D6.5 FRACTAL communication subsystem validation

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Abstract:
Deliverable "6.5 FRACTAL communication subsystem validation" details the specification, integration, testing and validation of stand alone wireless communications sub system for FRACTAL nodes carried within Task 6.4.

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Contents

1 History

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1.1	30/3/2023	Sections 2.1, 2.1.1, 2.1.2 and 2.1.3 added	Konstantin Mikhaylov (UOULU)

2 Summary

The deliverable D6.5 reports the validation tests definition for the communication sub-system as well as the obtained results and is directly linked to Task 6.4 (T6.4): Integration, Testing and Validation of Stand Alone Communications Sub-System. To ensure repeatability of the results and support wide re-use of the enabled wireless connectivity technologies, the details about the hardware (HW) used and the detailed instructions for their configurations are also included in the deliverable.

The core of D6.5 is composed of the following main sections:

- Section 4 introduces and discusses the communication architectures selected for implementation.
- Section 5 details the HW platforms and components used, and the configurations required to make them work, including step-by-step instructions for enabling wireless connectivity.
- Section 6 describes the experimental methodology, measurement tools and other tools used in the experiments, and their configurations.
- Section 7 details the experimental environment and the procedures for validating the connectivity and executing the performance measurements.
- Section 8 reports and discusses the measurement results.
- Section 9 summarizes the conclusions.

The key contributions of D6.5 in the context of FRACTAL are:

i. Detailed instructions (the "working receipts[1]") for enabling and establishing radio based wireless connectivity for FRACTAL nodes for three potential communication topologies, which can be further utilized by use cases and services either in the context of FRACTAL project, or during the future exploitation of FRACTAL project's results.
ii. The designed test cases and measurement campaign for characterizing the key performance indicators for wireless connectivity, which can be further re-used by use-cases in the context of FRACTAL project, or by other studies serving as a reference.
iii. The obtained numeric results demonstrating the performance of specific technologies and architectures, and enabling their comparison. Importantly, these results shed light onto potential real-life application-level performance of the different approaches thus facilitating selection of the technology and architecture to be used for a specific application, scenario or use case. Also, they can serve as a reference for further improvements.

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[1] Note that at the time of writing no public instruction for connecting a 5G radio to an IoT platform is available.

2.1 Achievements

2.1.1 Highlights

The key achievement of T6.4, further detailed and elaborated on by D6.5, is the successful implementation of integration, testing and validation of a stand-alone communications sub-system. The deliverable provides step-by-step field-test-validated instructions on how a Fifth-Generation Technology Standard for Cellular Networks (5G) cellular wireless and IEEE 802.11 modems can be integrated and used with a FRACTAL node. Notably, the results of the measurements demonstrate what performance for communication throughput, latency and energy consumption can be achieved, thus establishing a reference for further studies and developments. Moreover, we present results not for just a single network topology as initially planned but for three different network topologies based on cellular (i.e., 5G) and IEEE 802.11 wireless standard and their combination.

2.1.2 Lowlights

On the low end, we must admit and emphasize that since the practical measurements have been carried out in a particular mobile network having specific configuration – the 5G Test Network (5GTN) of the University of Oulu. Therefore, the observed performance in the networks of other mobile network operators featuring different configurations and resource availability may differ from the ones reported. Therefore, the obtained results should be considered indicative rather than conclusive; and the focus should be paid more to the trends than the specific values. Achieving higher performance is also possible since our tests and measurements were carried out in a non-standalone (NSA) 5G mobile network.

2.1.3 Results or Novelties

First, to the best of our knowledge, this document is the first one which reports and offers a step-by-step instruction of how a 5G modem can be integrated with an Internet-of-Things (IoT) node. Second, our results illustratively highlight the pros and cons of either topology and technology and their effect on communication performance between same-tier and lower-upper-tier FRACTAL nodes, thus facilitating the selection of the proper topology and technology for specific use cases and applications. Notably, we show that neither of the topologies is universal – “a jack of all trades.” This calls for a careful analysis to select the most suitable communication architecture for specific target requirements, and the results presented in the current deliverable for communication performance and energy consumption support such analysis. Finally, to the best of our knowledge, the energy consumption profiles of the IoT-grade 5G cellular modems throughout different phases of their operation presented in the deliverable are the first ones openly reported in the literature.

3 Introduction: background, objectives and approach

Background

The connectivity is a key enabler and a pre-requisite for the whole IoT paradigm [1] and is thus in the very basis of the FRACTAL concept. The diversity of the IoT application and services caused emergence of myriads of various IoT-grade communication technology featuring different characteristics and addressing the needs of various IoT applications [2]. Not surprisingly, given the cost- and resource-limited nature of IoT applications, and the imposed mobility and easy deployment requirements, the connectivity over wireless technologies, and specifically based on the radio frequency (RF) communication, became especially popular. Table 1 illustrates the characteristics and features of selected state-of-the-art and prospective radio access technologies (RATs) for IoT. Note, that as of today the IoT RAT landscape composes more than one hundred RATs, which differ for the used frequency bands, medium access and radio resources management approaches, implied traffic patterns and operation environment(s), resource availability, etc.

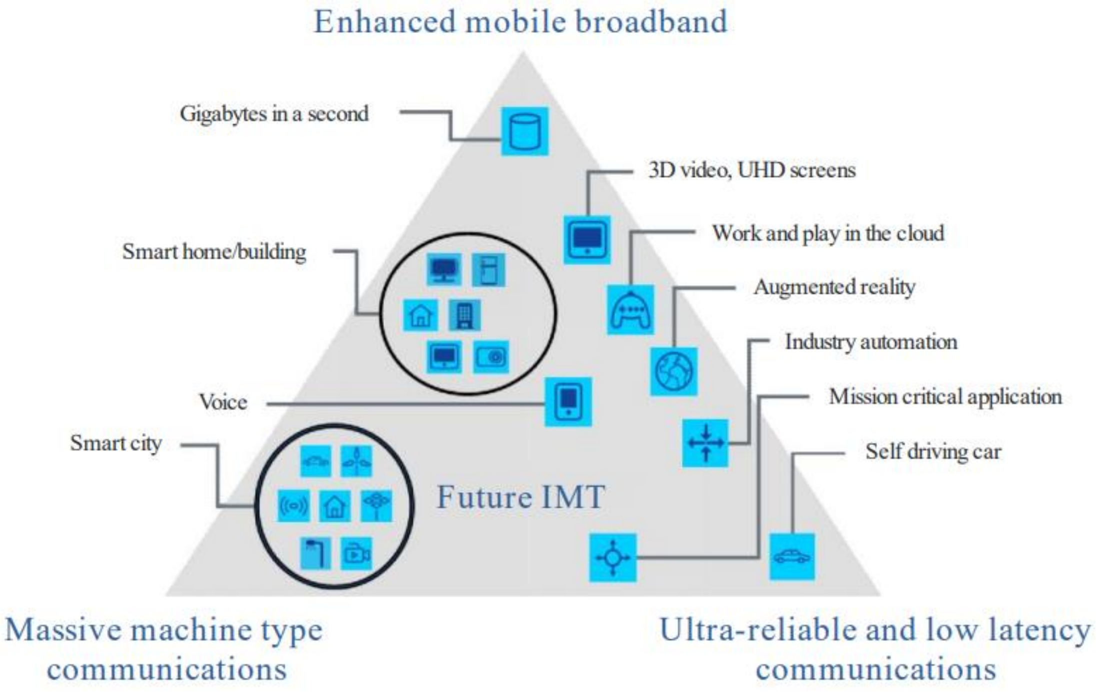

Figure 1 – The "5G triangle": EMBB, mMTC and URLLC and their applications, adopted from [3].

One of notable paradigm shift of the recent years in wireless connectivity was the introduction of the dedicated machine type communication (MTC) technologies by the 3rd Generation Partnership Project (3GPP) into the International Mobile Telecommunications (IMT) standards[2]. This was done by adding the two new categories of RATs dedicated for IoT use cases (i.e., the Massive MTC (mMTC) and Ultra-Reliable and Low Latency Communications (URLLC)) to the Enhanced Mobile

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[2] According to International Telecommunication Union (ITU) the "IMT" or "International Mobile Telecommunications" is the umbrella term for mobile systems and services."

Broadband (EMBB) technology addressing the needs of conventional human-centric terminals and the systems with similar requirements. The mMTC focuses predominantly on interconnecting resource- and performance-limited IoT terminals, with limited communication requirements. On contrary, the URLLC focuses on the most high-end machines and their applications imposing stringent throughput and latency/reliability requirements. This has brought to life the well-known "5G triangle," depicted in Figure 1, which demonstrates the three extreme cases of 5G MTC: the mMTC, URLLC and EMBB, and maps some illustrative application classes to these RATs. To address these needs, a number of new RATs and enhancements have been introduced as a part of evolution from Fourth-Generation Technology Standard for Cellular Networks (4G) to 5G and beyond. The most notable of them are the Narrow Band IoT (NB-IoT) and Long Term Evolution (LTE) MTC (LTE-M) for mMTC, the Cellular Vehicle-to-Any (C-V2X) as a part of URLLC solution for Intelligent Transportation Systems (ITS), and the 5G New Radio (5G-NR) creating the basis for the further evolution of EMBB and wide enablement of URLLC. Notably, the 5G-NR introduces a novel and much more flexible radio resource grid, covering also much higher frequency bands than those possible for 4G, thus creating the basis for further IMT evolution and enabling effective addressing of the needs of novel applications and use cases. This is also worth noting, that beyond the major development at the Radio Access Network (RAN) side, the 5G has reworked the system architecture based on functional architecture paradigm. Specifically, the network functionalities which have been previously implemented by dedicated HW units have been transformed into the network functions, which now "can be implemented either as a network element on a dedicated HW, as a software (SW) instance running on a dedicated HW, or as a virtualised function instantiated on an appropriate platform, e.g. on a cloud infrastructure" [4]. The softwarization of the network functions paves the way to further improve the scalability and flexibility of the management of the core network and enable new functionalities and services for the users.

As can be seen from Table 1, besides cellular radio access technologies, a significant number of non-cellular technologies are available. These include the various evolutions and specialised versions of the Institute of Electrical and Electronics Engineers (IEEE) 802.11 (WiFi) standard, including the IEEE 802.11ah for Machine-to-Machine (M2M) connectivity and IEEE 802.11p for Intelligent Transportation Systems (ITS). Given the popularity of the IEEE 802.11 family as the means for Wireless Local Area Network (WLAN), this is hardly surprising. Another very popular technology for low-end and low-power IoT devices is the Bluetooth Low Energy (BLE), which has been introduced as a part of Bluetooth specification version 4.0 and further enriched with features in the subsequent specifications (the most recent version is 5.3). The BLE offers multiple alternatives for implementing energy-efficient wireless connectivity (i.e., by primary or secondary advertising, by establishing the connection between the devices, and even though multihop ad-hoc communication). However, one of the major downsides of this technology is the lack of the native and widely adopted support for Internet Protocol (IP) and IP-based protocols; this effectively restricts the use of BLE in the context of FRACTAL project. Another notable class of technologies is the Low Power Wide Area Network (LPWAN) technologies, which include, e.g., LoRaWAN and SIGFOX. These technologies feature similar characteristics to that of cellular NB-IoT already discussed above but operate in license-free Industrial, Scientific and Medical (ISM) sub-one-gigaHertz bands. This design decision enables to substantially reduce the monetary costs and enable private network deployments (for LoRaWAN); but this also imposes many limitations relative to the maximum duty cycle on the one hand, and results in lower overall quality-of-service and increased probability of packet losses due to interferences. Another notable feature is that neither LoRaWAN nor SIGFOX do support IP-based communication from a device level.

This is also worth mentioning the two classes of radio access technologies which are currently in active development. The first one is the URLLC and the DECT-2020 technology, which has been recently announced. The other one is the non-terrestrial networks (NTN), and, especially, the NTN 5G connectivity, the work on which actively continues in the 3GPP. However, for neither of these two technologies there are the HW implementations commercially available.

Category	Backscatter	Short-range wireless and IoT		URLLC	UWB	ITS		Broadband	mMTC and LPWAN			Satellite	
Technology	RFID/NFC	BLE	IEEE 802.11ax	DECT-2020	IEEE 802.15.4z	ITS G5/ IEEE 802.11p	C-V2X	4G/5G	NB-IoT	LoRaWAN	SIGFOX	NTN 5G	Inmarsat
Deployment status	available	available	available	in development	available	first prototypes		available	available			in development	available
Standardization body	multiple	Bluetooth SIG	IEEE	ETSI	IEEE	ETSI/IEEE	3GPP/ETSI	3GPP/ETSI	3GPP/ETSI	LoRa alliance	proper	3GPP	proper
Frequency band	multiple	2.4 GHz ISM	2.4 & 5 GHz ISM	1.9 GHz DECT	2.5-6 GHz ISM	5.9 GHz ITS bands		400 MHz – 30 GHz licensed	700-2200 MHz licensed	sub GHz ISM		n/a	1600 MHz, L-band
Average consumption	passive	units mW	hundreds mW	n/a	dozens mW	n/a		hundreds mW to units W	dozens mW			n/a	hundreds mW
Typical range	meters	hundreds meters	dozens meters	dozens meters	dozens meters	hundreds meters		units kilometers	units-dozens kilometres			global coverage	
Maximum throughput	hundreds kbps	units Mbps	hundreds Mbps	units Gbps	hundreds Mbps	units Mbps		hundreds Mbps	dozens kbps	units kbps	dozens bps	n/a	dozens bps
Typical latency	units ms	dozens ms	units ms	below one ms	units ms	dozens-hundreds ms		dozen ms	hundreds ms to seconds		unists seconds	n/a	dozens seconds

n/a – information currently not available

Table 1 – Selected IoT-grade radio access technologies and their features and key performance metrics, reworked from [5]

Objectives and Approaches

Table 2 summarizes the objectives of FRACTAL project. The focus of T6.4 and D6.5 is primarily on Objective 4 and partially on Objective 2.

Objective 1 (O1)	Design and Implement an Open-Safe-Reliable Platform to Build Cognitive Edge Nodes of Variable Complexity
Objective 2 (O2)	Guarantee extra-functional properties (dependability, security, timeliness and energy-efficiency) of FRACTAL nodes and systems built using FRACTAL nodes (i.e., FRACTAL systems).
Objective 3 (O3)	Evaluate and validate the analytics approach by means of AI to help the identification of the largest set of working conditions still preserving safe and secure operational behaviours.
Objective 4 (O4)	To integrate fractal communication and remote management features into FRACTAL nodes

Table 2 - FRACTAL project strategic objectives [6]

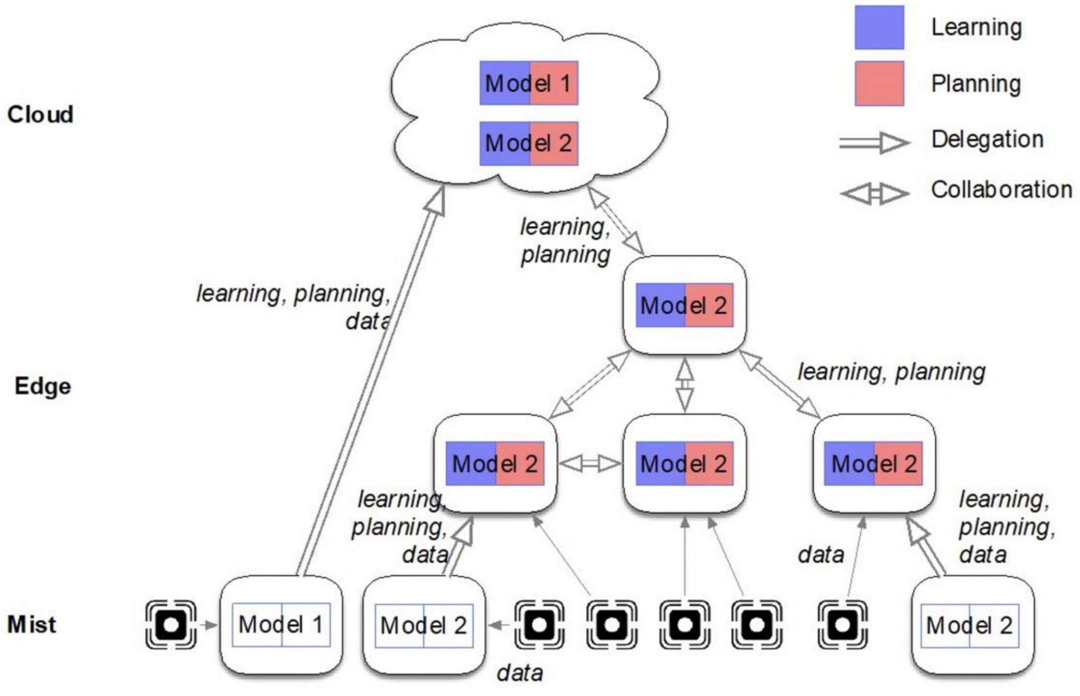

Figure 2 – The three-layer FRACTAL architecture (re-print of Figure 4 from D3.5).

As discussed in D2.3, D3.5 and D3.6 (see Figure 2; reprint of Figure 4 from D3.5) there are three tiers of FRACTAL HW nodes: low (mist), medium (edge), high (cloud) versions that all share similar interfaces and interact with each other. The simpler nodes can acquire data and delegate more complex tasks to nodes with higher complexity. The FRACTALITY approach calls for establishing efficient connectivity between the nodes of the same level, as well as with the nodes residing on the upper/lower layers. In case if the communication needs to base on IP, this further narrows down the number of radio access technologies and architectures, which can be effectively employed, as was discussed above.

The approach followed by T6.4 is thus composed of the four sequential steps specified in Table 3. These steps are further detailed in D6.5 in Sections 4, 5, 6 and 7, and 8, respectively.

Step 1	Analyse the FRACTAL requirements for wireless communication and determine the architectures and technologies;
Step 2	Select the HW and implement support for selected wireless communication functionalities for a test platform;
Step 3	Validate the operation of wireless connectivity and numerically assess the relevant performance metrics;
Step 4	Report the results of the measurements and carry out their analysis.

Table 3 – T6.4 approach

4 Communication architectures and radio access technologies selection

The architecture shown in Figure 2 features a network of hybrid topology, having elements (subnetworks) structured using star, tree, mesh and peer-to-peer topologies. Given the sheer diversity of the potential IoT use cases and applications and their specific requirements, which FRACTAL aims to approach, this is hardly surprising that we need to enable and support multiple topologies and connectivity options. Of these topologies, two can be considered as the dominant ones:

- the tree (the star topology can be treated as a subcase of tree topology);
- the mesh (the peer-to-peer can be considered a subclass of mesh topology).

Notably, also depending on the target application or use case, the distance between the FRACTAL nodes might vary greatly – from units of meters to multiple kilometers. Also, the application would determine the traffic pattern and wireless communication key performance indicators, which have to be provided. However, as a rule of thumb, with the increase of the FRACTAL node's tier, its capabilities (e.g., computing power and available resources) and communication needs will raise. Owing to this, the upper-layer nodes are also likely to operate using more complex communication protocols (typically build on top of IP). This implies the need of the underlying radio access technology(ies) to support IP-based communication.

Departing from this consideration and the state-of-the-art of the radio access technologies discussed in the previous section three distinct topologies to be addressed by D6.5 were selected:

Topology 1: IEEE 802.11 based last mile, illustrated in Figure 3;
Topology 2: Direct cellular (5G) backbone, illustrated in Figure 4;
Topology 3: IEEE 802.11 based last mile over cellular (5G) backbone, illustrated in Figure 5;

The Topology 1, shown in Figure 3, implies the use of the IEEE 802.11 Wireless Local Area Network (WLAN) radio access at the FRACTAL nodes. This technology has been specifically designed and widely utilized in high-throughput star networks operating in 2.4 GHz and 5 GHz ISM bands. The combination of sufficiently wide frequency bands, advanced modulation-coding schemes and advanced media access schemes, and support for Multiple Input Multiple Output (MIMO) enable high throughput and low latency (under no or limited interference conditions); however, operation at above-2GHz ISM bands prevents sufficiently long-range communication. Notably, multiple implementations of mesh connectivity over IEEE 802.11 are available and have been reported [7][8].

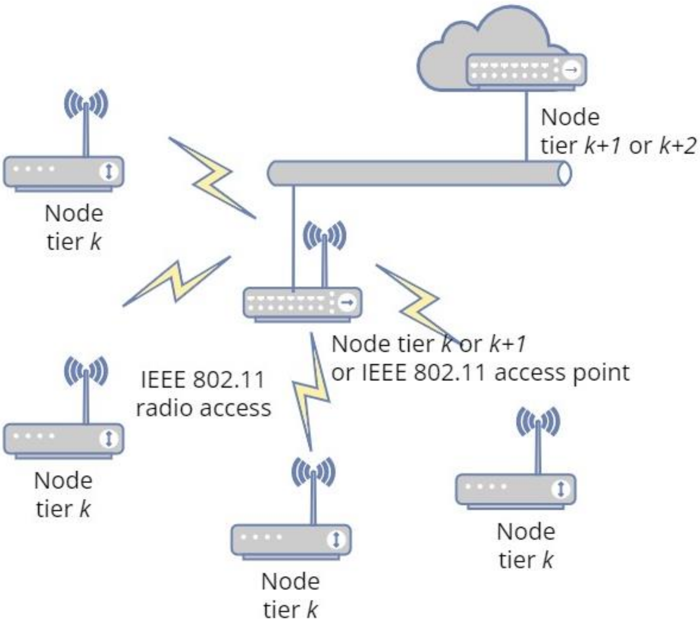

Figure 3 – Topology 1: IEEE 802.11 based last mile

The Topology 2, depicted in Figure 4, suggests equipping FRACTAL nodes with cellular, and specifically the 5G, wireless connectivity. The Orthogonal Frequency Division Multiple Access (OFDMA), new frequency bands, licensed spectrum and fully controlled access to the time-frequency resources enable both high throughput and substantial communication range. The downsides of this are the extra monetary costs (for enabling access to the spectrum) and substantial infrastructure investments. This is also worth noting that the cellular technologies (all the way from 1G to 5G) have been primarily[3] designed with tree-like topology in mind, implying user equipment (UE) communicating to a base station, while the base stations are merged into a single centralised network with dedicated gateways enabling Internet connectivity. As a result of this, the efficiency of peer-to-peer connectivity between a two UEs, especially if they are located close to each other, would be often low. Another important thing to note is that the performance of a cellular network is heavily dependent on its configuration and available resources (to give a practical example - the width of the frequency bands allocated for uplink and downlink communication in case of Frequency Division Multiple Access (FDMA) or amount of time allocated for uplink and downlink in case of Time Division Multiple Access (TDMA)) and may vary substantially from one network to another, between the individual base stations and even between sectors of one base station within a network of a single operator.

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[3] Except for the so-called sidelink connectivity, which has been enabled as a part of LTE specifications package to be used for public safety communications. It has been further reworked within C-V2X for ITS use cases.

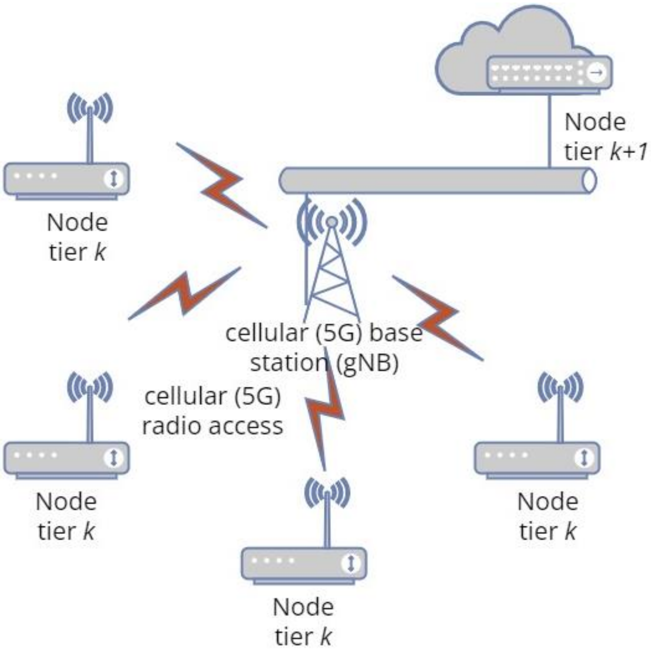


Figure 4 – Topology 2: Direct cellular (5G) backbone

Finally, Topology 3, illustrated in Figure 5, focuses on the scenario where both technologies are combined. Specifically, a star or mesh IEEE 802.11 network is employed for communication between the same-tier FRACTAL nodes, and cellular (5G) radio access is used for communicating to the nodes at the upper tier.

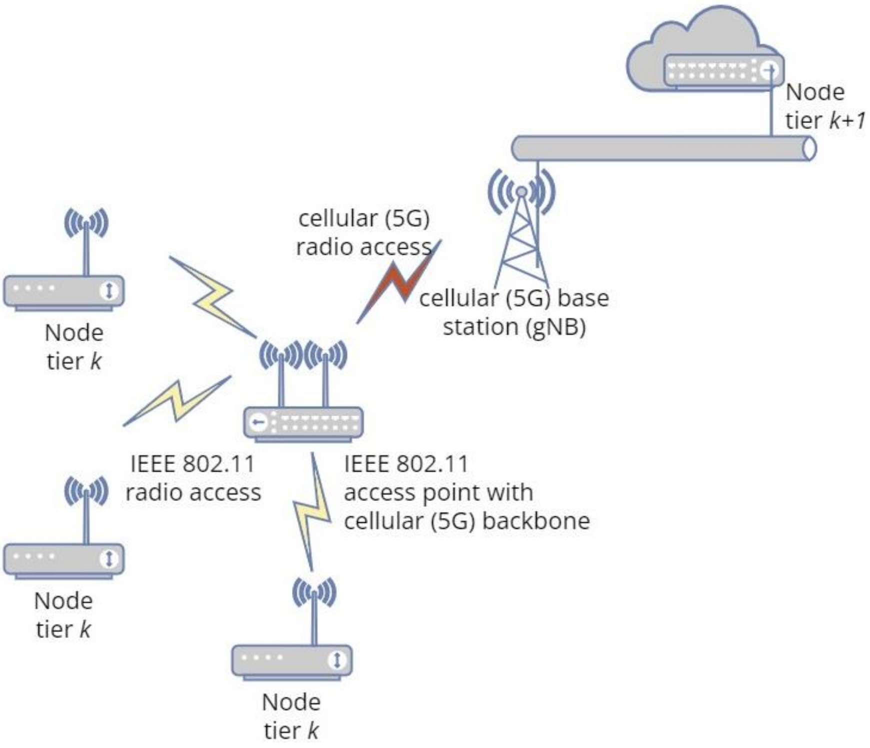


Figure 5 – IEEE 802.11 based last mile over cellular (5G) backbone

These three network topologies and radio access technologies enable to cover the majority of the potential target use cases and IoT applications envisaged for FRACTAL and thus have been selected as the baseline set of scenarios for our implementation, as discussed in the next chapter. Notably, though there exist a number of other specialized IoT-grade radio access technologies for low-tier nodes (e.g., IEEE 802.15.4, BLE, ANT for mesh/peer-to-peer; LoRaWAN and SIGFOX for tree/star) these technologies impose substantial limitations (e.g., for packet size, maximum throughput) and do not support IP-based communication from node level, which substantially reduces their flexibility and limits their applicability. For these reasons, these technologies were not considered in this study, though they might still be potential for application and use cases with specialized and stringent connectivity requirements. This is also worth noting, that aside of these three topologies, we have also enabled and carried pre-trials for the cellular IoT connectivity based on NB-IoT technology; however, the results of these pretrials demonstrated low and not very stable overall performance, thus they are not included in the current deliverable.

5 Integration: implementation and configuration

Each of the three subsections of the current chapter focuses on one of the selected target topologies; Section 5.1 – on IEEE 802.11 based last mile, Section 5.2 – on Direct cellular (5G) backbone, and Section 5.3 – on IEEE 802.11 based last mile over cellular (5G) backbone. Within each subsection we first detail and justify the selection of the HW, and then provide a step-by-step instruction for setting up and configuring the SW at a HW platform.

5.1 Topology 1: IEEE 802.11 based last mile

5.1.1 Hardware

To enable IEEE 802.11 wireless connectivity, two types of devices are required:

- An IEEE 802.11-compatible radio module for FRACTAL nodes
- An IEEE 802.11-compatible access point (AP) to coordinate the communication between the FRACTAL nodes

5.1.1.1 IEEE 802.11 radio module

Given the popularity of the IEEE 802.11 standard, there are multiple options for radio modules and modems which can be used. Based on the analysis of the cost, form-factor, technical characteristics and availability of the drivers for the SW platforms the TP-link AC1300 Archer T3U Plus WiFi Universal Serial Bus (USB) dongle [9] was selected. The test node with the dongle attached is illustrated in Figure 6.

This dongle features the USB 3.0 interface for the USB connection. The module supports both 2.4 GHz and 5 GHz frequency bands and operation in accordance with IEEE 802.11 a/b/g/n/ac standards. The maximum supported transmit power is 18dBm in 2.4 GHz band and 20 dBm in 5 GHz band.

Figure 6 – Illustration of the test node equipped with TP-link AC1300 dongle

5.1.1.2 IEEE 802.11 access point

To further enrich the functionalities of the system, as AP we have selected the TeleWell Industrial 5G AP [10] specifically designed for M2M applications, which is depicted in Figure 7. The AP supports B1 – B5, B7, B8, B12 – B14, B17 – B20, B25, B26, B28 – B30, B46, B66, B71 LTE bands and n1 – n3, n5, n7, n8, n12, n20, n28, n38, n40, n41, n48, n66, n71, n77 – n79 5G bands. It has four cellular 5G antennas and two antennas for WLAN. The AP can deploy both 2.4 GHz and 5 GHz networks supports standards 802.11 b/g/n. There are two slots for Subscriber Identity Module (SIM) cards and a cellular connection can be established via SIM-A or SIM-B. This router supports 9 to 36V DC power input and we use DC12V/2.5A power adapter for powering up the router. The instructions for preparing (e.g., power supply and antenna connection; SIM card) and deploying the AP are provided in its manual [10]. Note, that for IEEE 802.11 only based communication there is no need to enable cellular connectivity, however, this functionality will be used later as a part of Topology 3 and discussed in Section 5.3. The selection of this AP was primarily due to this reason – the possibility of using the same AP for IEEE 802.11 and integrated IEEE 802.11 and cellular (5G) tests.

Figure 7 – Illustration of the TeleWell Industrial 5G AP used as IEEE 802.11 AP

5.1.2 Software and configurations

5.1.2.1 Enabling support of WLAN at node

To enable the support of WLAN using Archer T3U Plus AC1300 dongle at the test node, it is required to install Realtek RTL88x2BU WLAN USB Driver. Installation of this driver can be done using the following steps [11].

Step 1: Install the required packages.

-
  ```
  sudo apt install -y build-essential dkms git iw
  ```

Step 4: Create a directory to hold the downloaded driver.

-
  ```
  mkdir -p ~/rtl_driver
  ```

Step 5: Move to the newly created directory.

-
  ```
  cd ~/rtl_driver
  ```

Step 6: Download the driver.

-
  ```
  git clone https://github.com/morrownr/88x2bu-20210702.git
  ```

Step 7: Move to the newly created driver directory.

- `cd ~/rtl_driver/88x2bu-20210702`

Step 8: Run the installation script (install-driver.sh)

- `sudo ./install-driver.sh`

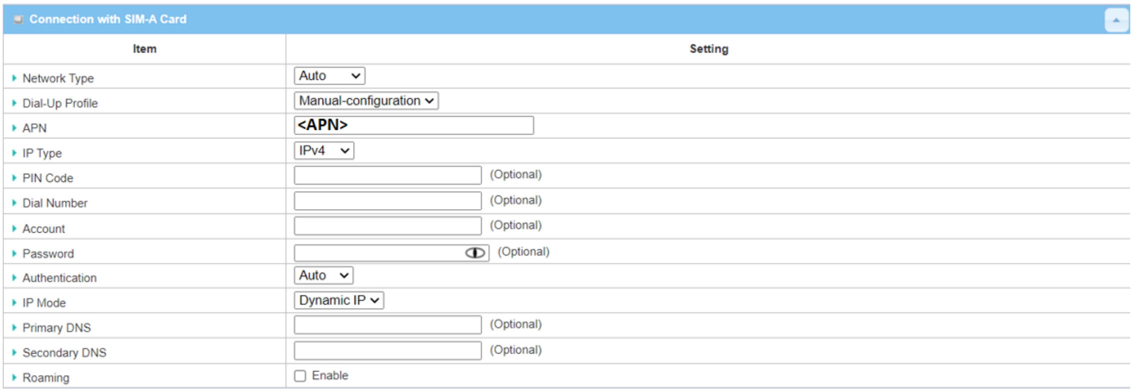
Step 9: Restart the node (only if you have not done this in step 8).

After the reboot, one can connect to the AP through WiFi, following the conventional procedures (i.e., selecting the network and entering the key).

5.1.2.2 Configuration of WLAN access point

Login to the router's web User Interface (UI) can be done using the router IP address (by default 192.168.123.254). Entering http://192.168.123.254 in a web browser on a computer connected to the same WLAN, takes the user to the login page of the router. By default, logging credentials for both username and password are 'admin'. For security reasons, it is required to change the logging credentials. This can be done as explained in the router's user manual [7].

For enabling cellular connectivity, this is required to set the Access Point Name (APN) according to the Internet Service Provider (ISP). This can be done from connection setup window (Basic Network > WAN & Uplink > Connection Setup) of the router's web UI. Changing the Dial-Up profile option to 'Manual-configuration', we are allowed to set the APN for either SIM card. In our case we configure the APN as shown in Figure 8; we leave all the other default configurations unchanged.

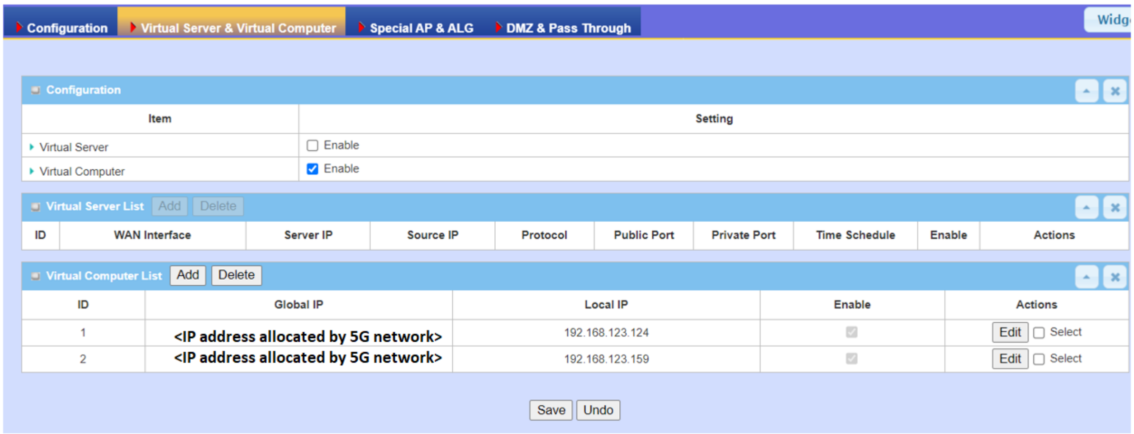


Connection with SIM-A Card

Item	Setting
Network Type	Auto
Dial-Up Profile	Manual-configuration
APN	**<APN>**
IP Type	IPv4
PIN Code	(Optional)
Dial Number	(Optional)
Account	(Optional)
Password	(Optional)
Authentication	Auto
IP Mode	Dynamic IP
Primary DNS	(Optional)
Secondary DNS	(Optional)
Roaming	☐ Enable

Figure 8 – APN configuration for TeleWell Industrial 5G AP

Since the IP address is assigned by the cellular network only to the AP, in case a node needs to be accessible by the upper tiers node, there is a need to enable port forwarding. For this, we enable virtual computer port forwarding function (Basic Network > Port Forwarding > Virtual Server & Virtual Computer) using AP's web UI. Virtual Computer allows us to assign LAN hosts to global IP addresses, so that they can be visible to outside world [10]. The example configurations are shown in Figure 9.



Item	Setting
Virtual Server	☐ Enable
Virtual Computer	☑ Enable

ID	WAN Interface	Server IP	Source IP	Protocol	Public Port	Private Port	Time Schedule	Enable	Actions

ID	Global IP	Local IP	Enable	Actions
1	**<IP address allocated by 5G network>**	192.168.123.124	☑	Edit ☐ Select
2	**<IP address allocated by 5G network>**	192.168.123.159	☑	Edit ☐ Select

Figure 9 – Illustration of port forwarding configuration for TeleWell Industrial 5G AP

Note that the IP address allocated by the cellular network to the AP can be obtained from WAN Interface IPv4 Network Status in Status > Basic Network > WAN & Uplink. As the result of these configurations, once the node is connected to AP through WLAN, the local IP address of the node can be obtained from the Status > LAN & VLAN. It is also possible to configure a static IP address on the test node using the MAC address of the WiFi dongle and an IP address chosen from the IP Pool of the AP Dynamic Host Configuration Protocol (DHCP) server. To do this, we need to navigate to DHCP Server window from Basic Network > LAN & VLAN > DHCP Server. By clicking on the Fixed Mapping button we can enter the MAC address of the WiFi dongle and an IP address chosen from the IP Pool of the DHCP server. MAC address of the WiFi dongle can be obtained from `ifconfig` Linux terminal command once the test node connected to the WiFi network. Further information about the configuration of the AP can be obtained, if needed, from its manual [10].

5.2 Topology 2: Direct cellular (5G) connectivity

5.2.1 Hardware

To enable the direct cellular (5G) connection, we use Quectel RMU500-EK Evaluation Board (EVB) with RM500Q 5G module. The complete instructions on how to prepare the EVB with RM500Q (e.g., power supply; dissembling & assembling; SIM card; attachment of the module to the evaluation board) are available in its user guide [12]. The EVB can be powered by an external power adapter through the power jack (J101) on the EVB. It can be also powered by the USB (i.e., USB-C) interface through the power jack (J301) on the EVB. Here, We use the power jack (J301) to connect the EVB with the host.

At the time when development was carried (i.e., in 2022 and early 2023) the RM500Q is the only 5G module commercially available and adapted for IoT usage, thus selection of this platform had no alternatives.

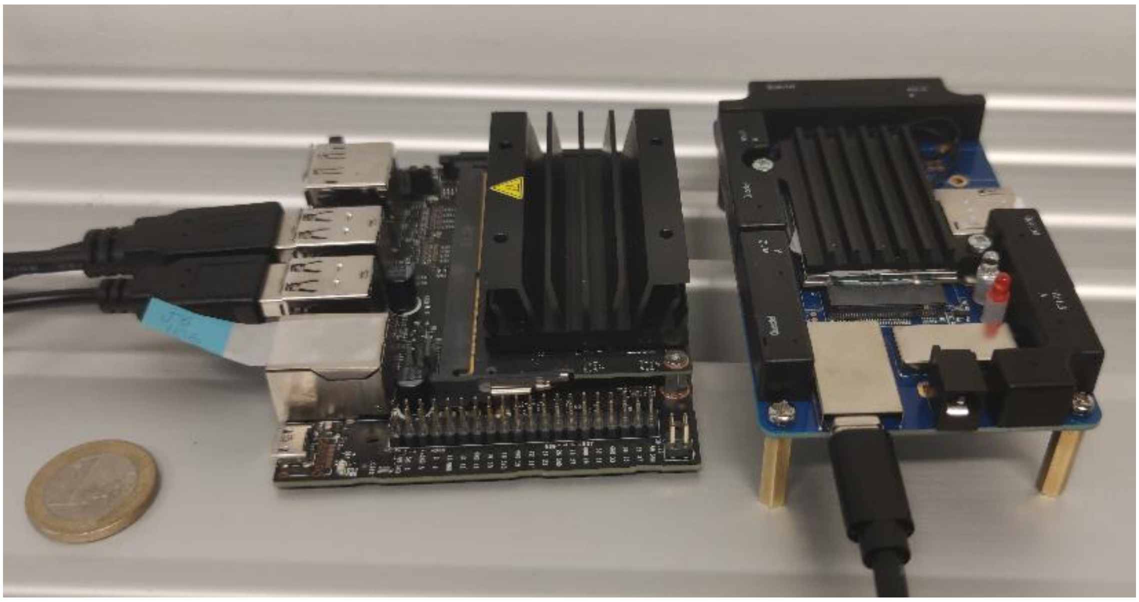


Figure 10 – Illustration of test node (to the left) connected to Quectel RM500Q 5G board (to the right) over USB-C

5.2.2 Software and configurations

It is required to install Linux 5G USB drivers on the node to be able to connect to the 5G network using Quectel RM500Q 5G module. Based on testing several options, we use GobiNet driver for 5G connection. Once the driver installation is done, it is required to execute the necessary attention/Hayes (AT) commands to RM500Q 5G module in order to establish the 5G connection. To be able to give AT commands on RM500Q, we are required install Quectel USB Serial Option Driver. Additionally, we also install Qmi_WWAN driver which is also a 5G USB driver. Based on the USB network adapter, it will use either GobiNet or Qmi_WWAN driver. To setup a data call, we use Quectel's Connect Manager (quectel-CM) tool. Following steps present the installation of drivers and other configurations required to perform the node.

Boot the node and install 5G drivers.

Step 1: Connect and power the device using power cable.

Step 2: Download the Quectel 5G USB drivers from here.

Step 3: Extract all the zip files and rename the folders so that the folder names do not contain "&" symbol. Otherwise, this will show errors.

- `sudo make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu- install`

Step 4: Go to the extracted Qmi_wwan directory and install the driver.

- `sudo make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu- install`

Step 5: Go to the extracted GobiNet directory and install the driver

```
sudo make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu- install
```

Step 6: Go to the extracted SerialOption/v4.9.111 directory and install the driver. Driver version is based on the kernel version (Uname -r)

```
sudo make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu- install
```

Install the Quectel-CM

Step 1: Go to the QConnect directory and install the QConnect manager.

```
sudo make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu-
```

Step 2: Prepare “busybox udhcpc” tool

Quectel-CM will call “busybox udhpc” to obtain IP and DNS, and “busybox udhpc” will call script file */usr/share/udhcpc/default.script* to set IP, DNS and routing table for Linux board.

The source codes of “busybox udhpc” tool can be downloaded from here, then enable CONFIG_UDHCPC with the command below and copy the script file *[BUSYBOX]/examples/udhcp/simple.script* to Linux board (renamed as */usr/share/udhcpc/default.script*).

```
sudo make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu- menuconfig
```

go to Netwok Utilities > udhcpc and press Y to enable it. Press ENTER and exit. Finally save the configuration.

```
sudo make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu-
sudo make ARCH=arm64 CROSS_COMPILE=aarch64-linux-gnu- install
```

Test AT Commands

Step 1: Install and run UART port tools such as “minicom”, “busybox microco”, “socat”.

```
sudo apt-get install socat
```

When the USB serial option driver has been installed in the module, the device files named as ttyUSB0, ttyUSB1, ttyUSB2, etc. will be created in directory /dev.

The AT port is usually /dev/ttyUSB2, which is the second ttyUSB port created by the USB serial option driver.

Step 2: Run the Socat on ttyUSB2 and test ‘at+cops’ command.

```
sudo socat - /dev/ttyUSB2,crnl
at+cops?
```

AT commands for 5G connection

Set the <APN> (replace <APN> with the value of APN for the target network)

- `AT+CGDCONT=1, "IP","<APN>", "0.0.0.0"`

Search for LTE band B7 (Note: the band depends on the telecom operator, B7 is the configuration in the 5G Test Network (5GTN))

- `AT+QNWPREFCFG="lte_band",7`

Search for 5G New Radio (NR) NSA band n78

- `AT+QNWPREFCFG="nsa_nr5g_band",78`

Set network search mode to search only LTE & NR5G bands

- `AT+QNWPREFCFG="mode_pref",LTE:NR5G`

Set not to disable 5G NR standalone (SA)/NSA

- `AT+QNWPREFCFG="nr5g_disable_mode",0`

Query current Serving Cell

- `AT+QENG="servingcell"`

Should be able to see 5G NR cell if the 5G network is available.

Unlock for uncommercial network capability.

- `AT+QMBNCFG="Select","ROW_Commercial"`

Set roaming Preference to home network.

- `AT+QNWPREFCFG= "roam_pref",1`

Alternatively, one can also use the following single line instead giving AT commands one by one.

- `AT+CGDCONT=1,"IP","<APN>","0.0.0.0";+QNWPREFCFG="lte_band",7;+QNWPREFCFG="nsa_nr5g_band",78;+QNWPREFCFG="mode_pref",LTE:NR5G;+QNWPREFCFG="nr5g_disable_mode",0;+QENG="servingcell";+QMBNCFG="Select","ROW_Commercial";+QNWPREFCFG= "roam_pref",1`

In addition to these one can get the signal quality output (such as signal strength; network mode; serving cells;) from following AT commands. Definitions for these commands can be found from AT commands manual [17].

- `AT+QENG="servingcell";+qnwinfo;+qsinr;+qrsrq;+qrsrp;+csq`

Setup a data Call from quectel-CM tool

Step 1: Open a terminal from quectel-CM directory.

Step 2: Give root access and setup a data call from the APN.

- `Sudo su`
- `./quectel-CM -s <APN>`

5.3 Topology 3: IEEE 802.11 based last mile over cellular (5G) backbone

5.3.1 Hardware

5.3.1.1 WiFi dongle

The same hardware as described in Section 5.1.1 was used.

5.3.1.2 WiFi access point

The same hardware as described in Section 5.1.1 was used.

5.3.2 Software and configurations

The required configurations have been already described in the Section 5.1.

5.3.2.1 Enabling support of WiFi at test node

We use a WLAN connection to the AP at test node. Required IEEE 802.11 driver installation has been described in Section 5.1.2 in this document.

5.3.2.2 Configuration of WiFi access point

The AP configuration on the test node is same as in Section 5.1.2 in this document.

6 Testing and measurement tools

In the following sections we start by discussing the produced test plan, then detail the measurement and other tools used in for testing and describe the way the required functionalities (e.g., time synchronization to enable accurate measuring of the delay or deployment of a Secure File Transfer Protocol (SFTP) server used for stress traffic testing). In the last subsection, the information about the carried pre-testing to ensure correct operation of the deployed system is reported.

Test identifier (ID)	Description of the test
Test 1	A test node communicating to an upper-tier node (server) over cellular (5G) connection; office environment
Test 2	A test node communicating to a same-tier node over cellular (5G) connection; office environment
Test 3	A test node communicating to an upper-tier node (server) over IEEE 802.11 with cellular (5G) backbone connection; office environment
Test 4	A test node communicating to a same-tier node over IEEE 802.11 with cellular (5G) backbone connection; office environment
Test 5	A test node communicating to an upper-tier node (server) over IEEE 802.11 connection; office environment
Test 6	A test node communicating to a same-tier node over IEEE 802.11 connection; office environment
Test 7	A test node communicating to an upper-tier node (server) over cellular (5G) connection; direct line-of-sight to base station
Test 8	A test node communicating to a same-tier node over cellular (5G) connection; direct line-of-sight to base station
Test 9	A test node communicating to an upper-tier node (server) over IEEE 802.11 with cellular (5G) backbone connection; direct line-of-sight to base station
Test 10	A test node communicating to a same-tier node over IEEE 802.11 with cellular (5G) backbone connection; direct line-of-sight to base station

Table 4 – Test plan

6.1 Test plan

To comprehensively test and measure the key performance metrics of interests for the different configurations we came up with the set of tests specified in Table 4. Test identifiers (IDs) 5 and 6 implement Topology 1, IDs 1,2,7 and 8 focus on Topology 2, and IDs 3,4,9 and 10 the hybrid topology – Topology 3. Notably, for Topologies 2 and 3 we carry the measurements for two radio channel conditions of the cellular link, implying direct line-of-sight (LoS) between the cellular modem and the antenna of the base station, and location of the cellular modem indoors with no LoS to the base station. Further information about the locations and the measurement environment is available in Section 7. Furthermore, each of the test ID composes three subtests, detailed in Table 5.

Subtest identifier (ID)	Description of a subtest
Subtest x.a, x=1..10	Measurement focuses on estimating the delay for small size packets. The *ping* command is used to generate the traffic. The payload of the ping packet is set to 10 bytes and the period of transmissions is set to 1 second. Unless stated otherwise, the measurement for 1000 packets is done.
Subtest x.b, x=1..10	Measurement focuses on estimating the delay for bigger packets. The *ping* command is used to generate the traffic. The payload of the ping packet is set to 900 bytes and the period of transmissions is set to 1 second. Unless stated otherwise, the measurement for 1000 packets is done.
Subtest x.c, x=1..10	Measurement focuses on estimating the throughout. The throughput capability is measured through two approaches: (i) the conventional speed tests and (ii) by deploying an Secure File Transfer Protocol (SFTP) server and measuring time required to upload and download a test file (1.6 GB[4], unless stated otherwise)

Table 5 – Subtest composition in each test

In total, 10 test x 3 subtests = 30 experiments have been executed. In each experiment, along with the metrics of interest, we also monitored and logged the relevant information about the radio channel conditions (e.g., Received Signal Strength Indicator (RSSI), Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Signal-to-Interference-Noise Ratio (SINR) and ID of the cell, to which the nodes were connected). More details about the test procedure are discussed in the following sections and Figures 11-16 further illustrate the network architecture during the different tests.

---

[4] As the test file we used the Nvidea OS image, available from https://developer.nvidia.com/embedded/l4t/r32_release_v7.1/t210/tegra_linux_sample-root-filesystem_r32.7.1_aarch64.tbz2

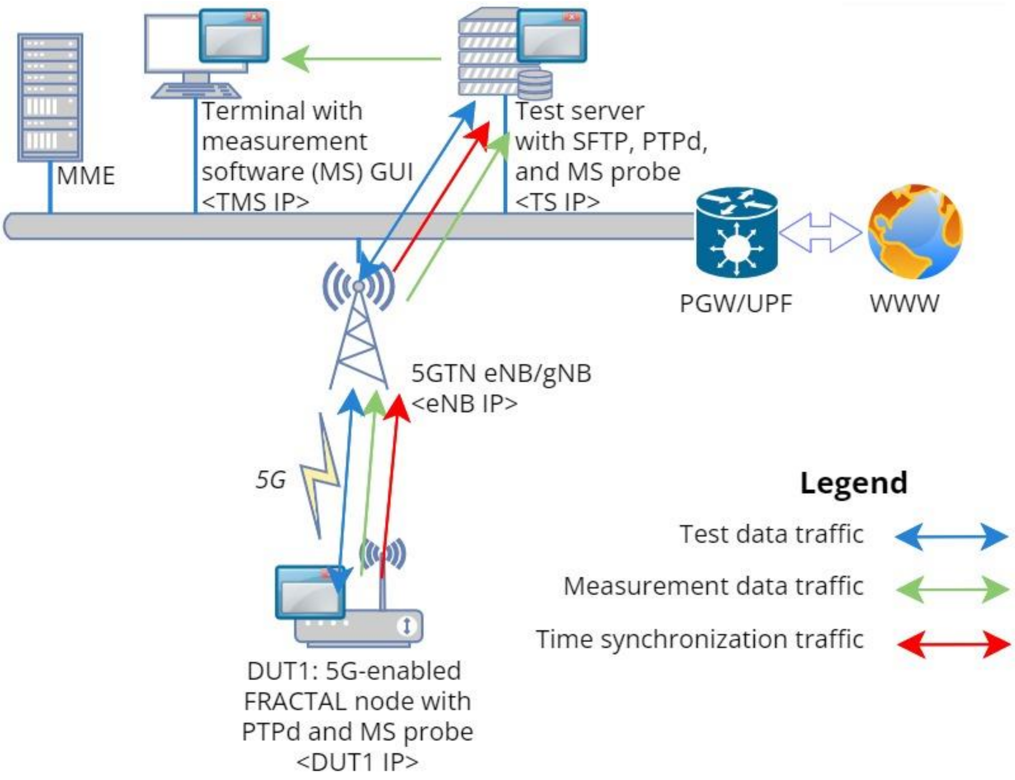


Figure 11 – Network architecture for Tests 1 and 7

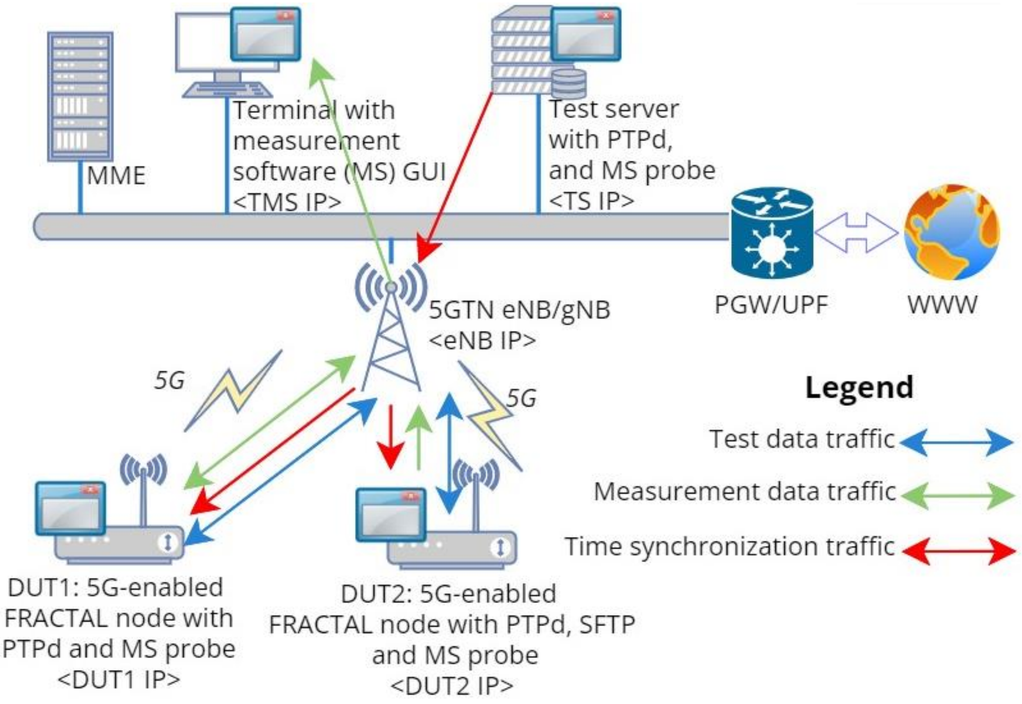


Figure 12 – Network architecture for Test 2 and 8

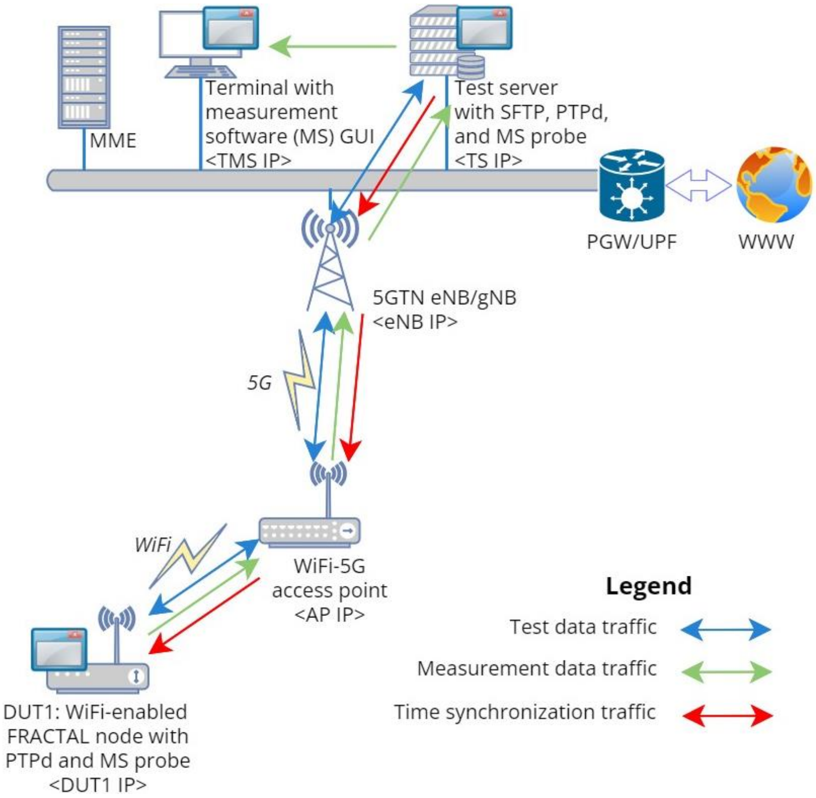


Figure 13 – Network architecture for Tests 3 and 9

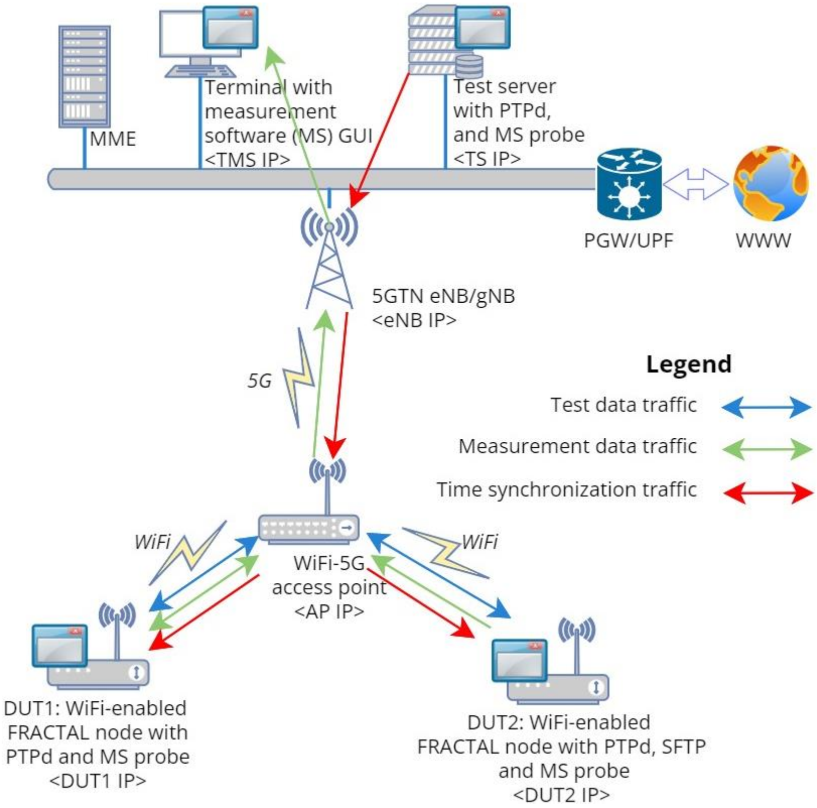


Figure 14 – Network architecture for Tests 4 and 10

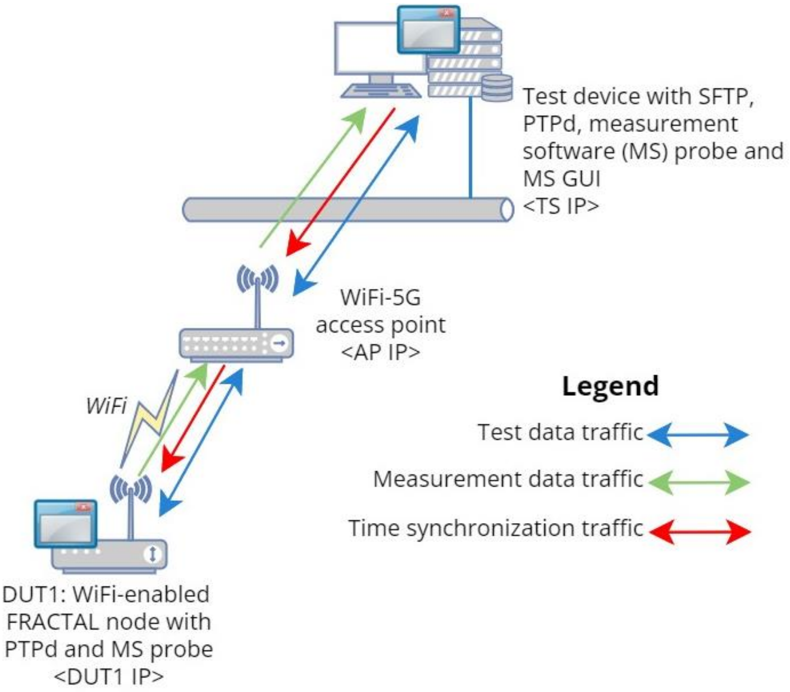


Figure 15 – Network architecture for Test 4

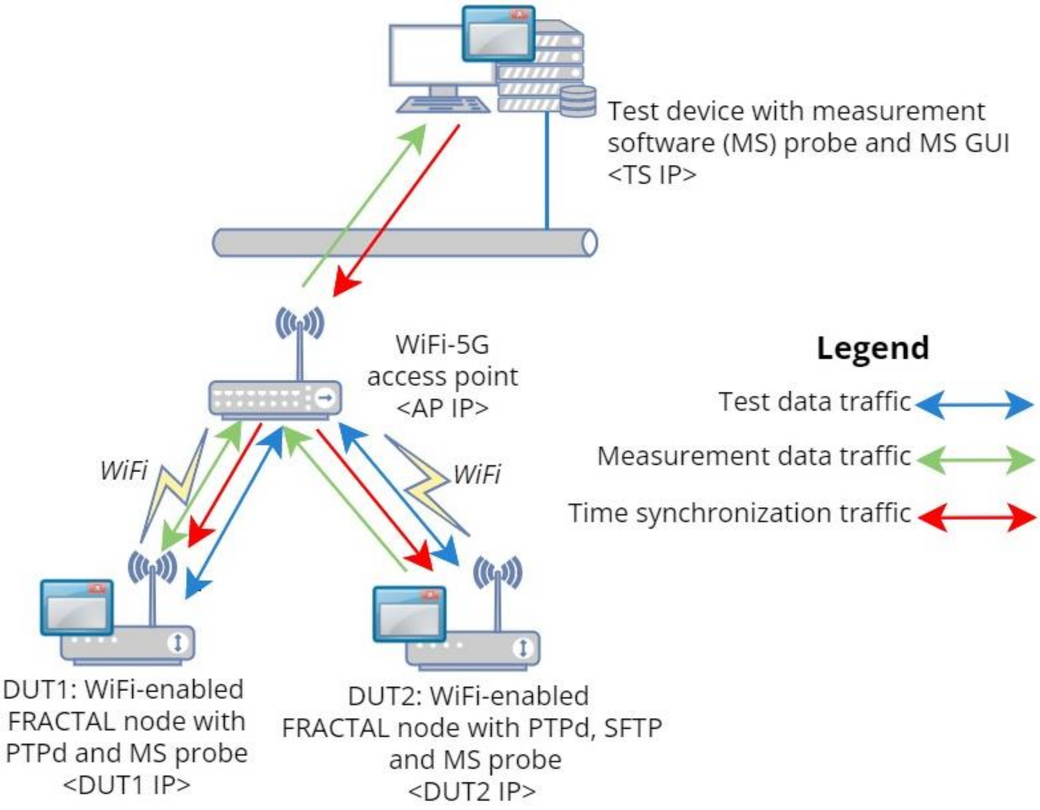


Figure 16 – Network architecture for Test 5

6.2 Test devices, measurement and other tools

The current section focuses on the HW and SW tools and instruments used during our experiments to collect the data or generate the traffic.

As discussed in Section 6.1, the test network is composed of the following main components:

- one or two test FRACTAL nodes, depending on the test;
- an upper tier FRACTAL node, as which we used an edge server located in the core network of 5GTN;
- telecommunication infrastructure, which depends on the test case (i.e., the base station of 5GTN and 5GTN core network when communication over cellular (5G) is studied, and an IEEE 802.11 AP when IEEE 802.11 based communication is employed);

and additionally

- for tests dealing with cellular (5G) connectivity we utilized another computer located in 5GTN core network to establish synchronization between the measurement probes using Precision Time Protocol (PTP) and collect the data from these probes;
- for tests with IEEE 802.11 and without cellular (5G) connectivity we used a laptop equipped with an SFTP server, PTP and measurement probes and connected to the AP over Ethernet interface. This was done primarily due to security reasons to protect 5GTN from possible attacks.

Furthermore, to facilitate the experiments execution and switching between the different tests and subtests, we first carried an analysis of the HW and SW components required, and then instrumented two test FRACTAL nodes with all the needed SW components to allow all the planned tests. The summary of the components used in every test and the overall set of components installed at different devices is presented in Table 6. The deployment of the "communication-enabling" SW components has been already detailed in Section 5. In the rest of this section, we will discuss individually the various HW and SW elements used in our test, which have not yet been discussed.

Test and subtest	Test node 1 (device-under-test 1)	Test node 2 (device-under-test 2)	Test server (i.e., node of the upper tier)	Test laptop
1 and 7	- cellular drivers - Qosium probe -SFTP client -PTPd master/slave	n/a	- Qosium probe - Qosium scope -SFTP server -PTPd master/slave	n/a
2 and 8	- cellular drivers - Qosium probe -SFTP client -PTPd master/slave	- cellular drivers - Qosium probe -SFTP server -PTPd master/slave	- Qosium probe - Qosium scope -PTPd master/slave	n/a
3 and 9	- IEEE 802.11 drivers - Qosium probe -SFTP client -PTPd master/slave	n/a	- Qosium probe - Qosium scope -SFTP server -PTPd master/slave	n/a
4 and 10	- IEEE 802.11 drivers - Qosium probe -SFTP client -PTPd master/slave	- IEEE 802.11 drivers - Qosium probe -SFTP server -PTPd master/slave	- Qosium probe - Qosium scope - PTPd master/slave	n/a
5	- IEEE 802.11 drivers - Qosium probe -SFTP client -PTPd master/slave	n/a	n/a	- Qosium scope - Qosium probe - PTPd master/slave
6	- IEEE 802.11 drivers - Qosium probe -SFTP client -PTPd master/slave	- IEEE 802.11 drivers - Qosium probe -SFTP server -PTPd master/slave	n/a	- Qosium scope - Qosium probe - PTPd master/slave
Overall	*- IEEE 802.11 drivers* *- cellular drivers* *- Qosium probe* *-SFTP client* *-PTPd master/slave*	*- IEEE 802.11 drivers* *- cellular drivers* *- Qosium probe* *-SFTP client* *-SFTP server* *-PTPd master/slave*	*- Qosium probe* *- Qosium scope* *-SFTP server* *-PTPd master/slave*	*- Qosium probe* *- Qosium scope* *-SFTP server* *-PTPd master/slave*

Table 6 – SW components of the individual network elements required for the tests.

6.2.1 Test nodes

As already mentioned, during the experiments we have used two test nodes, each having a full set of SW components required for the tests (see Table 6). During tests 1,2,7 and 8 the 5G modem was attached to the test nodes; during other tests – the IEEE 802.11 modem was attached. Additionally, to control and interact with the test nodes, each of them was equipped with USB mouse and keyboard. To monitor the status of the node, each of them was connected to a screen via a High-Definition Multimedia Interface (HDMI) cable. An illustration of the test bed for Test 7 taken during pre-trials is shown in Figure 17. Throughout the tests, except for the power supply measurements, the test nodes and AP were powered with alternating current (AC) power.

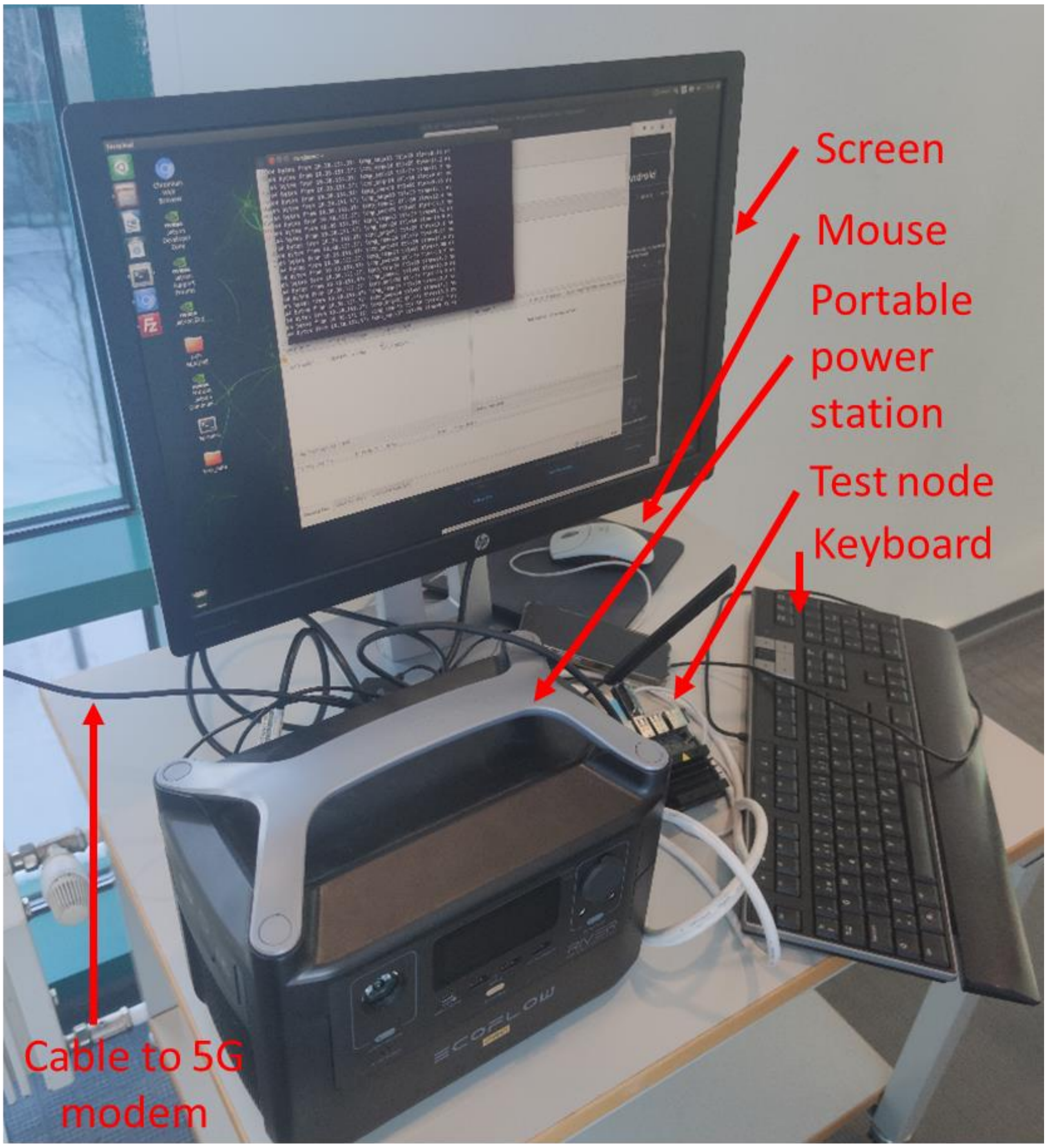
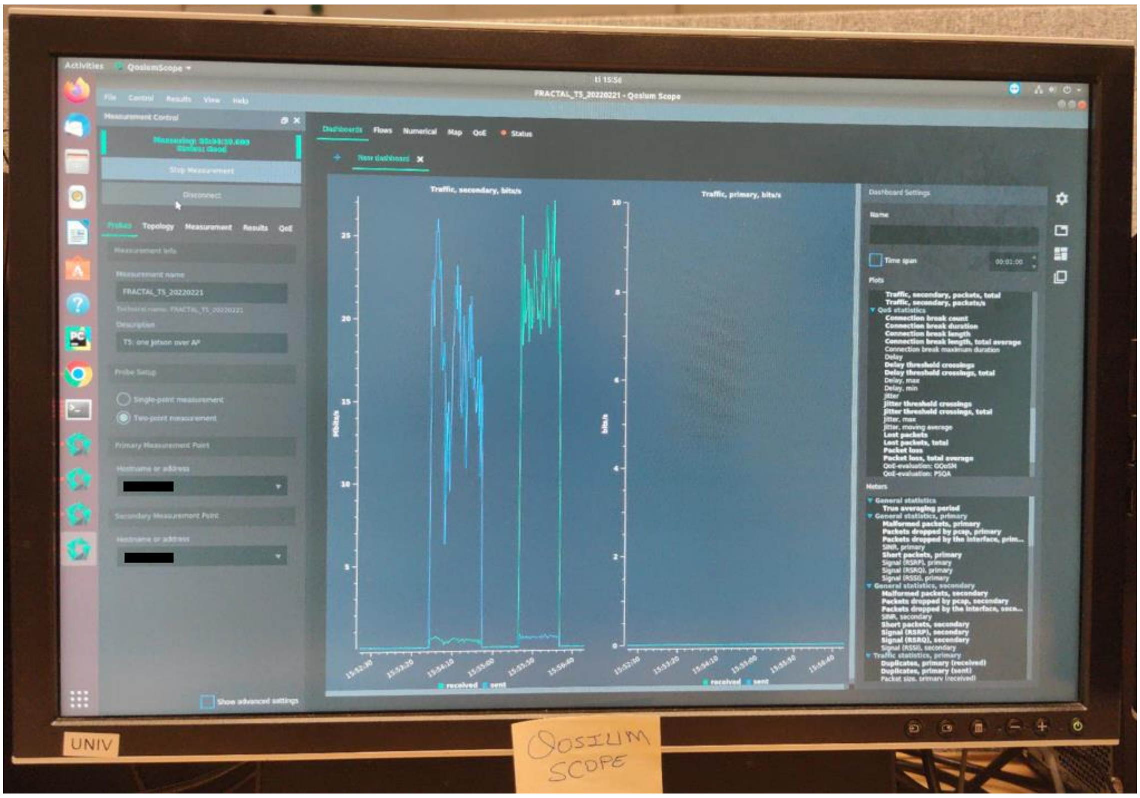


Figure 17 – Photo of a test bed (taken during pre-trials of Test 7) & the key elements of the test bed

6.2.2 Qosium tool

For accurately measuring the communication key performance indicators we have utilized the Qosium tool from Kaitotek OY [13]. Qosium is passive Quality of Service (QoS) and Quality of Experience (QoE) real-time performance measurement and monitoring system for wired and wireless networks, also having features for network performance visualization. Being passive, the Qosium measures the QoS of real applications on the network without causing major disruptions. The tool is composed of the two components – the network probes, which are the passive measurement tools and should be deployed at the points to be measured, and a single Scope SW tool used to control the measurements and log the data. More information about the tool, its capabilities and set-up procedures are available from its manual [14]. Note, that a specialized pre-compiled version of the Qosium probes was provided by the manufacturer for deployment on the test nodes. The deployment was done in accordance with the instructions provided by the manufacturer. An illustration of the Qosium Scope GUI taken during pre-trials is depicted in Figure 18.



Measurement name: FRACTAL_T5_20220221

Technical name: FRACTAL_T5_20220221

Description: T5: one Jetson over AP

○ Single-point measurement

● Two-point measurement

Primary Measurement Point

Hostname or address: [redacted]

Secondary Measurement Point

Hostname or address: [redacted]

Figure 18 – Photo of Qosium Scope interface taken during pre-trials (illustrating two-point measurement of throughput between a test node and a server for a 100 MB file; IP addresses of probes are blacked out for the sake of ensuring network security).

6.2.3 DC power analyzer

To characterize the power consumption of the test devices we have employed the N6705B Direct Current (DC) power analyzer from Agilent/Keysight. The tool allows to configure the output voltage from 0 to 20 V and observe and record the current consumption with the sampling rate up to 50 000 samples per second. The accuracy of voltage configuration is below 0.1% and current measurement – below 0.1%. More information is available from [15]. For our tests the power analyzer was configured to operate in data logger mode to record the energy consumption profile of the test node through all phases of its operations. The collected data were further imported for post-processing in MATLAB. The test bed used for power consumption measurements is illustrated in Figure 19.

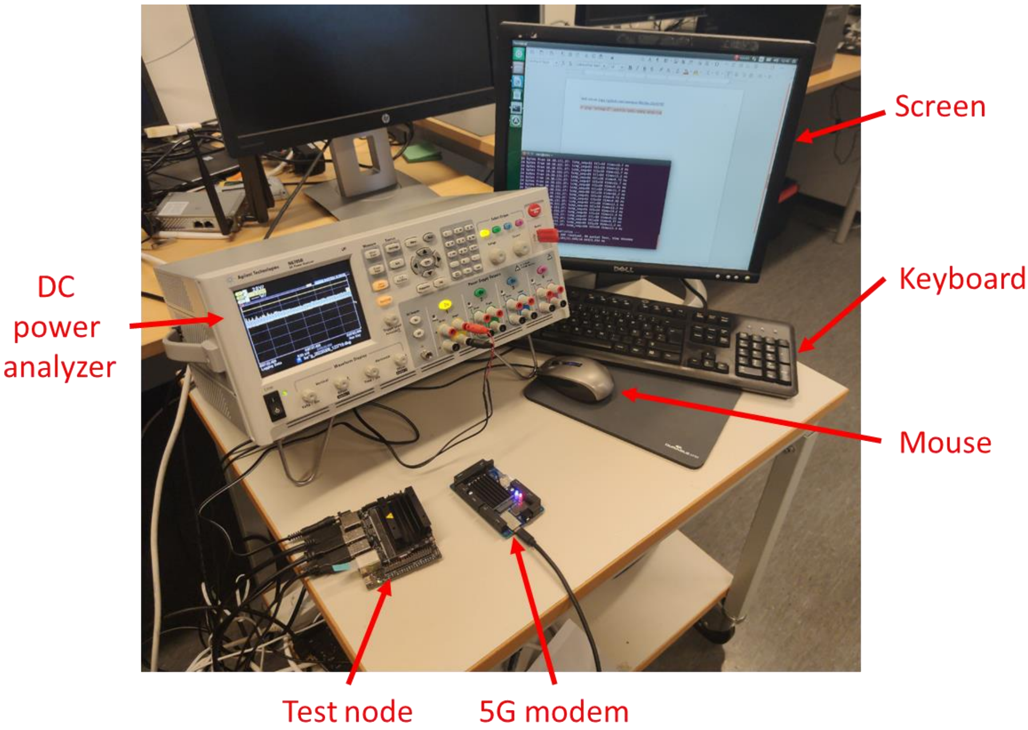


Figure 19 – Photo of test bed during power consumption measurement (for cellular (5G) communication)

Note, that to enable power consumption measurement the test device has to be connected and directly powered from the DC power analyzer. To enable for this, we have instrumented a cable allowing connection of the DC power analyzer directly to the barrel connector of the test node and modified the jumpers to make the test node operate from the supply provided to the barrel connector. Note, that the USB mouse and keyboard, used to control the test nodes, were powered from test node's USB interface and thus their consumption is included in the total measured value. On the other hand, the screen is equipped with own power supply unit and thus its consumption (except for the consumption for communication and current leakage through HDMI) is not accounted for. Similarly, for measuring the consumption of the AP we have instrumented another cable and connected the AP to the DC power analyzer directly.

6.2.4 Test laptop

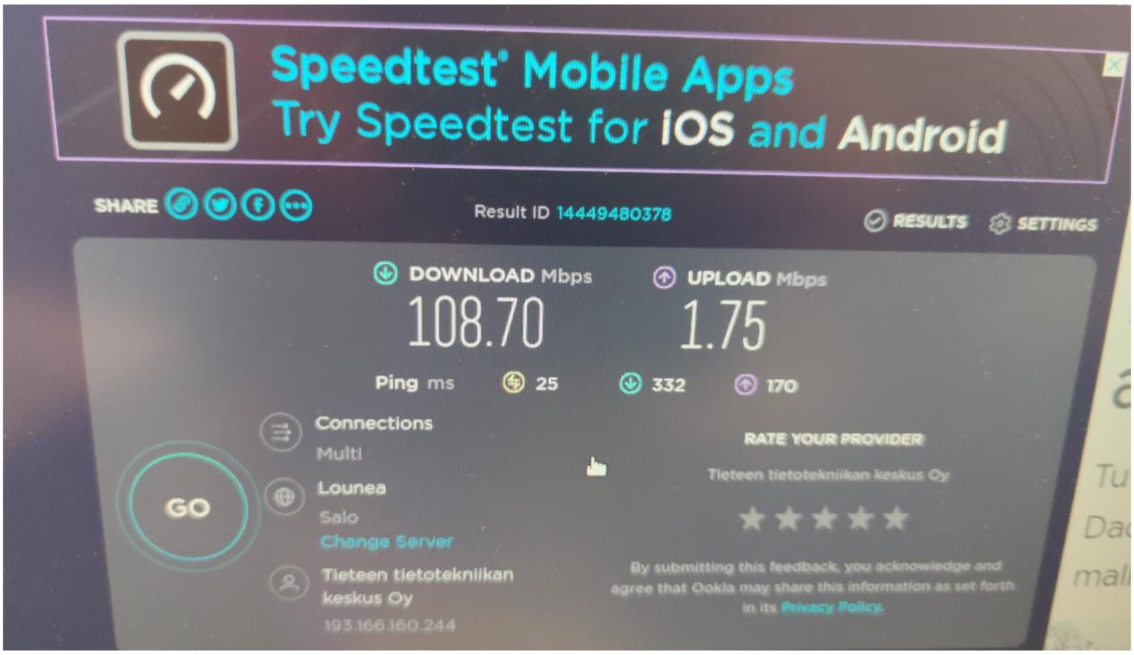
Some of the planned tests (i.e., IDs 5 and 6) required direct connection over Ethernet between the AP and an external computer. For these tests we used a battery powered notebook computer - the Lenovo ThnikPad T15 notebook with Intel Core i5 64-bit processor and Ubuntu 20.04.4 LTS operating system. The required ethernet drivers are installed by default in Lenovo computers. Thus, no other additional configurations are needed in this case. The local IP address of the notebook computer can also be obtained from the AP from the menu Basic Network > LAN & VLAN, once the notebook is connected to the AP via Ethernet. The required software components (see Table 6) were installed similarly to how this was done on the test node.

6.2.5 Portable power station

To carry out the measurements in different locations we had to address the issue of power supply. Therefore, the test bed during the tests was powered from EcoFlow 720Wh Pro Portable Power Station [16]. Each of the three AC power outputs can provide 600 W power, which is well above the expected consumption level of the test bed.

6.2.6 Speed test

For validating the connection and obtaining additional information about the performance of connectivity from a test device to Internet (note, that the main test points for the ten tests described above are located in the local network, radio access network of 5GTN, or in core network of 5GTN and thus these results are not directly comparable to the results, which can be obtained with the speed test), we have used a popular Internet speed test tool https://www.speedtest.net/. Speedtest GUI is shown in Figure 20.



By submitting this feedback, you acknowledge and agree that Ookla may share this information as set forth in its Privacy Policy.

Figure 20 – Photo of Speedtest interface taken during pre-trials

6.3 Time synchoronization

The System clock synchronization step is mandatory for those systems where applications rely on system clock to schedule traffic or present data. In our tests PTP was needed to ensure that the Qosium probes feature the same time reference. PTP is a protocol used to synchronize clocks in a network. The PTP-synchronized clocks are arranged in a master-slave hierarchy. The slaves are in sync with their masters which may be slaves to other masters. The PTP is a master-slave clock synchronization algorithm, which automatically builds and updates the hierarchy [18]. Several Linux distributions provide a package for Linux PTP. We use PTPd Linux package and installation of this package can be done from the following command.

-
  ```
  Sudo apt -y install ptpd
  ```

6.4 Traffic generation: SFTP

For the purpose of generating the traffic load, we also use Secure File Transfer Protocol (SFTP) which is a network protocol for securely accessing, transferring and managing large files and sensitive data over a Transmission Control Protocol (TCP)/IP network through port 22. An SFTP client and a server are also required for SFTP. Users can connect to a server and store files there using STFP client. The STFP server is used to store and retrieve files. When a user clicks a file, a request is sent over the network and eventually arrives at a server. The requesting device receives this data after that. Before being transferred, SFTP makes sure all data transfers are encrypted.

We use FileZilla software as the SFTP client. FileZilla is a free SFTP client software and can be downloaded from software center in a Linux OS. SFTP server installation can be done using following steps.

Step 1: Install Secure Shell Protocol (SSH)

-
  ```
  sudo apt -y install ssh
  ```

Step 2: Change SSHD configuration for SFTP group

-
  ```
  sudo nano /etc/ssh/sshd_config
  ```
- `paste the following lines at the end or bottom of the file`

```
Match group sftp
ChrootDirectory /home
X11Forwarding no
AllowTcpForwarding no
ForceCommand internal-sftp
```

Step 3: Restart SSH services

-
  ```
  sudo systemctl restart ssh
  ```

Step 4: Create SFTP users group

- `sudo addgroup sftp`

Step 5: Create a new SFTP user and set the password for this user

- `sudo useradd -m sftp_user -g sftp`
- `sudo passwd sftp_user`

Step 6: Grant full permissions to the specific directory

- `sudo chmod 700 /home/sftp_user/`

6.5 Testing

To ensure correct operation of the individual network components and of the whole testbed, as well as to ensure the integrity of the planned tests and their results, a set of pre-tests was carried. First, the elements of the testbed were tested independently to ensure stability of their operation. Next, three sets of pre-trials were organized during the three first weeks of February 2023 to validate interoperability and detect potential conflicts between the test bed components, familiarize with the tools used, their configurations and data formats, validate and tune the measurement procedures. During these trials all the critical deficiencies, capable to prevent execution of the measurement campaign, were detected and eliminated.

7 Validation

This section details our experiment environment and procedures.

7.1 Experiment environment

The measurements and experiments were executed in the 5GTN. This network is a full-scale micro-operator. It is a national Finnish joint effort of University of Oulu, Technical Research Center of Finland (VTT) and fifteen different industry partners. It is a complete 5G test system and worlds first open 5G test network. Currently 5GTN is an essential part of the 6G Flagship Program carried by the University of Oulu, Finland.

5GTN is designed and implemented to be scalable and to support various research and industry needs and experimentations. It has radio coverage in several locations in Finland: Oulu, Tampere, Ii, Sodankylä and Ylivieska. In Oulu there is radio coverage in the Oulu city center, University Hospital, VTT, Technology Park, University of Oulu and University of Applied Sciences campuses and also industry research and development premises in Rusko. The 5GTN structure and its key elements are depicted in Figure 21.

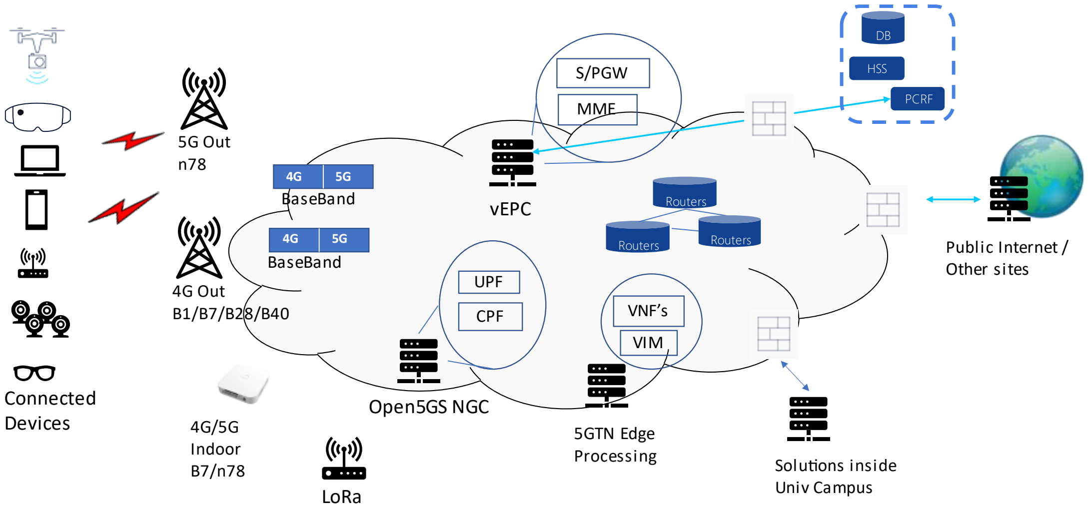


Figure 21 – 5GTN structure and key elements

The main features of 5GTN include:

- Uses both non-standalone (NSA) and standalone (SA) 5G architecture allowing dual connectivity where compatible devices can utilize both LTE and New Radio (NR) access
    - Support for both 4G and 5G connections through 4G and 5G Base Stations

- Own SIM cards
- Core network implemented in cloud environment
- Possibility to utilize four different Evolved Packet Core (EPC)'s:
    - EPC (CMM17)
    - OpenEPC
    - Cumucore EPC
    - Open5GS
- Bluetooth based tracking system with 200 nodes
- LoRa network
- WiFi and IoT networks
- 400+ IoT sensor platform operational at the campus[5]
- Energy consumption / production measurement environment
- Both centralized and distributed computing servers and GPUs
    - Edge servers available
    - Multi-access Edge Computing (MEC)
- Frequencies in use:
    - 700MHz (B28) Bandwidth (BW)=10MHz
    - 2100MHz (B1) BW=10MHz
    - 2300MHz (B40) BW=20MHz
    - 2600MHz (B7) BW=20MHz
    - 2600MHz (B7) BW=10MHz
    - 3.5GHz (n78) BW 60MHz
    - 26GHz (n258) BW 825MHz
- Base Stations and antennas:
    - Three 5G Macro cells (n78)
    - Indoor 5G radios (n78)
    - One 5G mmW cell (n258)
    - Macro cell (B28) with NB-IoT and Cat-M
    - Macro cell (B7), LTE-FDD
    - Macro cell (B40), LTE-TDD
    - 20+ Pico Base Stations (both B1 and B7) on air
    - 10+ Pico Base Stations available/in use for different tests

5GTN is an essential part of the 6G Flagship Program as thus is to evolve from 5G Test Network to 6G Test Network in 2023 and onwards. 5GTN has been, still is and also will be under constant development and evolution towards more comprehensive 5G and future 6G Test Network. Current plans include but is not limited to following technologies:

- Introduction of mmW technology in FR2 in several phases
    - Indoor first (February 2023)
    - Outdoor in second phase (2023)
- Newest UE's available: smartphones, modems, routers, sensors
- Renewal of 5G base stations (baseband and radios) for improved performance
- 5G core renewal

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[5] https://smartcampus.oulu.fi/manage/

- cRAN/o-RAN capable HW (under implementation)
- Introduction of larger OAI (Open Air Interface) capability (under implementation)
- Introduction of newest mobile edge computing and its application technologies
- 100Gbit/s backbone network
- SDN based core network infra
- Enlarge 5G coverage in the Oulu area
- More dynamic 5G network slicing

For the experiments discussed below the main 5G Macro three-cell base station operating in n78 frequency band as 5G NSA and employing TDMA, was employed. The available resources include 10 MHz spectrum for 4G and 60 MHz spectrum for 5G. The antenna tower hosting the antennas of the base station and its environment are depicted in Figure 22. The overall experiment environment and test locations are shown in Figure 23. The shortest ground-level distance from the location of antenna to the test position for test IDs 1-6 is about 61 meters, and for test IDs 7-10 – about 48 meters.

Figure 22 – Antenna tower of the University of Oulu hosting the 5GTN base station's antenna used in the tests.

Figure 23 – Bird's view on the experimental location (orange triangle denotes the position of 5GTN base station's antenna, green circle marks the test location for tests ID 7-10, and purple circle signalizes the test location for tests 1-6.

7.2 Measurement procedures

Recall, that we have three target topologies, as described in Section 5. For each of these topologies we considered two subcases. The first one (odd test IDs) implied two test nodes communicating with each other, while the other one (even test IDs) implied a test node communicating with a test server (TS). Altogether we considered six measurement scenarios; and for two topologies the measurements were carried in two different radio channel conditions – with direct LoS to 5G antenna, and in heavy indoor propagation; thus, resulting in 10 tests carried in total. For each of the measurement scenarios we performed two types of measurements. The first one focused on estimating the delay (subtests x.a and x.b, x=1..10) and was carried using *Ping* command, and the latter one addressed throughput and was done using SFTP server and client (subtest x.c, x=1..10).

- For measuring the delay, the ping command was used as:
  sudo ping <secondary probe local IP> -s <size in bytes> -c <number of pings>
- For throughput measurements the SFTP server (located wither at the server at Edge or on another test node, depending on the test) has been used. First, the client established the connection to the server. Next, a test file was uploaded to the SFTP server. After completing, the very same file was downloaded by the client from the server. The SFTP client was controlled through its GUI.

The general measurement procedure for each test is composed of the following steps:

Step 1: Power up the test devices and give them time to boot up;

Step 2: Enable PTP time synchronization for accurate timestamping:

Substep 2.a: At PTP master execute command: *sudo ptpd -I <interface> –masteronly -U -u <slave IP1> <slave IP2> -C*; where <interface> is the identifier of the interface used (can be obtained with command ifconfig) and <slave IPi> is the IP address of a slave PTP client;

Substep 2.b: At each PTP slave execute command: *sudo ptpd -I <interface> –slaveonly -U -u <master IP> -C*; where <interface> is the identifier of the interface used (can be obtained with command ifconfig) and <master IP> is the IP address of a master PTP;

Step 3: Launch measurement in Qosium Scope:

Substep 3.a: Select the Two-port measurement in Qosium Scope Probe Setup section in Probes tab.

Substep 3.b: Enter an appropriate test name and description of the test in Qosium Scope Measurement Info section in Probes tab.

Substep 3.c: Enter the local IP address of the test node in Qosium Scope Primary Measurement Point section Probes tab. (Note: depending on the test to run, the IP address should be obtained either with *ifconfig* commend or by checking the GUI of AP)

Substep 3.d: Enter the IP address of the TS in Qosium Scope Secondary Measurement Point section in Probes tab. (Note: depending on the test to run, the IP address should be obtained either with *ifconfig* command or by checking the GUI of AP)

Substep 3.e: Click on the Connect to Qosium Probe in Measurement Control section in Qosium Scope.

Substep 3.f: Select the correct primary probe and secondary probe network interfaces from Topology tab in Qosium Scope and leave all the other settings as default.

Substep 3.g: From Measurement tab, chose the Packet filter mode to manual filter and configur the manual filter between test node (local IP) and the target node. Leave all the other settings as default.

Substep 3.h: In Qosium Scope Results tab, enable the "get packet results" and enabled all the options in Save to File Settings section.

Substep 3.i: Click on start measurements in Qosium Scope Measurement Control section.

Step 4: Perform the Speed test (see Section 6.2.6) at DUT1 and log the results;

Step 5: Use *traceroute* to check the route between the test nodes (i.e., DUT1 and DUT2/TS) and log the results;

Step 6: Measure the radio channel conditions and log the results;

  - For tests IDs 3,4,5,6,9 and 10 – check the GUI of the AP (some parameters such as RSSI each device connected to AP through WiFi can be seen from Basic Network > WiFi > WiFi client list in router's web UI.)
  - For test IDs 1,2,7 and 8 – the RSRP, RSRQ, SINR and RSSI measurements were obtained by executing first:
    sudo socat - /dev/ttyUSB2,crnl
    where /dev/ttyUSB2 denotes the USB port to which the 5G modem is connected, and then AT command:
    at+qeng="servingcell";+qnwinfo;+qsinr;+qrsrq;+qrsrp;+csq
    Examplary results of this command's execution are depicted in Figure 24. Note, that to get the physically meaningful values, the returned by the command results have to be further processed as discussed in [20].
- Step 7: Start the experiment (either latency or throughput, as discussed above);
- Step 8: During the execution of the experiment the experiment notes were filled containing the timestamps of the measurement, the observed throughput and other relevant notes on experiment run;
- Step 9: After the end of experiment log the results (i.e., start/end time and total time required for transferring the test file in uplink/downlink as reported by SFTP client, or log the results of executing *ping* command);
- Step 10: Stop the measurement in Qosium Scope;
- Step 11 (done after all the measurements are completed): Copy the logs and collected by Qosium results and store them for further processing.

```
>>sudo socat - /dev/ttyUSB2,crnl
>>[sudo] password for cwc:
>>at+qeng="servingcell";+qnwinfo;+qsinr;+qrsrq;+qrsrp;+csq
        at+qeng="servingcell";+qnwinfo;+qsinr;+qrsrq;+qrsrp;+csq
        +QENG: "servingcell","NOCONN"
        +QENG:"LTE","FDD",<MCC>,<MNC>,<cellID>,<PCID>,3000,7,3,3,89,-61,-
        8,-37,19,15,60,-
        +QENG: "NR5G-NSA",<MCC>,<MNC>,<PCID>,-65,32,-11,636000,78,8,1
        +QNWINFO: "FDD LTE","<OPER>","LTE BAND 7",3000
        +QSINR: 26,26,29,32,NR5G
        +QRSRQ: -10,-10,-10,-10,NR5G
        +QRSRP: -75,-65,-63,-68,NR5G
        +csq: 31,99
OK
```

Figure 24 – Listing of exemplary at+qeng="servingcell" command results showing the status of the 5G connection and encoded RSSI, RSRP, RSRQ and SINR values (Note: the network-specific values of identifiers <MCC>,<MNC>,<cellID>,<PCID> and <OPER> were removed for information and network security reasons.)

Figures 25-31 present the photos illustration the test bed and environment, which were taken during the tests.

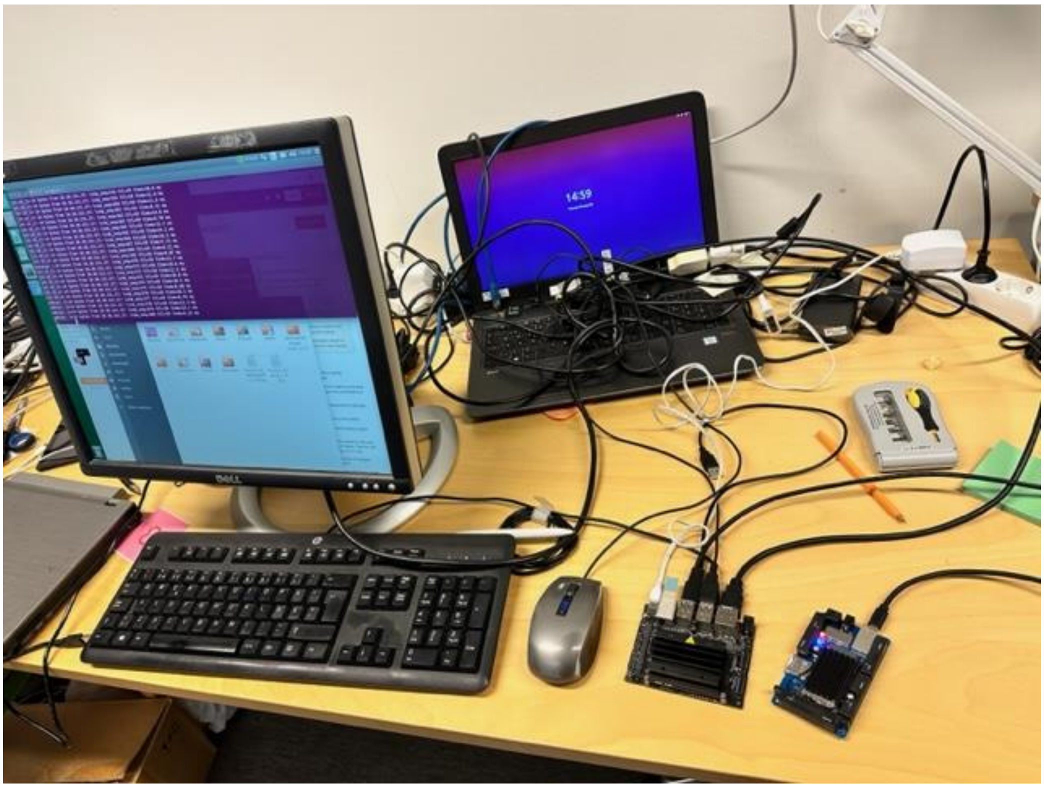

Figure 25 – Test bed during Test ID 1

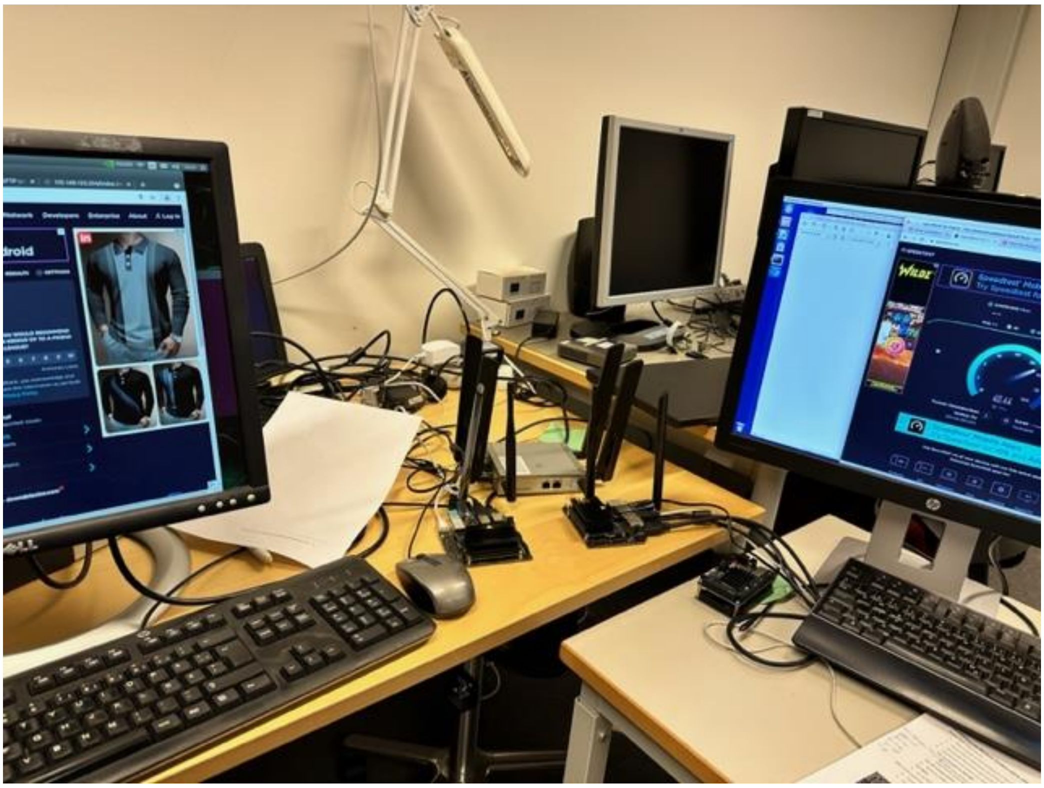

Figure 26 – Test bed during Test ID 4

Figure 27 – Test bed during Test ID 5

Figure 28 – Test bed during Test ID 6

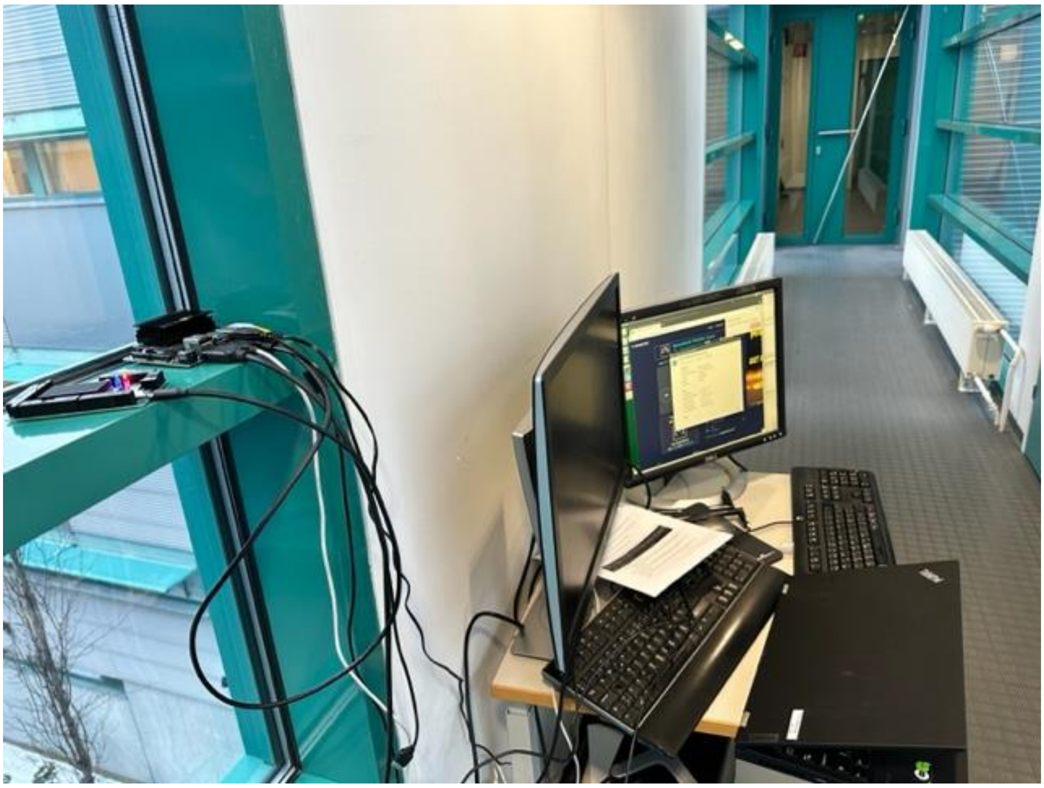

Figure 29 – Test bed during Test ID 7

Figure 30 – Test bed during Test ID 8

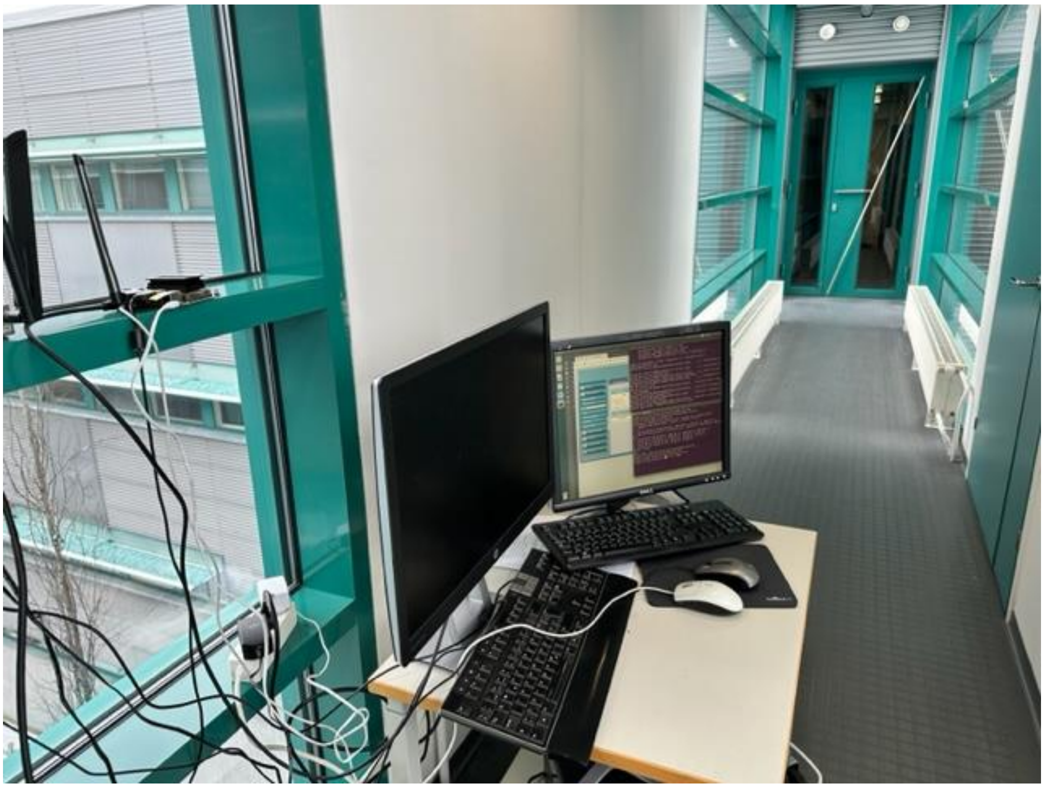

Figure 31 – Test bed during Test ID 9

8 Results

Each of the three following subsections focuses on one single key performance indicator – the maximum throughput, the minimum delay and the energy consumption. Meanwhile, Table 7 summarizes the radio-channel related metrics for each of the tests done. For cellular (5G) communication the table includes the data for SINR, RSRQ, RSRP and RSSI. For the three former metrics the results are provided for four antennas: primary receive (RX) (PRX), diversity RX (DRX), MIMO RX2 and MIMO RX. Also, a single RSSI value is reported. For the cases when communication was done using IEEE 802.11, the RSSI values for two antennas are listed. From the presented results this can be seen that for IEEE 802.11 the minimum signal level during the tests was in the order of -12 to -23 dBm, which suggests very good channel, which allows to use the fastest modulation-coding schemes. For cellular (5G) the level of the signal was around -100 dBm in case of indoor tests (test IDs 1 and 2) and -66 to -75 dBm for LoS tests (test IDs 7 and 8). This denotes [21] excellent channel conditions for LoS and mid-cell to cell edge conditions for indoor tests. This can also be seen that the radio conditions have been decently stable and similar within each group of tests.

Test ID	SINR (dB)				RSRQ (dB)				RSRP (dBm)				RSSI (dBm)	
	PRX	DRX	RX2	RX3	PRX	DRX	RX2	RX3	PRX	DRX	RX2	RX3	RSSI0	RSSI1
1.a	15	0	2	-1	-10	-13	-12	-16	-98	-100	-98	-117	-71	Not supported
1.b	15	1	3	2	-10	-14	-12	-12	-98	-101	-100	-108	-71	
1.c	15	-7	5	8	-10	-13	-11	-11	-98	-102	-95	-105	-71	
2.a	-1	-3	-2	3	-17	-14	-16	-11	-112	-101	-108	-99	-75	
2.b	1	2	2	9	-14	-13	-12	-11	-108	-100	-100	-96	-75	
2.c	8	0	-3	12	-10	-14	-13	-11	-99	-98	-99	-100	-69	
3.a	Not supported for this topology												-15	-28
3.b													-16	-28
3.c													-15	-28
4.a													-15	-28
4.b													-16	-28
4.c													-15	-28
5.a													-16	-28
5.b													-13	-27
5.c													-13	-32
6.a													-12	-34
6.b													-12	-26
6.c													-12	-23
7.a	30	26	-20	-20	-10	-10	-10	-10	-66	-68	-68	-73	-51	Not supported
7.b	30	25	24	30	-10	-10	-10	-10	-66	-68	-69	-75	-51	
7.c	30	26	25	30	-10	-10	-10	-10	-66	-67	-68	-75	-51	
8.a	31	26	25	30	-10	-10	-10	-10	-67	-68	-68	-75	-51	
8.b	26	26	29	32	-10	-10	-10	-10	-76	-66	-63	-68	-51	
8.c	26	26	29	32	-10	-10	-10	-10	-75	-65	-63	-68	-51	
9.a	Not supported for this topology												-19	-22
9.b													-19	-21
9.c													-19	-22
10.a													-23	-27
10.b													-23	-27
10c													-23	-27

Table 7 – Radio channel related metrics measured during the tests

8.1 Throughput performance

Table 8 summarizes the average uplink and downlink data rate obtained through three different methods: the speed test (measuring Internet access speed to the closest server of a specialized subset – refer to [19] for more details; first two columns), the SFTP measurement (discussed in Section 7.2) and by analysing the measurement results of Qosium Scope for each test ID. For calculating the average throughput from Qosium results, these have been imported in MATLAB and further processed. The average throughput has been separately calculated over periods of uplink and downlink traffic, as illustrated in Figure 31.

Test ID	Average Speed Test Result (Mbps)		Average Throughput Result from SFTP client (Mbps)		Average Qosium Scope Results (Mbps)	
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
1.c	13,2	169,67	11,2	40	11,78	42,39
2.c	6,85	149,29	2,4	2,9	2.75	3.76
3.c	26,29	48,31	26,4	21,6	26,83	22,24
4.c	28,07	40,05	77,6	56	measurement impossible due to issues with IP visibility	
5.c	25,63	47,23	170,4	126	169	131,37
6.c	20,95	50,32	70,8	56	measurement impossible due to issues with IP visibility	
7.c	46,05	185,83	42,4	75,2	46,81	82,4
8.c	31,86	147,29	14,4	18,16	14,59	16,96
9.c	36,36	44,42	36,8	18	38	18,67
10.c	36,61	41,24	80	55,2	measurement impossible due to issues with IP visibility	

Table 8 – Summarized results showing average throughput for different test IDs

As we can see from the Table 8, average Qosium scope results closely follow the results obtained from SFTP client software; however, the results of speed test may provide substantially different results. Notably, in tests (e.g., IDs 1.c and 2.c) the speed test results were substantially higher than the results of the other measurement methods. On the other hand, for other tests (e.g., 4.c and 6.c) the throughput through SFTP transfer was higher than the speed test. The primary reasons for this difference are the different routing and the difference in the protocols used on top of the IP. Namely, during the speed test all the traffic is sent to the nearest internet gateway and from there to the test server, while in case of SFTP some test scenarios (e.g., ones involving IEEE 802.11 protocol and node-to-node communication – like test ID 6.c) imply data transfers through a local network. Also, for three cases (i.e., 4.c, 6.c and 10.c) this was not possible to obtain the results from Qosium due to the issue with visibility of IP addresses (i.e., the Qosium Scope was located in external network, while both probes were in local network beyond the AP; thus the Scope was unable to upkeep stable connection to the probes).

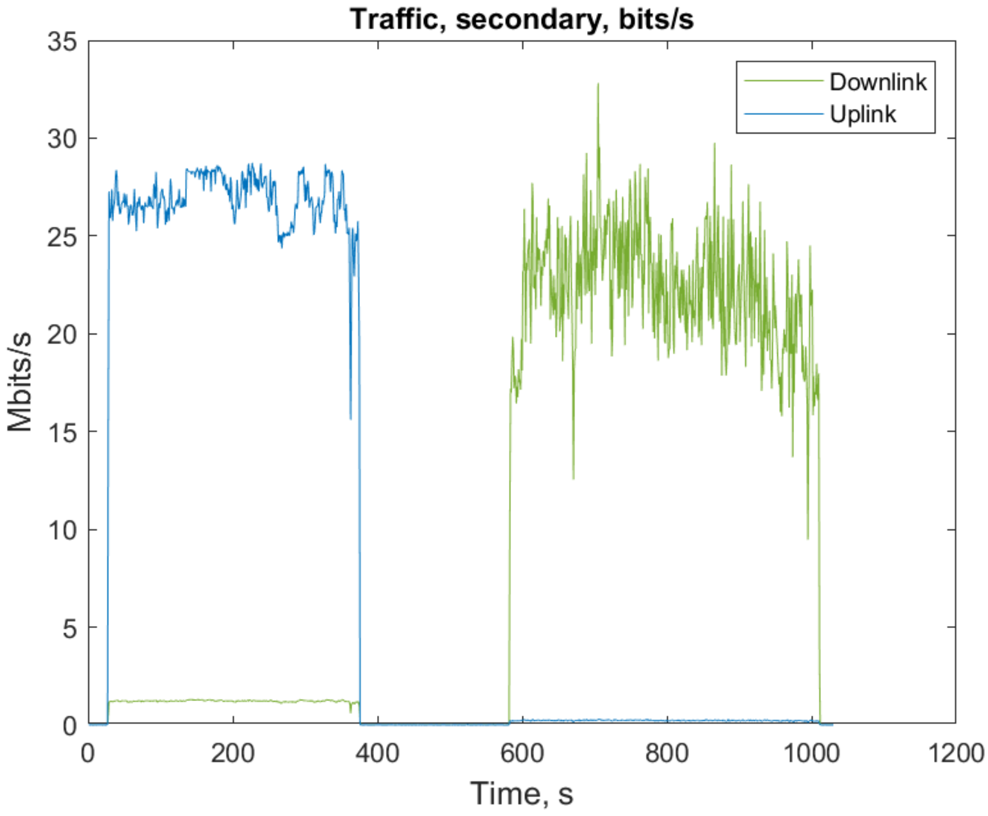

Figure 32 – Illustration of the throughput test traffic in Mbit/s from secondary Qosium probe (i.e., the FRACTAL node) for Test ID 3. The file is uploaded to remote SFTP server (high uplink traffic, small downlink traffic acknowledging reception) during the first phase, and then file is downloaded from SFTP server (high downlink traffic, small uplink traffic acknowledging reception) at the second phase.

From the presented results can be seen that for 5G only communication the maximum average throughput observed was 185 Mbps in downlink and 46 Mbps in uplink during the speed tests, and about 80 Mbps in downlink and 46 Mbps in uplink during SFTP tests. As already discussed, this difference is caused by (i) the different protocols used and (ii) different routing. The difference between the uplink and downlink performance is also expectable, since the 5GTN is configured in such a way that the available spectrum is allocated unequally for uplink and downlink; the amount of resources available for downlink exceeds that available for uplink.

From the results of test ID 2.c this can be seen that the throughput for communication between two nodes located under the same 5G base station is substantially lower than the throughput observed when a node is communicating to an upper tier node (i.e., the edge server). As has been already discussed in Section 3, the 5G communication does not support sidelink and thus in case of two 5G devices communicating to each other, all the traffic goes through a base station. Moreover, in case if two devices are located close to each other, both nodes might have to be served by the same beam, which may reduce the maximum throughput even more.

Also, this is worth noting that given the spectrum-resource-limited nature of the cellular network, the results of the tests may have been affected by the operation of other users.

Comparing results for test IDs 1 with 3, and 7 with 9 it can be seen that direct 5G connectivity allowed nodes to get higher throughput both in uplink and downlink compared to communication through an IEEE 802.11-5G AP. Also, comparing results for 1-4 with 7-10 one can see that the position of the test node relative to the base station plays a significant role and affects the experienced throughput, especially for uplink. Interestingly, the uplink throughput observed during the speed test measurement through IEEE 802.11-5G AP exceeded that for the nodes connected to 5G network directly. The reason for this might be the more efficient antennas of the AP, which enables it to use more advanced modulation-coding schemes.

From the results for test IDs 5 and 6 revealing the throughput for IEEE 802.11 WLAN connectivity, one can see that the uplink throughput reached 170 Mbit/s and downlink 130 Mbit/s. Notably, it can be noted that the throughput for IEEE 802.11 based communication between the two test nodes exceeded 70-80 Mbit/s in uplink and 50 Mbit/s in downlink. This supports the claim made in Section 3 that the WLAN-based connectivity is more efficient dealing with peer-to-peer communication, than the cellular connectivity. However, it is worth noting that this conclusion is valid only in the cases when the two nodes are (i) located close to each other and (ii) do not suffer from strong interferences. It can also be seen that the throughput performance for test IDs 4 and 10 are decently close to the results observed for test ID 6. This is not surprising, since in the presence of an AP with 5G backbone the 5G backbone link is not utilized when transferring the data between two devices connected to the same AP over IEEE 802.11 and thus the performance of connectivity is defined solely by the throughput of IEEE 802.11 technology.

Figures 33-38 present the plots of throughput obtained from Qosium for selected illustrative test cases, showing how these metrics have changed through the experiment. Though for the majority of the tests the throughput has been mostly stable, for other tests (e.g., IDs 2 and 8) there have been significant fluctuations in the observed throughputs.

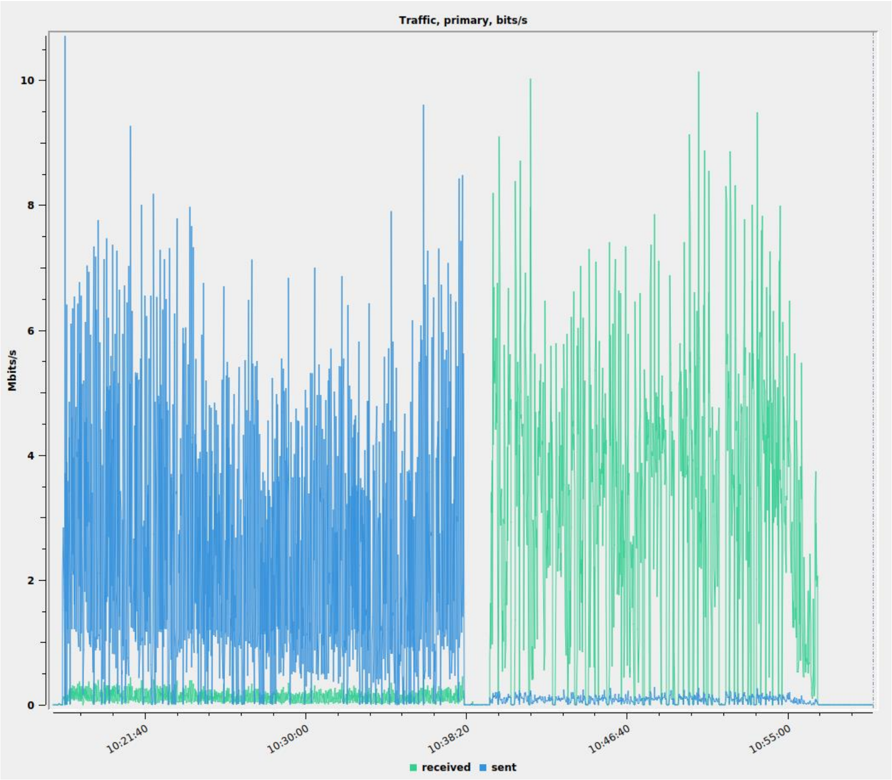

Figure 33 – Illustration of the throughput measured by Qosium Scope during Test ID 2.c

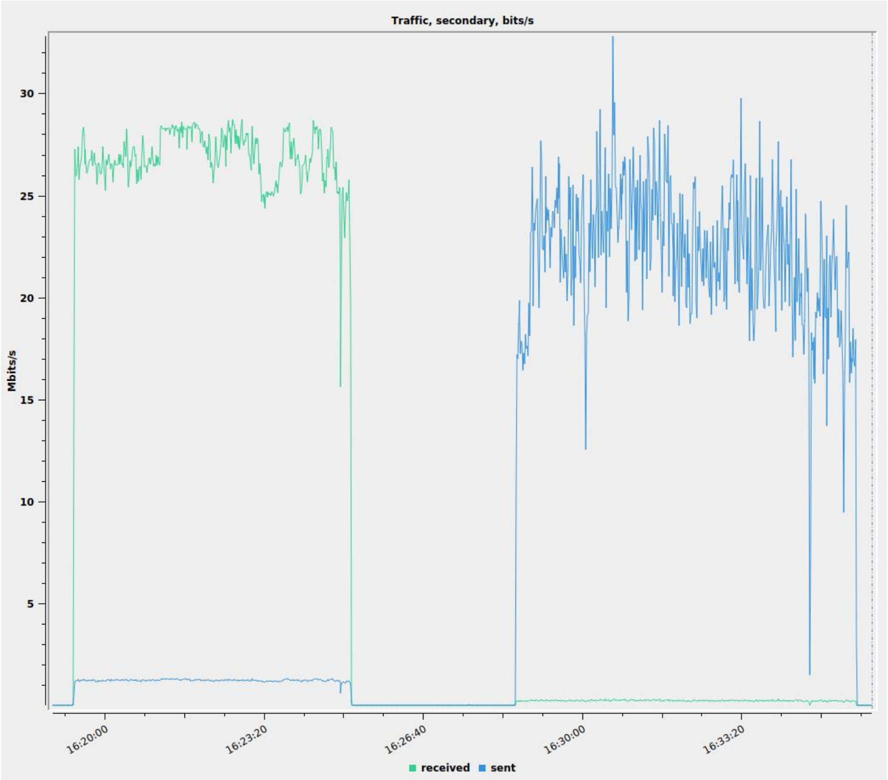

Figure 34 – Illustration of the throughput measured by Qosium Scope for Test ID 3.c

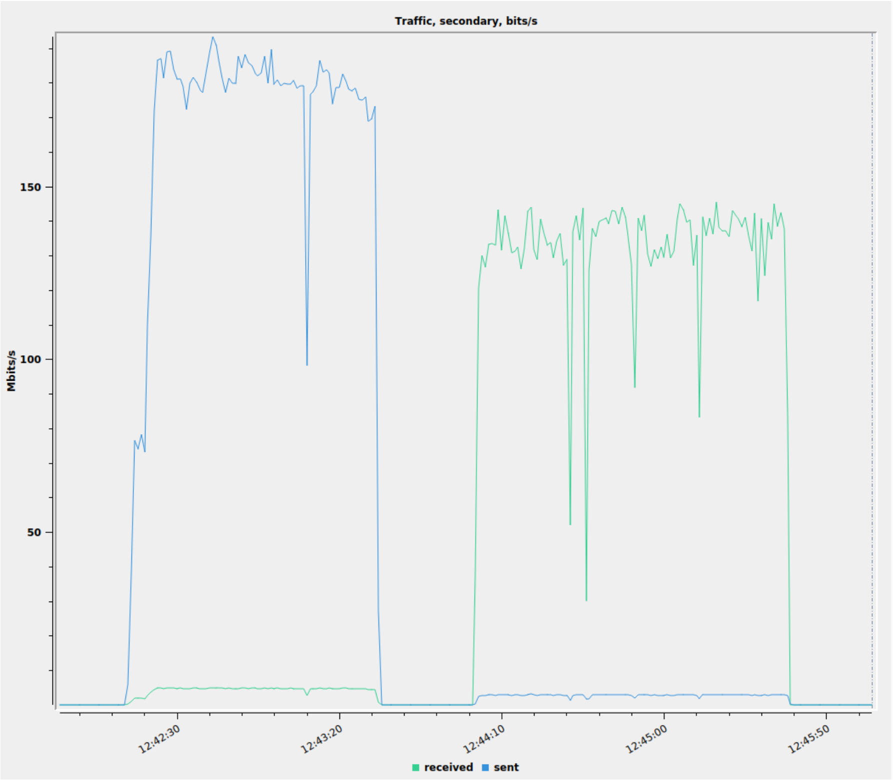

Figure 35 – Illustration of the throughput measured by Qosium Scope for Test ID 5.c

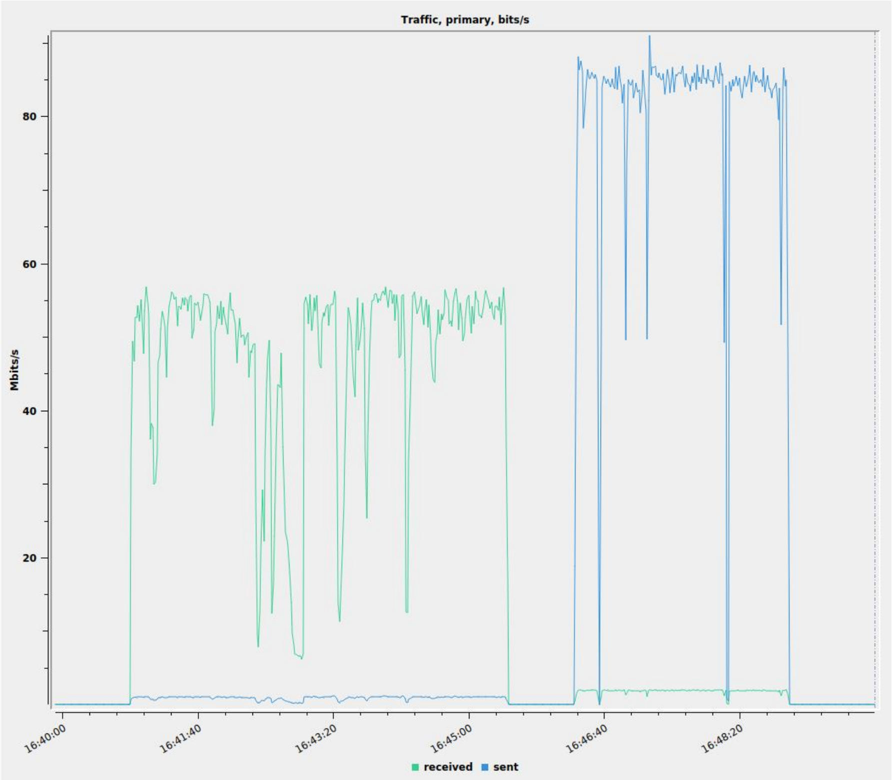

Figure 36 – Illustration of the throughput measured by Qosium Scope for Test ID 7.c

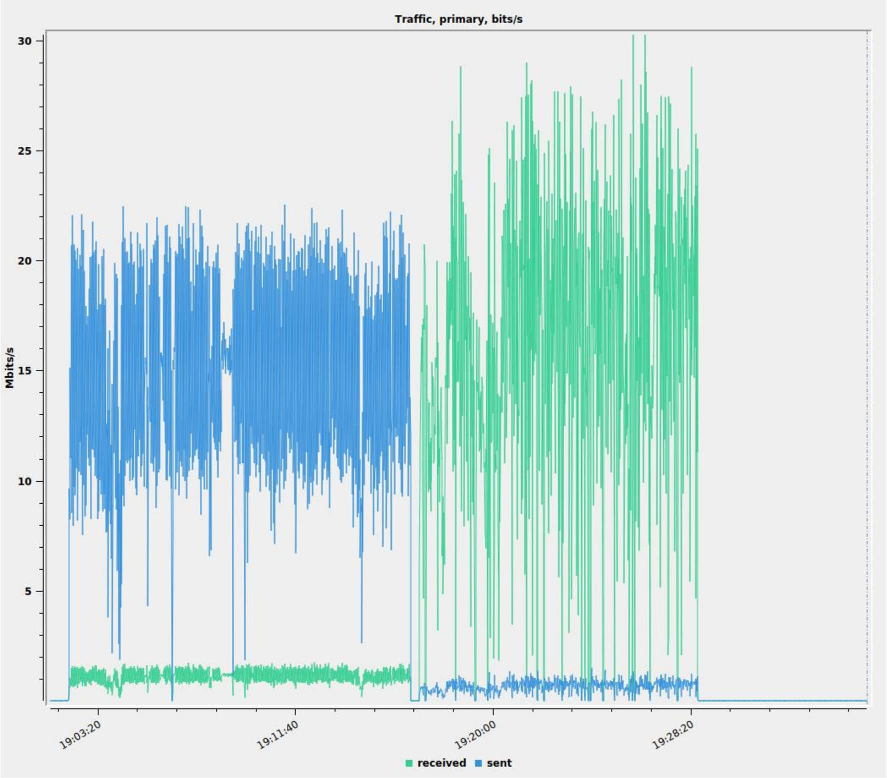

Figure 37 – Illustration of the throughput measured by Qosium Scope for Test ID 8.c

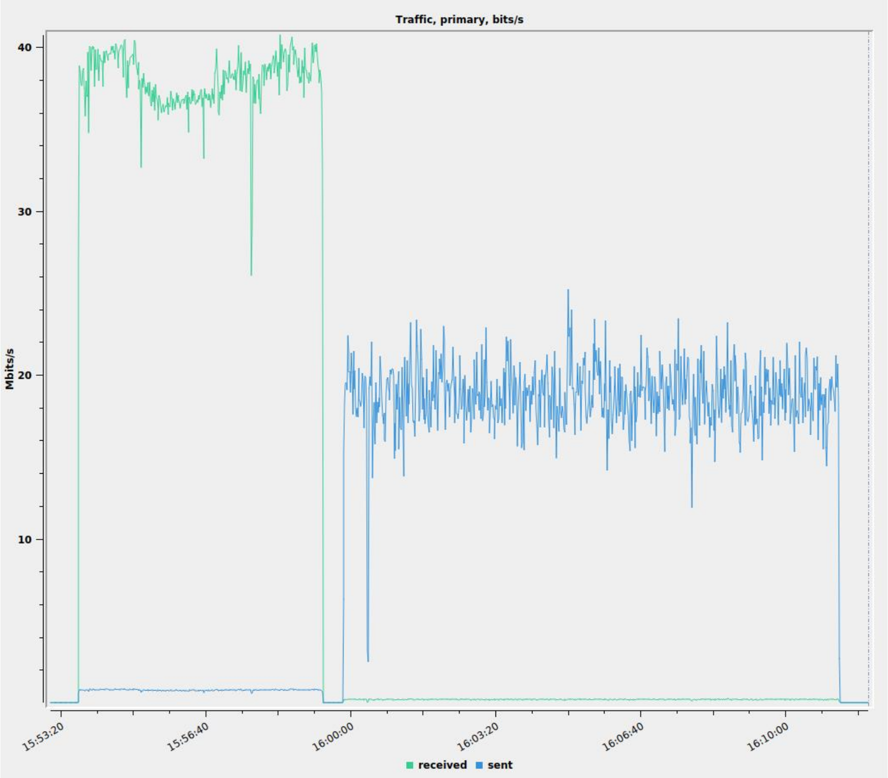

Figure 38 – Illustration of the throughput measured by Qosium Scope for Test ID 9.c

Overall, the results of the throughput tests lead us to the following conclusions:

- The cellular (5G) connection allows to obtain high throughput (e.g., 185 Mbps in downlink and 46 Mbps in uplink were observed) for the case when a test node communicated to an upper-tier node located in Internet (Cloud) or at the network Edge. The throughput available for two nodes interconnected through 5G and communicating between themselves over 5G is substantially lower (e.g., up to 18 Mbps in downlink and 14 Mbps in uplink were observed). Though the LoS to the base station is required to obtain the peak performance, we have seen in our experiments that also deep indoors with radio channel conditions close to cell edge enable sufficient throughput.
- The IEEE 802.11 communication also allowed to obtain quite high throughput (i.e., uplink throughput reached 170 Mbit/s and downlink 130 Mbit/s) when communicating to both upper-tier and same-tier nodes. Notably, it enabled reaching much higher throughput for communication between the same-tier nodes (70-80 Mbit/s in uplink and 50 Mbit/s in downlink for our test case). However, the performance of this technology can be affected by interferences and feature much more limited communication ranges, than those available with cellular technologies.
- Finally, the combination of the both approaches through utilizing an AP with 5G backbone and IEEE 802.11 local network resulted in quite a balanced solution, enabling a good throughput for both the communication of a node to an upper-tier node (done over cellular link, downlink throughput of 147 Mbps and uplink throughput of 32 Mbps), and between two nodes (over IEEE 802.11 link, 70-80 Mbit/s in uplink and 50 Mbit/s in downlink). This approach can be recommended for the clustered location of FRACTAL nodes.

However, it is important to make two notes. First, these results are average over a sufficiently long period of time, and we have observed that in short-term perspective the results might differ. Also, as we have observed, the obtained results depend on the location of the test nodes (e.g., in radio access network, Internet or in core cellular network), the traffic parameters and patterns (e.g., file size) and the protocol used. Second, one must note that the throughput performance is affected by the configuration of the network and its parameters (e.g., available resources and their distribution between uplink and downlink, and various logical channels for cellular, the version of the IEEE 802.11 protocol in use). Also, the performance strongly depends on the other users and external interferers. Therefore, the obtained results should be considered indicative rather than conclusive; and the focus should be paid more to the trends than the actual values.

8.2 Latency performance

Table 9 offers a summary of the results for latency measurements, combining the results obtained from *ping* commands showing the round-trip-time (RTT) with the delay measured by Qosium Scope tool in uplink (received) and downlink (sent) directions. Note, the results are presented for two different message payload sizes.

Test ID	Size of a mesage[6] (bytes)	Round-trip-Time (ms) reported by Ping				Qosium Scope delay measurement (ms)	
		Minimum	Average	Maximum	Mean Deviation	Average Received Delay	Average Sent Delay
1.a	24	7,336	11,897	30,798	2,331	6,96	6,19
1.b	908	11,189	17,309	122,911	5,608	7,43	6,99
2.a	24	14,692	24,202	1598,861	55,737	16,24	13,63
2.b	908	22,73	48,142	2089,212	130,567	18,58	14,73
3.a	24	13,361	24,958	44,06	4,469	Data unavailable	
3.b	908	20,484	34,219	63,844	5,373		
4.a	24	1,38	1,936	15,48	0,681	1,04	0,94
4.b	908	1,693	2,263	10,479	0,642	0,91	1,06
5.a	24	1,293	1,632	3,142	0,273	2,89	0,91
5.b	908	1,412	2,14	7,695	0,705	3,33	1,03
6.a	24	1,489	2,007	6,447	0,608	0,87	1,02
6.b	1008	1,796	2,563	11,871	0,83	1,3	0,95
7.a	24	7,636	11,856	27,22	2,371	6,83	5,78
7.b	908	10,928	16,528	31,741	2,728	7,55	5,77
8.a	24	14,461	20,429	36,084	3,186	11,96	11,77
8.b	908	20,169	29,911	44,859	3,364	12,88	12,77
9.a	24	13,806	24,092	72,038	4,046	Data unavailable	
9.b	908	20,792	31,252	45,046	3,704		
10.a	24	1,502	2,418	13,909	1,272	1,26	1,51
10.b	908	1,655	2,833	11,164	1,201	1,34	1,54

Table 9 - Round-trip-Time and average delay.

---

[6] including headers; the *ping* size argument was set to either to 10 or to 900 bytes.

The results for test IDs 1,2,7 and 8 reveal that for the nodes directly connected to cellular (5G) network the average RTT was 12 and 24 ms when communicating to an upper-tier node for packets of 24 and 908 bytes, respectively. For the direct communication between same-tier nodes connected over 5G the delay was about twice higher – 24 and 48 bytes, respectively. The results of Qosium Scope, which show the delay for uplink and downlink communication separately, enable to detail the results more. This can be seen that the delay is distributed not uniformly – the downlink delay is slightly (about 10%) lower than the uplink one. Comparing the results for indoor position of the test nodes (test ID 1) and LoS (test ID 7) this can be seen that for both cases the latency in uplink remain about the same, while for downlink LoS allows to get slightly lower latency, especially for the higher payload value. However, it can also be seen that the LoS condition also substantially reduces the mean deviation. Still, especially when the communication is between the nodes of the same level the deviation of the RTT is quite high: 55 and 130 ms for test IDs 2.a and 2.b, respectively.

It can be seen that the communication using short-range IEEE 802.11 technology (test cases 5 and 6) demonstrates lower latency, than communication over a long-range cellular network. The difference is especially notable for the case when two same tier nodes communicate between themselves. For example, comparing the results of test IDs 6 and 8, one can see that while IEEE 802.11 enables one-way delay around 1 ms, the cellular (5G) delay is around 12-13 ms. It is also worth noting that the mean deviation for RTT over IEEE 802.11 links is also very low – well below 1 ms. It can also be seen that the increase of payloads from 10 to 900 bytes resulted in a decently small increase of latency of less than 0.5 ms.

The combination of the two technologies and use of an AP (test IDs 3,4,9 and 10) shows somewhat contradictive trends. On the one hand, when communication is done to an upper-tier node (test IDs 3 and 9) the RTT exceeds that for the 5G only link (test IDs 1 and 7) by more than 10 ms. This is caused due to the need or using two wireless legs (i.e., test node -> AP -> 5G base station) based on the different technologies, as well as due to the need to relay the packets between the two radio transceivers inside the AP. Not surprisingly, this also results in higher deviation of the latency compared to the 5G-only based communication. However, communication between the two nodes of the same tier is done using the IEEE 802.11 technology and thus the latency is of the same order as for IEEE 802.11-only scenario.

Figures 39-46 present the plots of delay obtained from Qosium for selected illustrative test cases, showing how the delay changed in time throughout the experiment. It can be seen that when the cellular network is used in indoor environment, the delay may undergo through substantial sudden temporal fluctuations. This needs to be accounted for, when developing the real-time and delay-critical applications.

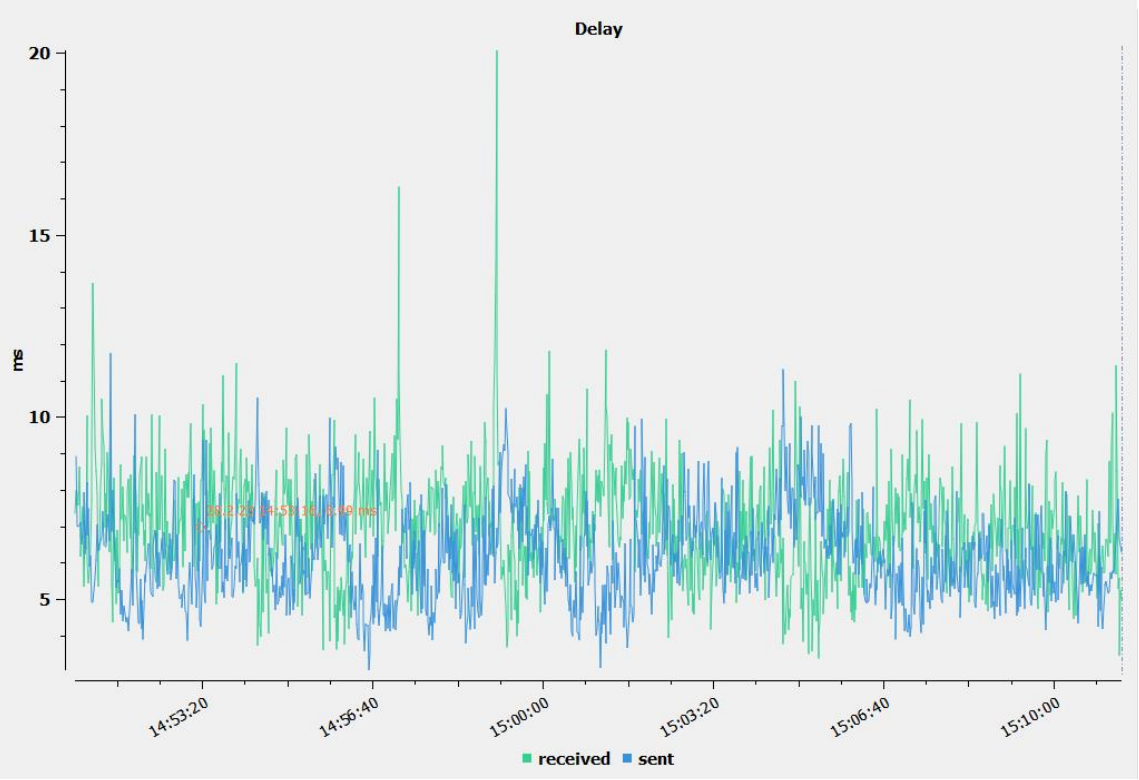

Figure 39 – Illustration of the delay measured by Qosium Scope for Test ID 1.a

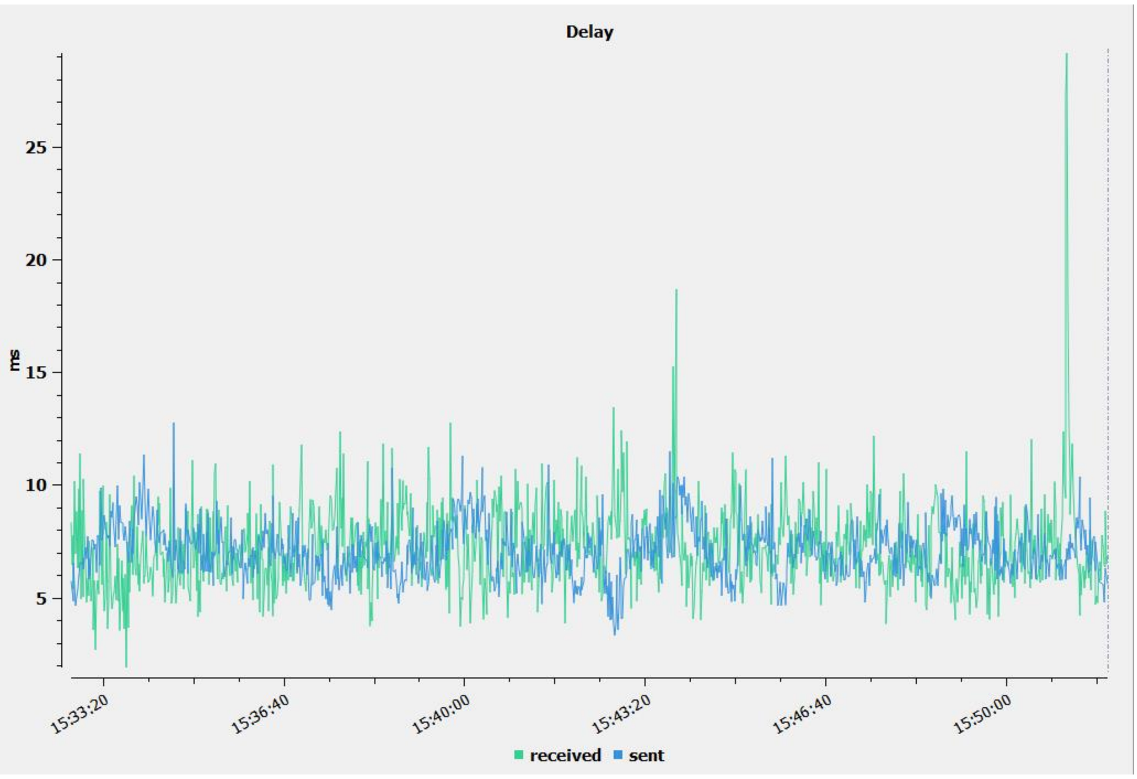

Figure 40 – Illustration of the delay measured by Qosium Scope for Test ID 1.b

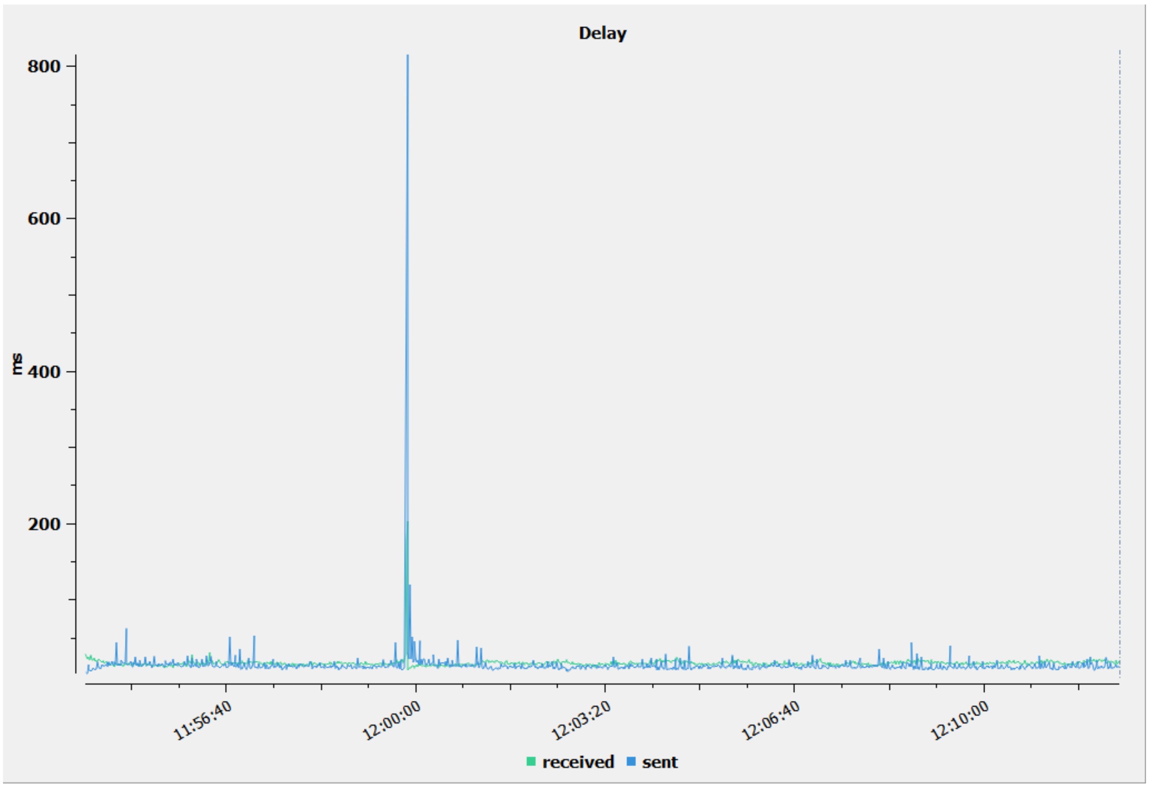

Figure 41 – Illustration of the delay measured by Qosium Scope for Test ID 2.a

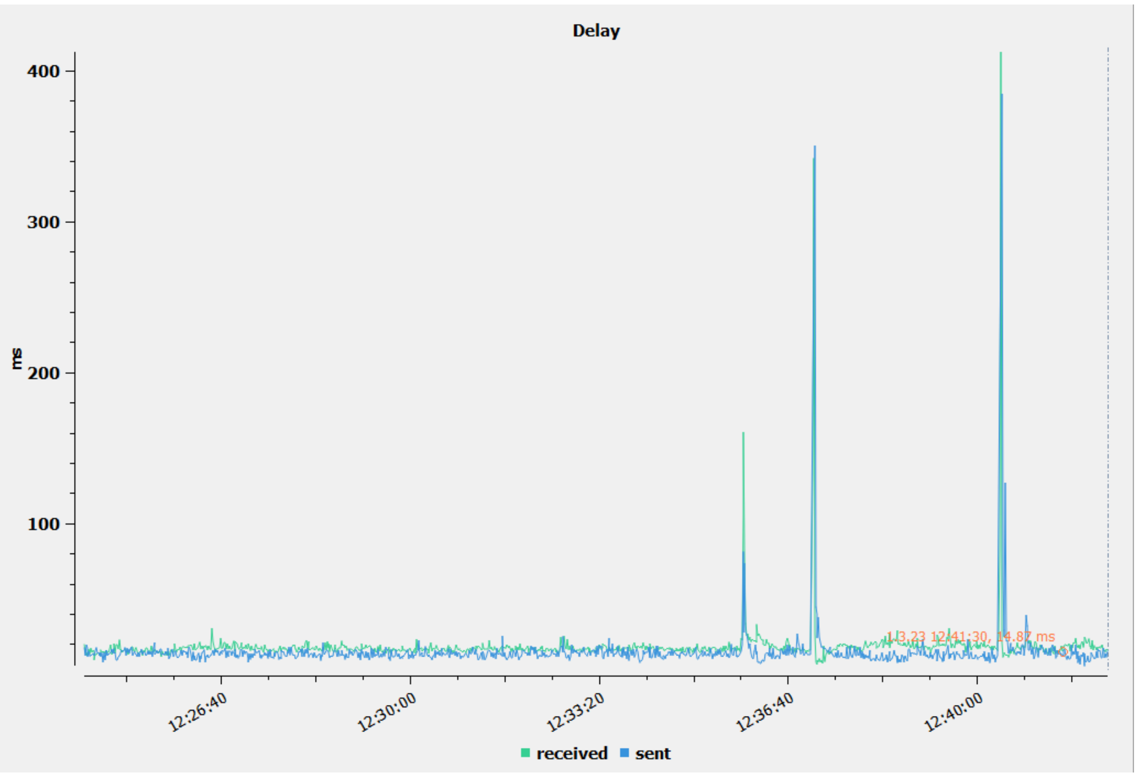

Figure 42 – Illustration of the delay measured by Qosium Scope for Test ID 2.b

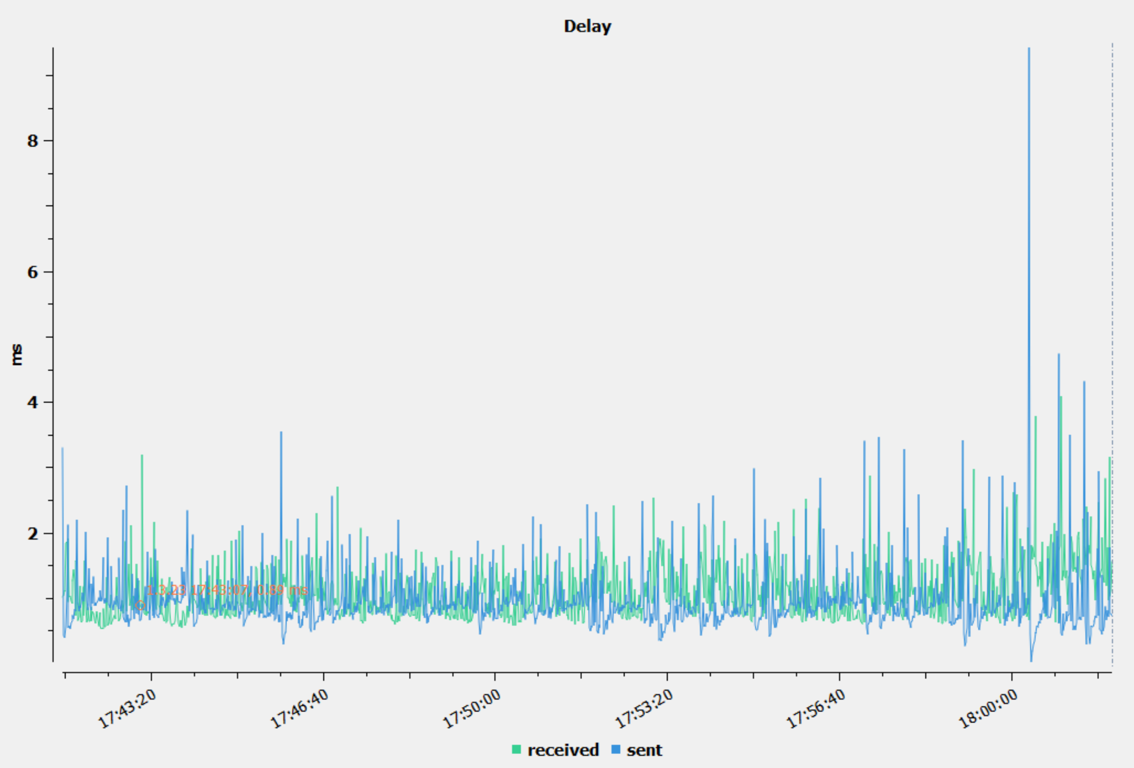

Figure 43 – Illustration of the delay measured by Qosium Scope for Test ID 4.a

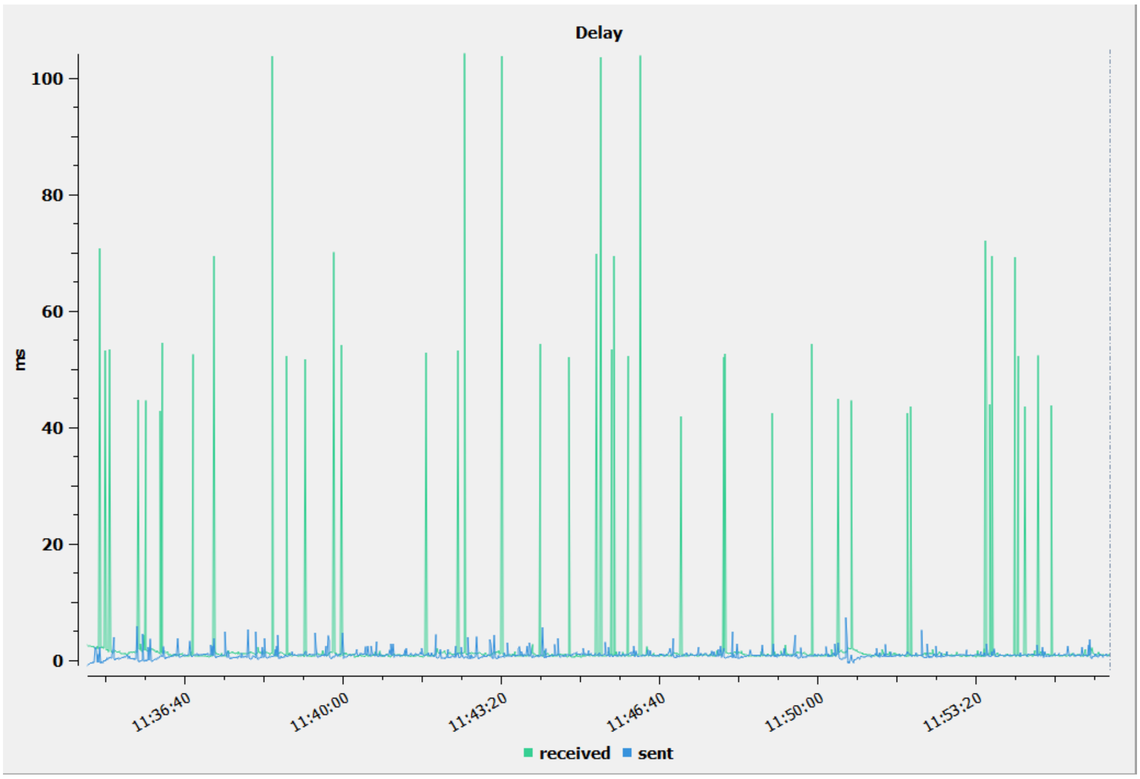

Figure 44 – Illustration of the delay measured by Qosium Scope for Test ID 5.a

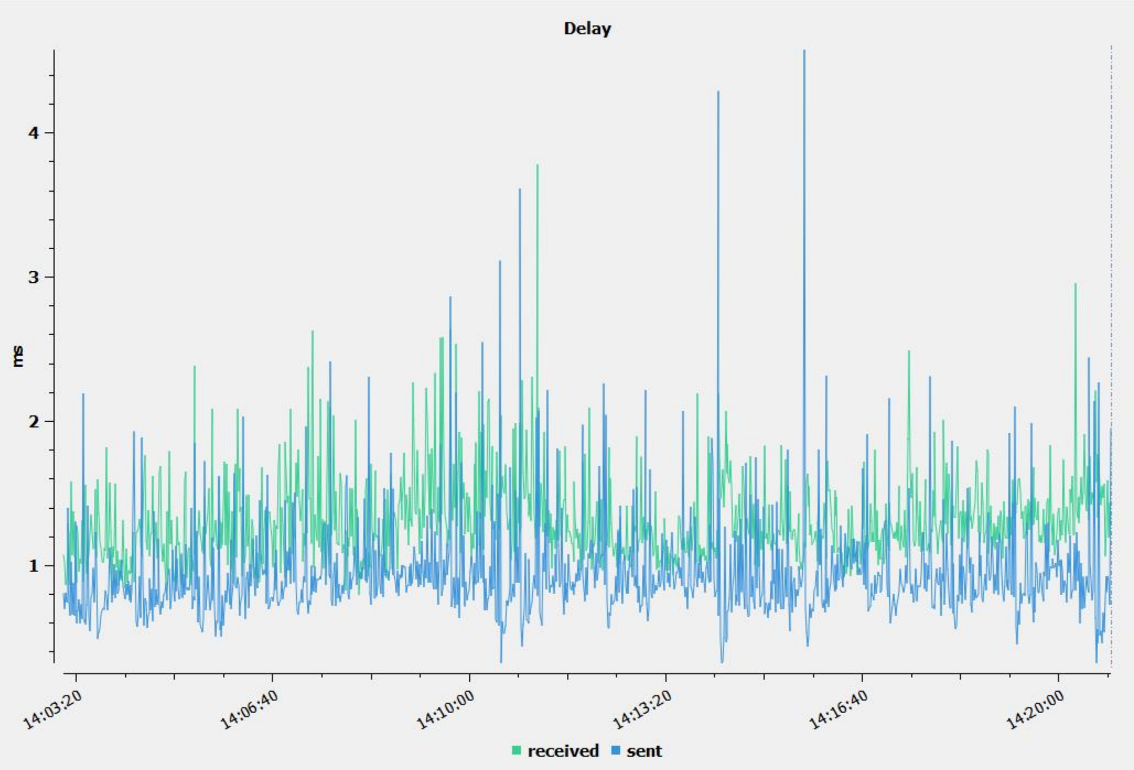

Figure 45 – Illustration of the delay measured by Qosium Scope for Test ID 6.b

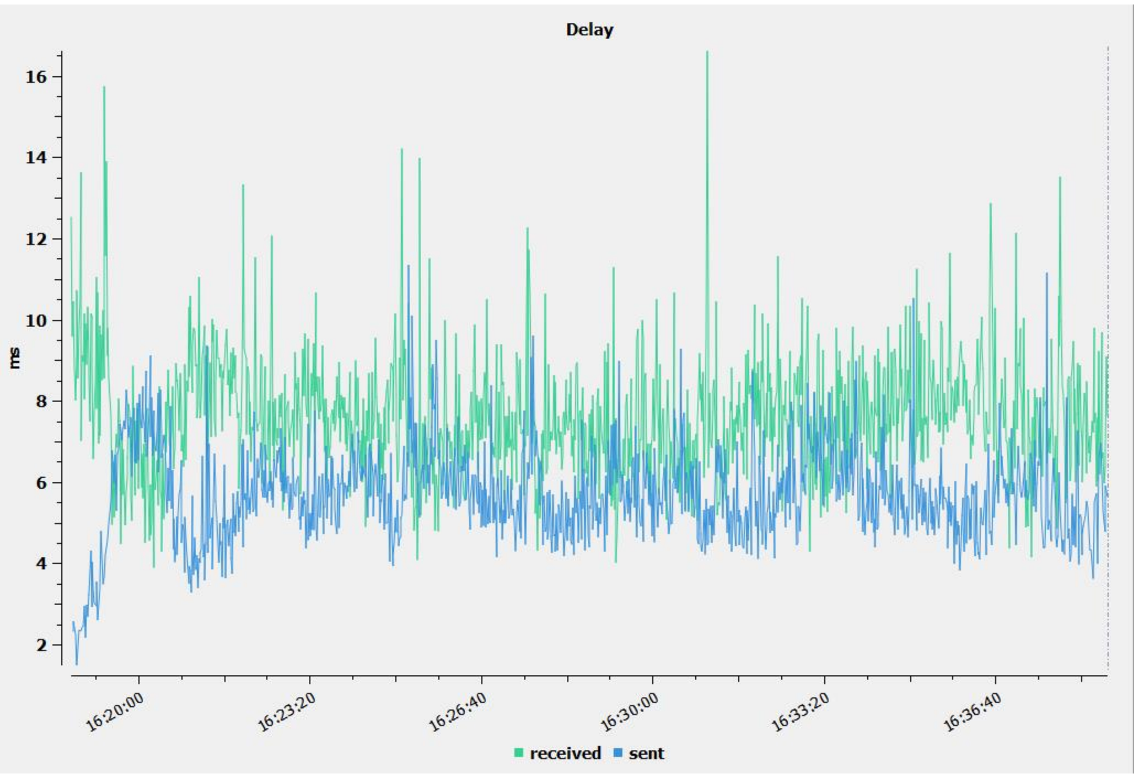

Figure 46 – Illustration of the delay measured by Qosium Scope for Test ID 7.b

Overall, the following conclusions can be made based on the obtained results:

- The cellular (5G) connection enabled one-direction communication latencies in the order of 6-8 ms for nodes communicating to an upper-tier node, and of 12-18 ms for same tier node communicating. For indoor position of the nodes the latency also suffered from substantial fluctuations, which could result in accidental delay of hundreds millisecond order. Under LoS position to the cellular base station the deviation of the latency has substantially reduced.
- The IEEE 802.11 communication enabled low communication delays of around 1 ms for both tested scenarios. The deviation of the latency was also rather low – well below 1 ms.
- Finally, for communications through the AP for same-tier nodes the latency is similar to that of the IEEE 802.11 technology case. For the case of communication to an upper-tier node, the latency exceeds that of the direct 5G-based connection by more than 10 ms and approaches 12-18 ms one way.

As already noted in Section 8.1, the presented results should be considered indicative rather than conclusive and the focus should be paid more to the trends than the actual values.

8.3 Energy consumption performance

Finally, Table 10 provides some insight into the power consumption of the node for communication. Moreover, Figures 47-50 illustrate the current consumption profile of the test node for different topologies measured by the DC power analyzer with the different phases of the experiment marked.

Average power consumption in Watts									
Refe-rence	Direct 5G connection			WiFi connection			AP		
	overall	Ping test	Speed test	overall	Ping test	Speed test	overall	Ping test	Speed test
2,3895	5,141	4,5536	9,3772	3,3897	2,9296	5,5021	3,8038	3,6845	5,1333

Table 10 - Average power consumption

Figure 47 illustrates the power consumption of the reference case. During this measurement the test nodes was not connected to any radio transceiver (i.e., neither the 5G modem, nor the WiFi dongle). Note that all the other peripherals (i.e., mouse, keyboard, and the screen) were connected to the node. During the measurements, the power logger was first started, then the power was applied to the node for it to boot up, then no commands have been given to the node until second 549 from the start of experiment, when the command for powering down the node was issued using the mouse and the GUI of the node. Further, the power was disconnected from the node and the logger was stopped. This offers a reference, allowing to estimate the background consumption of all the components of the node except for the radio transceivers. Interestingly, it can be seen that though no operations have been done with the node, there were some consumption peaks due to internal processes.

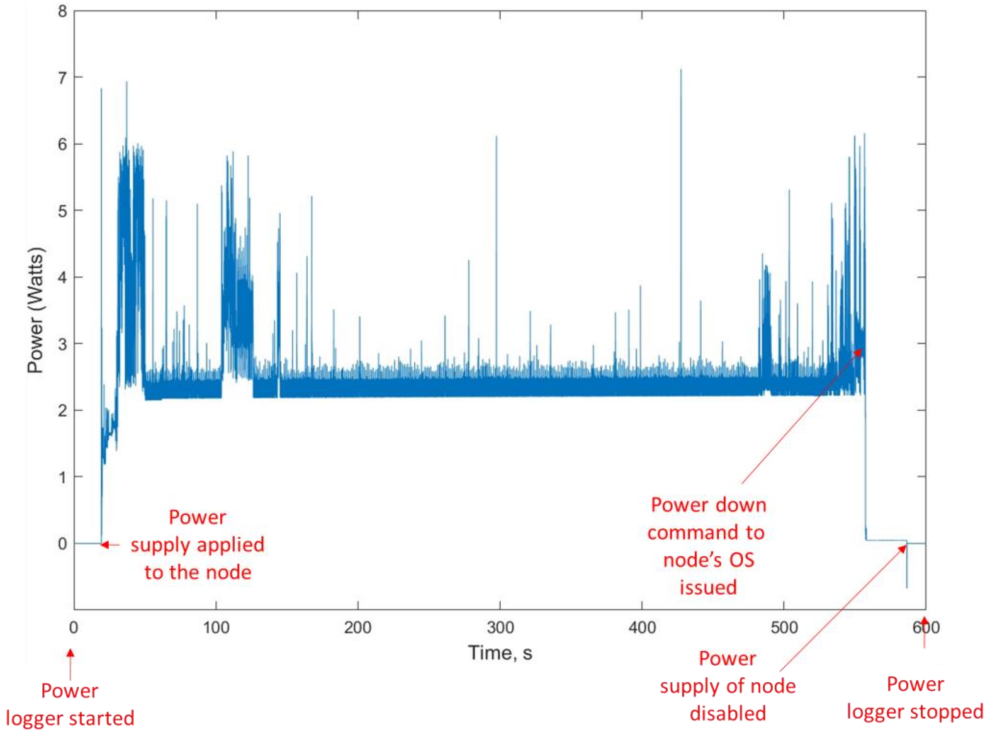

Figure 47 – Illustration of the power consumption for the reference

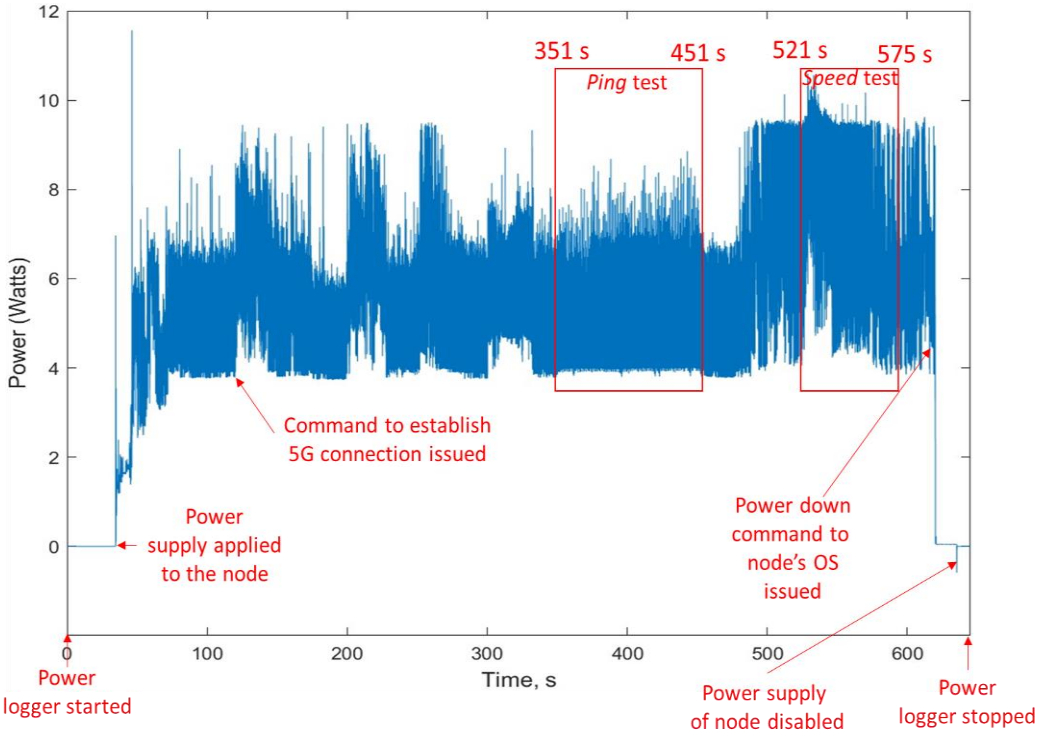

Figure 48 – Illustration of the power consumption for the node with 5G modem

Figure 48 shows the power consumption of the node equipped with the 5G modem (note, that no IEEE 802.11 modem was connected to the node during these measurements). The measurements were carried in the indoor environment (i.e., at the location for test IDs 1-4). Similarly to the previous case, we first enabled the logger and appended the power supply to the node. Two minutes after the start of the node, the command for the node to connect to the 5GTN was given. After that we have checked the connection status, signal strength and connected cell ID, and first launched a *ping* test (100 messages with 16 bytes payload, interval one second) and then the *speed* test. The run tests are shown on the chart as frames with the start and end time relative to the start of the experiment shown above. 26 seconds after the end of the speed test, the command for the node to power down was issues, then the power supply of the node was removed, and the logger has stopped.

From the results presented in Table 10 it can be seen that the overall average consumption for the 5G enabled node has more than doubled with respect to the reference case, increasing from 2.38 W to 5.1 W. Notably, during the speed test the average consumption was as high as 9.38 W, while the peak consumption exceeded 10 W. During the ping test, the average consumption was 4.55 W. Also, a number of other consumption peaks can be seen when the modem was connecting to the network and further (e.g., when checking the network status or preparing to launch the speed test).

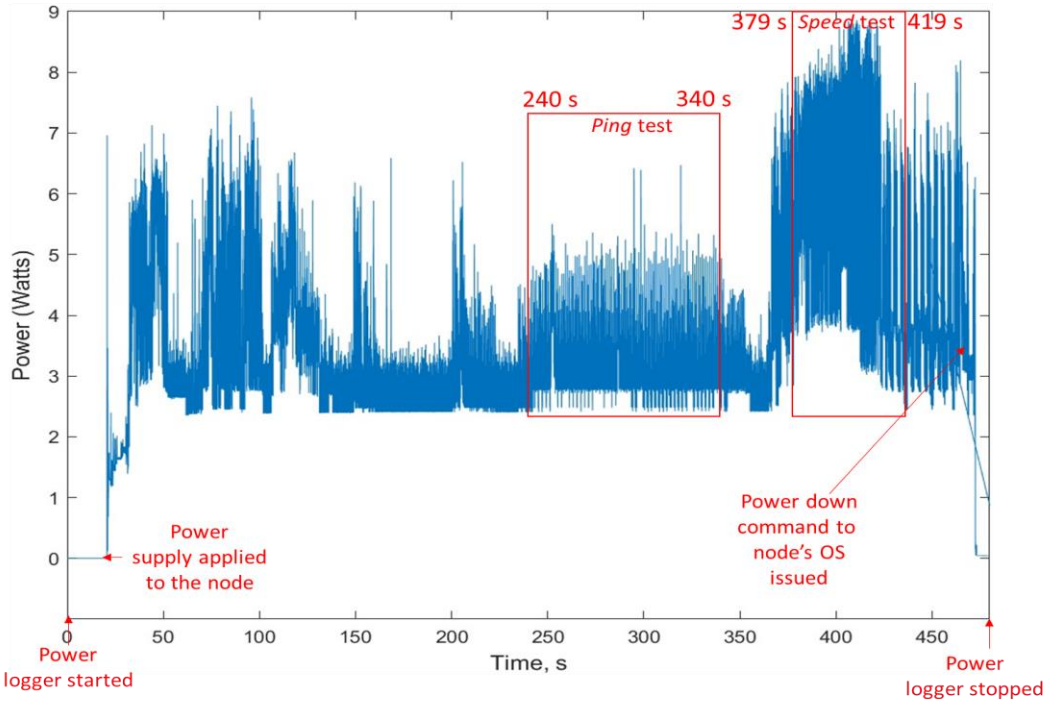

Figure 49 – Illustration of the power consumption for the node with an IEEE 802.11 modem

Figure 49 reveals the power consumption of a node with an IEEE 802.11 modem (no cellular (5G) modem was connected to the node during these measurements). Its overall testing procedure was similar to the one of the 5G modem, therefore we will not discuss it in detail.

From Table 10 and Figure 49 one can see that overall consumption for IEEE 802.11 enabled node was just one Watt higher than that of the reference case, and 1.8 W lower than that of the 5G-enabled node. During the *ping* tests the power consumption of the node was just 0.5 W higher than that of the reference case, while during the speed test the consumption was 3.1 W higher than the reference case. Interestingly, the peak consumption of the node during the experiments was decently high and approached 9 W.

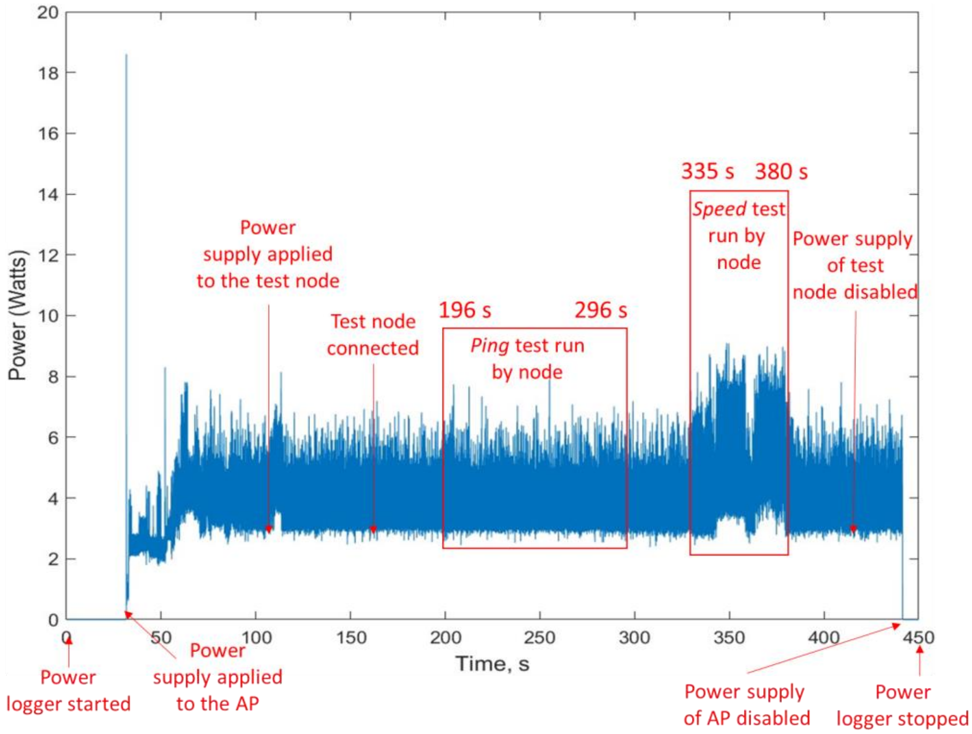

Figure 50 – Illustration of the power consumption for the AP with connected test node

Finally, Figure 50 demonstrates the power consumption of the AP with one single node connected to it and operating as discussed in the two previous paragraphs. It can be seen that the power consumption of the AP throughout the test remained mostly stable at around 3.7 W; however, when the node was executing the Speed test the AP's consumption has increased to about 5.1 W. The high peak in the power consumption observed when starting the AP is likely caused by the initial charging of the capacitors.

Overall, our results show that:

- The cellular (5G) connectivity increases the consumption of the node by 2-3 Watt for the case of low traffic, and by up to 7-8 W for high traffic loads.
- The IEEE 802.11 communication boost the consumption by 0.5 W for no traffic to low load traffic, and by 3-4 W for high traffic load.
- The consumption of the dedicated industrial 5G – IEEE 802.11 AP is in the order of 3.6-3.8 W for low traffic and increased to over 5W for high traffic load.

9 Conclusions

This deliverable focused on the specification, integration, testing and validation of stand alone wireless communications sub system for FRACTAL nodes. Specifically, we have developed, validated and measured not just a single one, but three different network topologies based on the use of IEEE 802.11 and cellular (5G) wireless connectivity. The deliverable offers the detailed step-by-step instruction on how these connectivity options can be enabled, and what performance with respect to such application-level key performance metrics as throughput, latency and overall energy consumption do they offer for various traffic patterns and communication scenarios (i.e., communication of the same-tier FRACTAL nodes and communication of a lower-tier node with an upper-tier one). The reported results cover a wide range of expected and foreseen FRACTAL node use cases and thus offer important insights to facilitate the selection and implementation of wireless connectivity for FRACTAL nodes and thus overall exploitation of the FRACTAL results. Beyond this, the reported procedures, especially those related to enablement of 5G connectivity for IoT node, are novel and can be beneficial also beyond the FRACTAL project context.

Nonetheless, it is important to disclaim that the since the operation of wireless systems is affected by environment and many configurable parameters (which can change also in time), the presented numeric results should be considered with care. We recommend treating them as indicative rather than conclusive; while focusing more on the trends than the specific values.

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11 List of figures

12 List of tables

13 List of abbreviations

3GPP – 3rd Generation Partnership Project
4G – Fourth-Generation Technology Standard for Cellular Networks
5G – Fifth-Generation Technology Standard for Cellular Networks
5G-NR – 5G New Radio
5GTN – 5G Test Network
AC – Alternating Current
AP – Access Point
APN – Access Point Name
AT commands – attention (Hayes) commands
BLE – Bluetooth Low Energy
BW – Bandwidth
C-V2X – Cellular V2X
DC – Direct Current
DECT – Digital Enhanced Cordless Telecommunications
DHCP – Dynamic Host Configuration Protocol
DRX – Diversity RX
DUT – Device Under Test
EMBB – Enhanced Mobile Broadband
EPC – Evolved Packet Core
ETSI – The European Telecommunications Standards Institute
EVB – Evaluation Board
FDMA – Frequency Division Multiple Access
HDMI – High-Definition Multimedia Interface
HW – Hardware
ID – identifier
IEEE – Institute of Electrical and Electronics Engineers
IMT – International Mobile Telecommunications
IoT – Internet of Things
IP – Internet Protocol
ISM – Industrial, Scientific and Medical
ISP – Internet Service Provider
ITS – Intelligent Transportation System
ITU – International Telecommunication Union
LAN – Local Area Network
LPWAN – Low Power Wide Area Network
LTE – Long Term Evolution
LTE-M – LTE MTC
M2M – Machine-to-Machine
MIMO – Multiple Input Multiple Output
MTC – Machine-Type Communication
mMTC – Massive MTC
NB-IoT – Narrow Band IoT
NSA – Non-standalone
NTN – Non-Terrestrial Network
n/a – Not Available
PRX – Primary RX
PTP – Precision Time Protocol
QoE – Quality of Experience
QoS – Quality of Service
RAN – Radio Access Network

RAT – Radio Access Technology
RF – Radio Frequency
RFID – RF Identification
RSRP – Reference Signal Received Power
RSRQ – Reference Signal Received Quality
RSSI – Received Signal Strength Indicator
RTT – Round Trip Time
RX – Receive
RX2 – MIMO-RX 2
RX3 – MIMO-RX 3
SA – Standalone
SFTP – Secure File Transfer Protocol
SIM – Subscriber Identity Module
SINR – Signal-to-Interference-Noise Ratio
SSH – Secure Shell Protocol
SW – Software
TCP – Transmission Control Protocol
TDMA – Time Division Multiple Access
TS – Test Server
UE – User Equipment
UI – User Interface
URLLC – Ultra-Reliable and Low Latency Communications
USB – Universal Serial Bus
UWB – Ultra-Wide Band
V2X – Vehicle-to-Any
VTT – VTT Technical Research Center of Finland
WLAN – Wireless Local Area Network