptop with the same wireless adapters as the rack CPE.

B. *Experimental steps*

To execute the capacity aggregation experiment we walk the factory along the direction indicated by the arrows in Figure 5. While walking we launch a downlink *iperf3* with 15 TCP threads originated in the MPTCP round-robin proxy depicted in Figure 1, which is instantiated as a virtual machine in the edge server of the portable rack. To generate the results depicted in Figure 2, we measure the aggregate and per-technology *iperf3* throughput in the mobile CPE. We carry out 20 different walks around the factory that deliver similar results, of which Figure 2 represents one sample.

For the latency-aware experiment, we generate uplink packets from the PLC towards the mock-up MES server, via the rack CPE. These packets consist of an XML-based description of each manufactured part. The rack CPE receives the incoming packets from the PLC and proxies them through a long-lived MPTCP connection maintained against the redundant MPTCP proxy (c.f. Figure 1). To compute the CDF of the uplink application packets depicted in the left part of Figure 3 we insert two probes, one at the entrance and one at the exit of the network, which duplicate packets towards a measurement server that computes the transit time by comparing the timestamp of each packet at the entrance and exit of the network. To compute the per technology CDF illustrated in the right part of Figure 3 we synchronize the rack CPE and the redundant MPTCP proxy and compare the timings of each packet at each end of the MPTCP connection using *wireshark*.

C. *Public materials*

The 5G-CLARITY multi-connectivity framework is available on Github[7].

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[6] The PLC is not shown in the figure as it was deployed in another part of the factory.

[7] https://github.com/jorgenavarroortiz/multitechnology_testbed_v0