Empirical Characterization of Wireless Connectivity Performance for Cognitive Edge IoT Nodes

Diluna Adeesha Warnakulasuriya, Konstantin Mikhaylov
Centre for Wireless Communications, University of Oulu
Oulu, Finland
{dwarnaku22@student.oulu.fi, konstantin.mikhaylov@oulu.fi}

***Abstract*—Cognitive edge nodes are becoming increasingly important for various Internet of Things (IoT) applications, requiring reliable, efficient and ubiquitous communication. This paper evaluates the performance of direct cellular (5G) and IEEE 802.11-based Wireless Local Area Network (WLAN) technology for cognitive edge nodes supporting network architectures potential for FRACTAL edge platform. The FRACTAL edge platform is flexible, scalable and supports different wireless technologies, making it a suitable platform for implementing cognitive edge nodes. The study assesses the network performance in terms of throughput, latency, and power consumption for three different network architectures. The findings reveal that IEEE 802.11 technology is more energy-efficient and favourable for latency for peer-to-peer communication scenarios, while 5G technology demonstrates high throughput for communication between a test node and an upper-tier edge node. This research sheds light on the feasibility and performance of these technologies for implementing cognitive edge nodes in various applications, providing valuable insights for researchers and practitioners in the field of wireless communication and edge computing.**

***Index Terms*—FRACTAL, edge computing, cognitive edge nodes, latency, throughput**

I. Introduction

The IoT enabled many new applications, resulting in the deployment of many hardware devices and sensors that can sense and process data. However, cloud computing, which is currently the most widely used paradigm for data processing and storage, has several limitations, including low throughput, high latency, and data privacy concerns. Edge Computing aims to address these limitations by moving data processing, storage, and computing tasks to the edge of the network, closer to the terminal devices. Edge computing distributes the computational load to routers, switches, base stations, and gateways, thus reducing the workload of the cloud. Recent advancements in System-on-Chip (SoC) enabled to make edge nodes cognitive and adaptive, which can improve overall system performance. The Cognitive Fractal and Secure EDGE based on a unique Open-Safe-Reliable Low Power Hardware Platform Node (FRACTAL) project enables a paradigm shift towards safe and scalable edge computing.

FRACTAL is a project funded by the European Union that aims to develop a decentralized, federated edge computing infrastructure for IoT applications. The FRACTAL architecture consists of interconnected edge nodes that can communicate with each other to share resources and data. The FRACTAL node is the building block of scalable decentralized IoT, which can construct an industry-standard cognitive edge [1]. The FRACTAL communication subsystem supports dynamic spectrum access and multi-hop communication. The strategic goals of FRACTAL include designing and implementing an open, safe, and reliable platform for building cognitive edge nodes, guaranteeing extra-functional properties, evaluating and validating the analytical approach utilizing Artificial Intelligence (AI), and integrating communication and remote management features into FRACTAL nodes.

This paper presents an empirical study on the performance of wireless technologies for cognitive edge nodes based on the FRACTAL edge platform over the University of Oulu 5G Test Network (5GTN). The study focuses on three key performance indicators (KPIs), namely latency, throughput, and power consumption and evaluates their performance in three different FRACTAL-based network architectures. The main contributions of the study include an evaluation of the suitability of 5G technology for cognitive edge nodes, a comprehensive evaluation of FRACTAL-based network architectures, an identification of factors influencing performance, and recommendations for optimizing performance. The findings of this study can be useful for researchers, network operators, and policymakers working on wireless communication and cognitive edge computing.

II. Related Works

The FRACTAL architecture and its applications have been discussed in several research papers. In [2], the authors propose a machine learning-based approach for dynamic resource allocation in FRACTAL edge networks. The approach involves using historical data to train a machine-learning model that predicts the resource requirements of IoT applications. Simulation experiments demonstrate the effectiveness of the approach in improving resource utilization and reducing power consumption. In [3], the authors propose a scalable IoT framework for energy management in connected buildings using the FRACTAL architecture. The framework involves the deployment of sensors and actuators throughout the building, which are used to collect data on energy consumption and environmental conditions. This data are processed using edge computing resources, and machine learning algorithms are used to predict energy consumption and optimize resource allocation. The authors show that the Fractal IoT framework can improve energy efficiency and reduce energy costs. Work

[4] provides an overview of the FRACTAL project, highlighting the importance of developing secure and energy-efficient edge computing systems. The paper describes the FRACTAL hardware and software architecture, which is designed to support cognitive and secure edge computing applications. The hardware platform includes microcontrollers, programmable logic devices, and sensors and supports hardware-based security features such as encryption and authentication. The software architecture includes cognitive agents that can reason about the environment and make decisions based on data collected from sensors.

Although the FRACTAL framework has made significant contributions to the field of edge computing, the aspects related to wireless connectivity and its effect are understudied. Study [5] investigates the performance of 5G networks in urban environments, highlighting the impact of altitude on coverage and throughput. Another study [6] compares the practical implementation of 5G networks to Forth Generation mobile technology (4G), showcasing 5G's superior throughput and lower latency. A comprehensive analysis [7] evaluates the performance of standalone (SA) and non-standalone (NSA) 5G networks, revealing slight differences in achievable uplink rates. The 5GENESIS research project [8] conducts extensive experiments to validate KPIs such as throughput and latency. A mathematical model [9] demonstrates the potential benefits of Random Access Network (RAN) virtualization and edge computing for reducing power consumption and latency in 5G networks. Another study [10] sheds light on the operational aspects of 5G, highlighting the challenges of capacity utilization, latency for tactile applications, and increased power consumption. Moreover, a study [11] focuses on latency analysis in 5G networks, emphasizing the importance of specific configurations to meet latency requirements in enhanced mobile broadband (eMBB) scenarios.

However, to the best of our knowledge, no prior research has explored the assessment of wireless connectivity performance for cognitive node edge computing. Hence, this paper aims to analyze network KPIs for particular communication architectures utilizing the FRACTAL framework.

III. Selected Communication Architectures

When selecting the Radio Access Technology (RAT) for a particular edge computing application, several factors, such as data transfer rates, latency, power consumption, range, and infrastructure requirements, should be considered. For FRACTAL, which aims to achieve low-latency communication, the choice of RAT should consider the latency requirement. Power consumption is also critical as FRACTAL nodes are often battery-powered devices with limited energy capacity, and various RATs have different power consumption profiles. In addition, the infrastructure requirements of the application, the cost of implementing a RAT topology, and the trade-offs between performance, cost, and feasibility must be considered.

Notably, the FRACTAL nodes can operate using multiple RATs, which allows them to adapt to different environments and network types as required. FRACTAL nodes can operate in various network topologies like peer-to-peer, star, tree, and mesh, making them flexible to changing network conditions. For communication, FRACTAL nodes require high-throughput and low-latency communication, which they achieve through advanced modulation-coding schemes and media access control protocols such as Orthogonal Frequency Division Multiple Access (OFDMA). These features enable efficient use of the available frequency spectrum, making FRACTAL nodes suitable for bandwidth-intensive applications like video streaming, virtual reality, and real-time gaming.

IEEE 802.11-based RATs such as Wireless Fidelity (WiFi) are suitable for last-mile connectivity within a FRACTAL subnetwork due to their high data rates, low latency, large coverage area, and compatibility with existing devices. Cellular RATs such as 5G are suitable for backbone connectivity between subnetworks due to their longer communication range, better coverage, support for mobility and handover, high throughput, and low latency. Other RATs such as Zigbee, Bluetooth and Long Range Wide Area Network (LoRaWAN) are not so well-suited for FRACTAL connectivity, as they prioritize low-power, long-range communication over high-throughput and low-latency. Considering the above state-of-the-art of RATs, the following three distinct topologies have been selected as the baseline for implementation and testing:

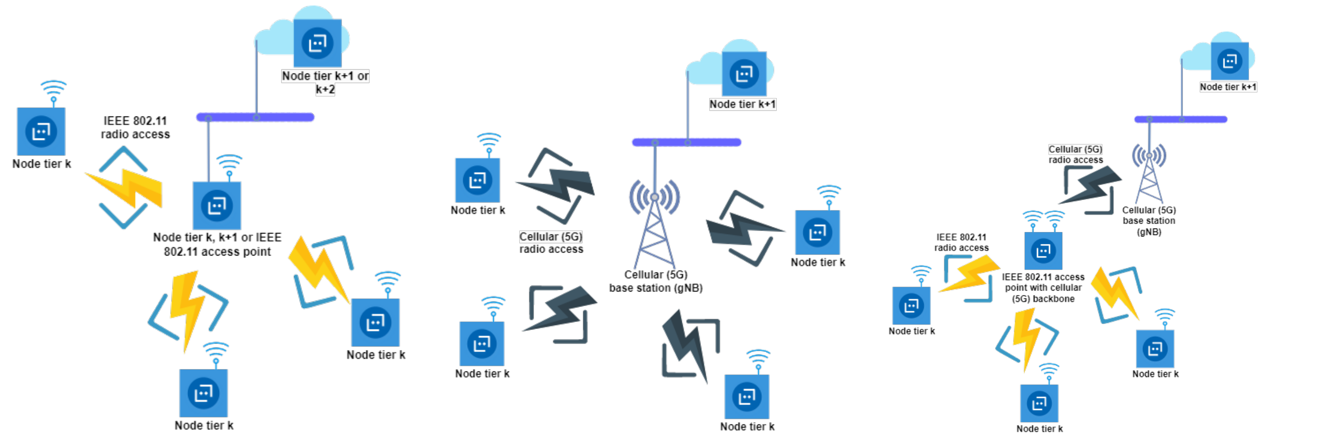
- Topology 1: IEEE 802.11 based the last mile,
- Topology 2: Direct 5G connectivity,
- Topology 3: IEEE 802.11 last mile over 5G backbone.

A. Topology 1: IEEE 802.11 based last mile

Figure 1(a) shows Topology 1 of the FRACTAL network, which utilizes the IEEE 802.11 Wireless Local Area Network (WLAN) radio access technology that operates in the 2.4 GHz and 5 GHz Industrial, Scientific, and Medical (ISM) bands. This technology supports high-throughput star networks with low latency and Multiple-Input Multiple-Output (MIMO), making it ideal for last-mile connectivity in residential and small business settings. Although it has a limited range and is susceptible to interference, mesh and star topologies can be configured to provide redundant paths and improve network resilience. The IEEE 802.11 technology offers flexibility in network deployment, easy extension and modification of network coverage area, and is cost-effective.

B. Topology 2: Direct cellular (5G) connectivity

The second topology proposed for FRACTAL nodes, shown in Figure 1(b), involves equipping them with direct 5G cellular connectivity. This technology offers both high throughput and extensive communication range by using OFDMA, new frequency bands, licensed spectrum, and controlled access to time-frequency resources. However, this incurs additional costs. Cellular technologies have traditionally been designed for a tree-like topology, where User Equipment (UE) communicates with a base station, which merges into a centralized network. Peer-to-peer connectivity between UEs may be inefficient, and network performance can vary substantially based on configuration and resource availability. This topology



(a) Topology 1: IEEE 802.11 based last mile. (b) Topology 2: Direct cellular (5G) connectivity. (c) Topology 3: IEEE 802.11 with 5G backbone.

Fig. 1. Selected topologies

is ideal for large-scale deployments, such as smart cities or industrial IoT applications, where high-speed and reliable connectivity is required between multiple devices and nodes. It offers benefits such as high-speed data transmission, low latency, and the ability to handle many connected devices while reducing infrastructure complexity and costs.

C. Topology 3: IEEE 802.11 last mile over 5G backbone

Topology 3, depicted in Figure 1(c), combines the star or mesh IEEE 802.11 network with cellular (5G) radio access to achieve both high-speed connectivity and extended coverage. The IEEE 802.11 wireless technology is used for the final leg of connectivity between the Internet Service Provider (ISP) or Edge and the end-user, while 5G cellular technology acts as a backbone for the last-mile network. The hybrid topology offers a cost-effective solution for delivering high-speed connectivity over an extended coverage area.

IV. Implementation

This section presents a summary of the implementation of the chosen communication architectures. The implementation includes the selection and configuration of different hardware and software platforms.

A. Selection of hardware

To enable IEEE 802.11 wireless connectivity for topology 1 and 2: an IEEE 802.11-compatible radio module for FRACTAL nodes and an IEEE 802.11-compatible Access Point (AP) to coordinate the communication between the FRACTAL nodes are needed. After evaluating various factors such as cost, form factor, technical specifications, and driver availability for software platforms, the TP-link AC1300 Archer T3U Plus WiFi Universal Serial Bus (USB) dongle[1] was chosen as the radio module for FRACTAL nodes. The dongle supports both the 2.4 GHz and 5 GHz frequency bands while operating according to IEEE 802.11 a/b/g/n/ac standards, and has a maximum supported transmit power of 18 dBm in the 2.4 GHz band and 20 dBm in the 5 GHz bands.

[1]https://www.tp-link.com/us/home-networking/usb-adapter/archer-t3u-plus/

The TeleWell Industrial 5G AP[2] was chosen as the access point to enhance the capabilities of the system. This router is designed for M2M applications and supports Long-Term Evolution (LTE) bands and 5G bands. It has four cellular 5G antennas and two WLAN antennas and can deploy both 2.4 GHz and 5 GHz networks supporting IEEE 802.11 b/g/n standards. The AP has two SIM card slots and can be powered with 9 to 36 V DC power input. The DC 12 V/2.5 A power adapter was used for this purpose. The manual for the AP provides instructions on how to prepare it for use and how to deploy it. The decision to choose this AP was primarily due to its flexibility in being able to be used for both IEEE 802.11 and integrated IEEE 802.11 and cellular (5G) tests.

For direct cellular (5G) connection for topology 2, the Quectel RMU500-EK Evaluation Board (EVB)[3] with the RM500Q 5G module[4] was chosen. The user guide for the EVB provides detailed instructions on how to prepare it for use. The RM500Q is the only 5G module commercially available and adapted for IoT usage at the time when the development was carried out.

B. Configuration of software

To establish cellular connectivity, the Access Point Name (APN) must be set according to the ISP and port forwarding must be enabled to allow the node to be accessible by upper-tier nodes. This can be done by enabling virtual computer service from the router's web User Interface (UI). Virtual computers assign a Local Area Network (LAN) hosts to global Internet Protocol (IP) addresses so that they can be visible to the outside world. To enable WLAN connectivity, the Realtek RTL88x2BU WLAN USB driver must be installed, and the router's UI must be accessed to change login credentials, set the APN, and enable port forwarding. The local IP address of the node can be obtained from the router's UI and a static IP address can be configured for the test node using the DHCP server's IP pool and the MAC address of the WLAN dongle.

[2]https://telewell.fi/en/productcommunication/internet-at-home/5g/TW-5G+router/5g-industrial-router-all-4g-and-5g-bands-supported

[3]https://www.4gltemall.com/quectel-rm500q-gl-dev-evb-kit.html

[4]https://www.quectel.com/product/5g-rm50xq-series

TABLE I
PRODUCED TEST PLAN AND NOTATIONS

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

More details on these configurations of the AP can be found in its manual [12].

The process of establishing a direct connection to the 5G network using the Quectel RM500Q 5G module involves installing the Linux 5G USB drivers on the test node, specifically the 'GobiNet' driver. The Quectel USB 'serial option' driver is also necessary to issue Attention/Hayes (AT) commands to the RM500Q. The 'Qmi-WWAN' driver is an alternative to the 'GobiNet' driver, depending on the USB network adapter used. To set up a data call, the Quectel Connect Manager (quectel-CM) tool was used.

V. Experimental Setup

This section provides information about the measurement environment, tools and methods used in testing.

A. Experimental environment

This tests were conducted within the 5G Test Network (5GTN)[5] located in Oulu, Finland. The 5GTN is the open 5G test network, which functions as a full-scale micro-operator. The network has been designed to support various research and industry needs and experiments while remaining scalable. It offers both non-standalone (NSA) and standalone (SA) 5G architecture, with the ability to use its own SIM cards, and support for both fourth Generation (4G) and 5G connections through 4G and 5G Base Stations. In this study, a 5G NSA macro three-cell base station operating in the n78 frequency band and using Time Division Multiple Access (TDMA) was utilized, with available resources of 10 MHz of spectrum for 4G and 60 MHz of spectrum for 5G. The antenna tower that hosted the base station's antennas and test locations are presented in Figure 2.

B. Measurement tools

The Qosium tool from Kaitotek OY[6] was used for measuring communication performance indicators in the experiments. Qosium is a passive real-time performance measurement and monitoring system that measures the quality of service (QoS) of real applications on the network without causing major disruptions. The tool consists of two components: the network probes and the Scope SW tool. The network probes are passive measurement tools deployed at the points to be measured, while the Scope SW tool is used to control the measurements and log the data.

Fig. 2. 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.

System clock synchronization is critical for applications that rely on accurate timing. In the study, Precision Time Protocol (PTP) was used to ensure that the Qosium probes had the same time reference. PTP synchronizes clocks in a network in a master-slave hierarchy. The PTPd Linux package was used for the installation and configuration of PTP on the test nodes.

The Secure File Transfer Protocol (SFTP) was used to generate traffic load during the experiments. SFTP is a secure network protocol used for accessing and transferring large files and sensitive data. It requires both a client and a server to function, with the client used to connect to the server and store files, while the server is responsible for storing and retrieving files. The FileZilla software was used as the SFTP client, which is free software that can be downloaded from the software center in a Linux OS. Moreover, A speed test tool [7] was used to validate the connection and gather performance information from a test node to the internet. However, the results from this tool cannot be directly compared to the results from the ten tests described above since the main test points for those tests were located in the local network, radio access network of 5GTN, or in the core network of 5GTN.

For tests which required a direct Ethernet connection between the AP and an external computer, we used a Lenovo ThinkPad T15 notebook computer with an Intel Core i5 processor and Ubuntu 20.04.4 LTS operating system. The notebook computer had pre-installed Ethernet drivers, and we

[5]https://5gtn.fi/
[6]https://www.kaitotek.com/qosium
[7]https://www.speedtest.net/

obtained its local IP from the web UI of the AP. Additionally, the power supply issue in different locations was addressed by powering the test bed from an EcoFlow 720Wh Pro Portable Power Station[8]. The Agilent/Keysight N6705B DC power analyzer[9] was used to measure the power consumption of the test devices with high accuracy. The tool allows for configuring the output voltage and recording the current consumption with a high sampling rate.

To facilitate testing, two test nodes were instrumented with all necessary software components. The experiments utilized two test nodes, each equipped with a complete set of required software components. The 5G modem was attached to the test nodes during specific tests, while the IEEE 802.11 modem was attached during other tests. Additionally, each node had a USB mouse and keyboard for control and interaction, and their status was monitored using a screen connected via HDMI cable. The test nodes and access points were powered using alternating currents throughout the tests, except for power supply measurements.

C. Experimental procedures

The experimental procedures involved conducting measurements in three target topologies, each with two subcases, resulting in six measurement scenarios. Two types of measurements were performed for each scenario: delay estimation using the Ping command and throughput measurement using an SFTP server and client. The general measurement procedure involved powering up the test devices, enabling PTP time synchronization, launching the measurement in Qosium Scope, performing a speed test at the test node, using Traceroute to check the route between the test nodes, measuring the radio channel conditions, executing the experiment while noting timestamps and relevant observations, logging the results, stopping the measurement in Qosium Scope, and copying the logs and collected results for further processing.

For the power consumption measurements, the power analyzer was set to data logger mode to record the current consumption profile of the test node throughout all phases of its operations. The collected data were imported for post-processing in MATLAB. To measure power consumption, the test device must be directly connected to the DC power analyzer, and a cable was instrumented to allow for this connection. The USB mouse and keyboard used to control the test nodes were powered from the test node's USB interface, and their consumption was included in the total measured value. When measuring the consumption of the AP, At first, we measured the power consumption of one of the test nodes as a reference which was not equipped with either IEEE 802.11 WLAN connection or direct cellular (5G) connection. And then measured the power consumption of the test node connected to IEEE 802.11 WLAN connection, direct cellular (5G) and just the AP.

[8]https://eu.ecoflow.com/products/river-pro-portable-power-station

[9]https://www.keysight.com/fi/en/product/N6705B/dc-power-analyzer-modular-600-w-4-slots.html

TABLE II
SUBTEST COMPOSITION IN EACH TEST

Subtest ID	Description of the 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.
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.
Subtest x.c, x=1..10	Measurement focuses on estimating the throughput. The throughput capability is measured through two approaches: (i) the conventional speed tests and (ii) by deploying an SFTP server and measuring the time required to upload and download a test file (1.6 GB)[a]

[a] As the test file we used the Nvidea OS image, available: https://developer.nvidia.com/embedded/-l4t/r32release_v7.1/_t210/tegra_linux-samplerootfilesystem_r32.7.1_aarch64.tbz2.

Table I specifies a set of tests designed to measure performance metrics for different FRACTAL-based network configurations. Test Identifiers (IDs) 5 and 6 are for topology 1, test IDs 1, 2, 7, and 8 focus on topology 2, and test IDs 3, 4, 9, and 10 correspond to the hybrid topology which is topology 3. For topologies 2 and 3, measurements were conducted under two radio channel conditions of the cellular link, one with a direct line-of-sight (LoS) between the cellular modem and the base station antenna while the other one with the cellular modem located indoors without LoS to the base station. Each of the test IDs consists of three subtests as detailed in Table II.

The experiment involved 30 subtests (10 tests with 3 subtests each) to comprehensively test and measure key performance metrics for different configurations. In each subtest, the relevant information about the radio channel conditions was monitored and logged, including metrics such as 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.

VI. SELECTED MEASUREMENT RESULTS

Each of the three following subsections focuses on one single KPI result obtained from the measurements – the throughput, the delay, and the power consumption. Meanwhile, results of radio channel-related metrics showed an excellent RSSI during the measurements. In the course of testing topology 1, the minimum RSSI recorded by the nodes in non-LoS conditions was -28 dBm, while in LoS conditions, it was -27 dBm. While testing topology 2, the minimum RSSI measured in non-LoS conditions was -75 dBm, while in LoS conditions, it was -51 dBm. Finally, during the testing of topology 3, the minimum RSSI observed was -34 dBm.

A. Throughput measurement results

Table III provides an overview of the average uplink and downlink data rates obtained using three different methods.

TABLE III
SUMMARY OF RESULTS FOR AVERAGE THROUGHPUT FOR DIFFERENT TEST IDS

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	11,20	40,00	11,78	42,39
2.c	6,85	149,29	2,40	2,90	2.75	3.76
3.c	26,29	48,31	26,40	21,60	26,83	22,24
4.c	27,52	47,46	32,90	49,80	33,32	53,92
5.c	25,63	47,23	170,40	126,00	169	131,37
6.c	30,00	47,00	52,24	62,14	52,77	61,92
7.c	46,05	185,83	42,40	75,20	46,81	82,4
8.c	31,86	147,29	14,40	18,16	14,59	16,96
9.c	36,36	44,42	36,80	18,00	38,00	18,67
10.c	36,61	41,24	80,00	55,20	81,34	55,38

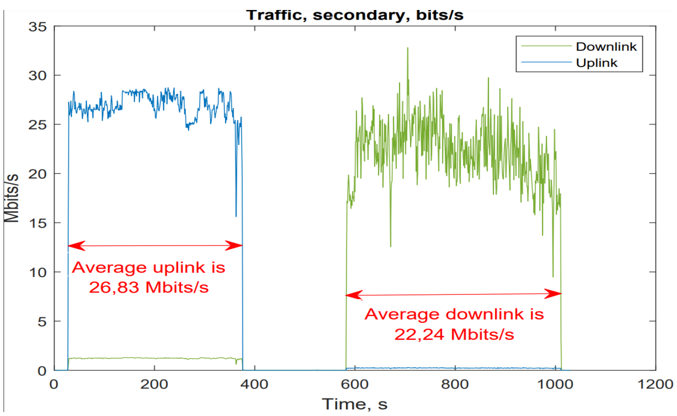


Fig. 3. Illustration of the throughput test traffic in Mbit/s from secondary Qosium probe (i.e., the node) for Test ID 3. The file is uploaded to a remote SFTP server (high uplink traffic, small downlink traffic acknowledging reception) during the first phase, and then the file is downloaded from the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

The first method is the speed test, which measures the internet access speed to the nearest server of a specialized subset. The second method involves SFTP measurement, and the third method analyzes the measurement results of Qosium Scope for each subtest IDs x.c. To calculate the average throughput from Qosium results, the data were imported into MATLAB and further processed. The average throughput was calculated separately for the periods of uplink and downlink traffic, as shown in Figure 3. It can be seen that Qosium scope results are mostly consistent with SFTP client software, except for the variations in results from speed tests. The reason for the discrepancies lies in the different routing and protocols used on top of IP. Moreover, it is essential to note that the current load on the network can affect speed test results, leading to varying results despite high signal quality.

For 5G communication, the maximum average throughput achieved during speed tests was 185 Mbps in the downlink and 46 Mbps in the uplink. Similarly, during SFTP tests, the throughput was around 80 Mbps in the downlink and 46 Mbps in the uplink. The results of test ID 2.c showed that the throughput of communication between two nodes located under the same 5G base station is significantly lower compared to the throughput observed when a node is communicating with an upper-tier node, such as an edge server.

In test IDs 5 and 6, the throughput for IEEE 802.11 WLAN connectivity reached 170 Mbit/s and 130 Mbit/s in the uplink and downlink, respectively. The throughput for IEEE 802.11-based communication between the two test nodes exceeded 70-80 Mbit/s in the uplink and 50 Mbit/s in the downlink. The use of higher frequency bands and wider bandwidths in the physical layer (PHY) of IEEE 802.11 WLAN [13] allows for more data to be transmitted in a given period, resulting in higher throughput.

The throughput performance for test IDs 4 and 10 is comparable to the results observed for test ID 6 in the presence of an AP with a 5G backbone. However, in the case of local data transfer between two devices connected to the same AP, the data is transferred directly between the devices over the IEEE 802.11 wireless link. Therefore, the performance of the connectivity between the two devices in this scenario is defined solely by the throughput of IEEE 802.11 wireless technology.

B. Latency measurement results

Table IV 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 the Qosium Scope tool. Note that the results are presented for two different message payload sizes.

The latency results indicate that when nodes are directly connected to the cellular (5G) network, the average RTT for packets of 24 and 908 bytes when communicating with an upper-tier node was 12 and 24 ms, respectively. In contrast, when nodes of the same tier communicate directly over 5G, the delay is about twice as high, at 24 and 48 ms, respectively.

Comparing results for indoor (test ID 1) and LoS (test ID 7), the latency in uplink remained about the same. Meantime, the downlink of LoS allowed for slightly lower latency, especially for higher payload values. However, the LoS condition also substantially reduced the mean deviation. However, the

TABLE IV
RTT AND AVERAGE DELAY

Test ID	Size of a message[b] (bytes)	RTT (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[c]	
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	908	1,757	2,409	25,759	1,216	1,03	1,12
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[c]	
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

[b] Including headers; the ping size argument was set either to 10 or 900 bytes.
[c] Despite multiple attempts, the Qosium scope was unable to measure the delay, which remains unexplained and requires further investigation beyond the scope of the paper.

deviation of the RTT is quite high when communication is between nodes of the same level, as it is 55 and 130 ms for test IDs 2.a and 2.b, respectively.

Communication using short-range IEEE 802.11 technology (test cases 5 and 6) demonstrated lower latency than communication over a long-range cellular network. The difference was especially notable when two same-tier nodes communicated between themselves. For example, comparing results for test IDs 6 and 8, IEEE 802.11 enabled a one-way delay of around 1 ms, while the cellular (5G) delay was around 12-13 ms. The mean deviation for RTT over IEEE 802.11 links was also very low, well below 1 ms. Increasing payloads from 10 to 900 bytes resulted in a latency increase of less than 0.5 ms.

Using a combination of the two technologies (test IDs 5 and 6) and an AP (test IDs 3, 4, 9, and 10) showed somewhat contradictory trends. When communicating to an upper-tier node (test IDs 3 and 9), the RTT exceeded that for the 5G-only link (test IDs 1 and 7) by more than 10 ms. This was due to having two wireless legs (i.e., node -> AP -> 5G base station) based on different RATs and relaying packets between the two transceivers inside the AP. However, communication between two nodes of the same tier was done using the IEEE 802.11 technology, and thus the latency was similar to the IEEE 802.11-only scenario.

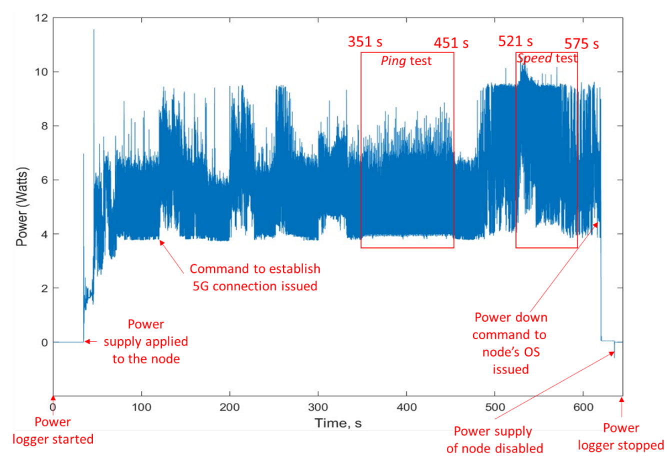


Fig. 4. Illustration of the power consumption for the node with 5G modem.

C. Power consumption results

Table V shows the average power consumption of the test node and the AP, and Figure 4 illustrates the consumption profile for one of the test cases. As it can be seen from the Table V, the average power consumption of the 5G-enabled node was more than double the reference case, increasing from 2.38 W to 5.1 W. During the speed test, the average consumption rose to 9.38 W, with a peak of over 10 W.

TABLE V
AVERAGE POWER CONSUMPTION

Average power consumption in Watts									
Reference	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

This increase in power consumption can be attributed to the higher processing load, the use of higher frequency bands, and the node using the 5G modem at maximum capacity during the speed test. During the ping test, the average consumption was 4.55 W, with consumption peaks occurring during the modem's connection to the network and the processes for maintaining network connection.

The overall power consumption of the IEEE 802.11-enabled node was slightly higher, at one Watt, compared to the reference case, and 1.8 W lower than the 5G-enabled node. During the speed test, the power consumption was 3.1 W higher than the reference case, with a peak consumption of about 9 W. The higher power consumption can be explained by the increased data transfer rate and associated processing required by the wireless interface, as well as various network management tasks that can consume additional power. The AP's power consumption remained stable at around 3.7 W but increased to about 5.1 W when the node executed the speed test, with a high peak in consumption likely caused by the initial charging of the capacitors.

VII. CONCLUSION

The study compared the performance of cellular (5G) and IEEE 802.11 communication technologies and found that cellular technology provides high throughput for communication with upper-tier nodes but lower throughput between two nodes interconnected through 5G. IEEE 802.11 offers high throughput but is limited by interferences and communication ranges. Combining both approaches through an AP with 5G backbone and IEEE 802.11 local network resulted in a balanced solution.

Latency measurement results showed that IEEE 802.11 WLAN features a low delay, especially for peer-to-peer like topology, compared to direct cellular (5G) communication. Note that latency is influenced by network architecture, communication technology, signal strength, and interference, etc.

The power consumption of wireless nodes and AP can vary significantly based on the wireless technology used and the activity performed. The 5G-enabled node consumed the most power, while the IEEE 802.11-enabled node had slightly higher power consumption than the reference case.

The study provides valuable insights for selecting wireless connectivity, but it is important to consider that wireless systems can be affected by the environment and configurable parameters, which can change over time. The results can help network designers make informed decisions about which wireless networking technology to use based on the specific needs of the application, considering factors such as data transfer rate, responsiveness, and power consumption.

In conclusion, there are several potential areas for future research in the field of wireless connectivity over FRACTAL nodes. While this paper examined three network architectures, there may be other architectures that could provide additional insights. It may also be valuable to examine how the performance of the three network architectures changes in different environments under various traffic loads and scale up with the number of devices. Additionally, future research could focus on specific use cases, such as industrial IoT or smart cities based on FRACTAL nodes.

ACKNOWLEDGMENT

The research was supported by the ECSEL JU FRACTAL (grant 877056) and Academy of Finland (AoF) 6GFlagship (346208) projects. The studies of K. Mikhaylov were supported by AoF RoboMesh (336060) and MRAT-SafeDrone (341111) projects.

REFERENCES

[1] J. Quévremont, et al., “WP2 Specifications & Methodology,” FRACTAL project deliverable, pp. 148, 2022.
[2] K. K. Leung, T. Salonidis, and B. J. Ko, “Machine Learning for Dynamic Resource Allocation at network edge,” Ground/Air Multisensor Interoperability, Integration, and Networking for Persistent ISR IX, p. 18, 2018.
[3] M. S. Anjana, et al., “Fractal IoT: A Scalable IoT Framework for Energy Management in Connected Buildings,” Proc. 1st ACM Int. Work. on Techn. Enablers and Innovative App. for Smart Cities and Communities, pp. 10-17, 2019.
[4] A. Lojo, et al., “The ECSEL Fractal Project: A cognitive fractal and secure edge based on a unique open-safe-reliable-low power hardware platform,” Proc. 23rd Euromicro Conf. on Digital System Design, pp. 393-400, 2020.
[5] S. Horsmanheimo, et al., "5G Communication QoS Measurements for Smart City UAV Services," Proc. 16th Eur. Conf. on Antennas and Propagation, pp. 1-5 2022.
[6] G. Soós, et al., "Practical 5G KPI Measurement Results on a Non-Standalone Architecture," Proc. IEEE/IFIP Network Operations and Management Symp., pp. 1-5, 2020.
[7] R. Mohamed, S. Zemouri and C. Verikoukis, "Performance Evaluation and Comparison between SA and NSA 5G Networks in Indoor Environment," Proc. IEEE Int. Mediterranean Conf. on Commun. and Networking, pp. 112-116, 2021.
[8] G. Xylouris et al., “Experimentation and 5G KPI measurements in the 5GENESIS platforms,” Proc. 1st Work. on 5G Measurements, Modeling, and Use Cases, pp. 1-7, 2021.
[9] R. Bassoli, et al., “Toward 5G Cloud Radio Access Network: An energy and latency perspective,” Trans. on Emerging Telecommun. Technol., vol. 32, no. 1, 2019. doi:10.1002/ett.3669
[10] D. Xu, et al., “Understanding operational 5G,” Proc. Annu. Conf. of the ACM SIG on Data Commun. on the App., Technol., Architectures, and Protocols for Comput. Commun., pp. 479-494, 2020.
[11] Y. Zhao, et al., "Latency Analysis and Field Trial for 5G NR," Proc. IEEE Int. Symp. on Broadband Multimedia Syst. and Broadcasting, pp. 1-5, 2022.
[12] TeleWell, “5G WAN: User Manual,” available (2022.03.10): https://telewell.fi/files/-TeleWell-5G-Industrial-router.pdf
[13] "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications" in IEEE Std 802.11-2020, pp.1-7524, 2021.