Experiences and challenges on testing and validating Network Aware PPDR XR Applications for 5G Advanced networks

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***Abstract*—This paper presents initial findings from the FIDAL project, which tests and validates network-aware PPDR XR applications for 5G advanced networks. Using a 5G testbed, we evaluated use cases highlighting the crucial role of 5G technologies in enhancing emergency response through improved connectivity and low latency. Preliminary results show the potential of 5G features in revolutionizing PPDR services. Our testbed performance evaluation supports realistic, large scale trial preparations, promising improved situational awareness and operational efficiency in critical communications.**

***Index Terms*—5G Networks, PPDR, Extended Reality (XR), Network Applications**

I. Introduction

In the communications context, Public Protection and Disaster Relief (PPDR) scenarios are defined as situations where communication must be established rapidly and efficiently during a critical event, and where this communication is vital to resolving the situation. These scenarios can vary from: day-to-day activities, where situations are resolved by authorities such as the police; planned events like athletic competitions and conferences where communication networks must be deployed; natural disasters (e.g. earthquakes, fires, floods) and man-made disasters (e.g. industrial accidents, terrorist attacks) threatening human life that need on-site pre-hospital treatment by first-aid responders. In this wide range of PPDR situations, the communication network plays an important role in disaster planning and management by supporting the efficient coordination across first responders, allocation and management of resources, smooth circulation of information and compartmentalisation, thus allowing the relief of the affected civilians. More specifically, PPDR solutions encompass a broad range of services aimed at ensuring public safety and efficient disaster management. These solutions can include, but are not limited to: (a) Real-time Communication Systems, (b) Surveillance and Monitoring, (c) Geolocation and Tracking, (d) Public Warning Systems, and (e) Command and Control Centers. The progress in 5G and the anticipated innovations in 6G technologies promise substantial improvements in connectivity, latency, and data throughput. These technological advancements will enable the development of sophisticated applications specifically designed for critical communications, emergency response, and disaster management.

The deployment of such networks, however, presents significant challenges. These systems must be highly available and reliable while providing secure communications, including data, voice, and possibly video, meaning high throughput with low latency. Furthermore, these communication networks must be either already deployed or ready to be deployed on demand in urban areas where network congestion might arise during such events and in remote areas where coverage might be limited. Additionally, the affected area might also suffer from infrastructure destruction in catastrophic events.

The rate of 5G adoption differs on a global scale. In this respect, at a European level, nations such as Germany and the UK have actively worked towards extensive coverage, while others encounter obstacles due to slower spectrum allocation and consumer hesitancy to upgrade. By 2025, it is anticipated that 35% of mobile connections in Europe will utilize 5G technology, underscoring continuous efforts to extend coverage to all populated areas by 2030 (GSMA, 2023). Considering this, the development and deployment of 6G technology will significantly transform PPDR services. The primary drivers for 6G include trustworthiness, sustainability, accelerated automation, and limitless connectivity. These advancements will tackle challenges not addressed by 5G, offering critical services, immersive communication, and seamless IoT integration. Incorporating 6G into PPDR systems promises to improve communication reliability, data security, and overall operational efficiency, ensuring strong responses to public safety needs.

The need for 5G. PPDR communication has a potential

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game-changer ally in the 3GPP 5G (and beyond) technologies developed in recent years. 5G offers features that align with the requirements of PPDR scenarios and address their challenges. Enhanced Mobile Broadband (eMBB) provides significantly higher data rates and capacity, enabling communication between first responders with high-quality video streaming when necessary. The Ultra-Reliable Low-Latency Communication (URLLC) allows for near-instantaneous data transmission, which is critical for time-sensitive operations. Massive Machine-Type Communications (mMTC) supports a vast number of connected devices, facilitating the deployment of sensors and IoT devices that enhance situational awareness. Network Slicing enables the creation of virtual, isolated networks within the 5G infrastructure, ensuring dedicated resources that guarantee performance for emergency services during catastrophic events or network congestion. Multi-access Edge Computing (MEC) provides computational power at the network edge, allowing data processing closer to the source, which reduces latency and improves decision-making speed. MEC also enhances security, as data remains local for processing, ensuring operational status even if communication with remote infrastructures is disrupted.

These capabilities can significantly change the modus operandi of first responders in crisis situations. For instance, real-time high-quality video from drones, whether autonomous or controlled by humans, along with cameras in first responder vehicles or on their persons, can provide faster and more accurate situational awareness, leading to more efficient handling of incidents.

5G also offers significant advantages for PPDR and XR applications beyond low latency and higher bandwidth. When combined with MEC, data processing can occur closer to the source, facilitating faster and more secure real-time decision-making for PPDR and enhancing the immersive experience for XR applications. Both types of use cases benefit from 5G's ability to support multiple devices simultaneously without sacrificing service quality, ensuring continuous service during unfolding events in either PPDR or XR scenarios. Furthermore, both applications leverage 5G's network slicing, which provides dedicated, secure resources tailored to specific use cases.

The authors of this paper are involved in FIDAL, a Horizon Europe Project under stream D of the Smart Networks and Services Joint Undertaking (SNS JU). The projects aim is to explore and demonstrate Beyond 5G technologies by implementing large scale trials and pilots to promote architectures that allow multiple experimentation sites with a multi-stakeholder approach in the PPDR and Media areas. The ultimate goal is to support these verticals by stretching the respective Key Performance Indicators (KPIs) [1] of the use cases on the way to Beyond 5G by understanding the needs and advancing the solution performance and KPIs.

This paper will explore and evaluate the role 5G networks can have in advancing PPDR capabilities by examining how PPDR challenges are addressed and demonstrating the validation of such scenarios in 5G capable testbeds.

II. Previous & Ongoing Work

In recent years, multiple European-funded projects have focused on communications, particularly in relation to Public Protection and Disaster Relief (PPDR) scenarios. These projects span various sectors, highlighting the significance of 5G networks and representing some of the state-of-the-art advancements in this area.

1) Public Safety and First Responders: Numerous initiatives have targeted first responder scenarios over 5G systems, addressing PPDR challenges such as interoperability and the integration of national mission-critical mobile broadband systems. Notable projects in this domain include i) Respond-A, ii) Broadway, iii) 5GASP, iv) DARLENE, and v) BroadEU.Net.

2) Healthcare: In the healthcare sector, projects have explored the advantages of 5G networks for remote patient monitoring. An example is 5G-HEART, which highlights how 5G can enhance healthcare delivery through improved connectivity.

3) Manufacturing and Logistics: Other projects have investigated the use of 5G networks—both public and private—for remote control and automation. These findings are applicable to PPDR scenarios, allowing for the remote operation of equipment in hazardous environments. Key projects include i) 5GLOGINNOV and ii) 5G-SMART.

4) Advanced Communication Networks and AI: While not directly involved in PPDR, two significant projects—i) Hexa-X and ii) Hexa-X-II—have focused on 6G networks, emphasizing the deployment of advanced communication networks through Artificial Intelligence (AI). The insights gained from these projects can contribute to ensuring service continuity in PPDR situations.

Collectively, these projects have advanced the understanding and development of practices and methodologies related to PPDR communications, addressing the unique needs of these scenarios. FIDAL aims to bridge these scientific areas by validating various scenarios in 5G (and beyond) networks and conducting large scale trials to showcase their capabilities.

The significance of 5G networks is further emphasized in recent literature. For instance, a network application approach toward 5G and beyond critical communications use cases has been explored in [2]. Additionally, the efficient support of extended reality (XR) services poses new challenges for existing and future wireless networks, as evaluated in a case study assessing the performance of different XR services [3], [4]. Finally, 5G PPDR experimentation encompasses virtualized and cloud-native technologies, architectures, deployment options, and field performance verification trials tailored for vertical-specific applications [5].

III. Methodology / Testing Approach

A. Patras5G testbed

This section describes the testing and validation procedure for various PPDR-related Use Cases (UCs) that were performed in Patras5G testbed [6] which is located in University of Patras. The Patras5G testbed represents a state-of-the-art, open infrastructure functioning as an "isolated" private

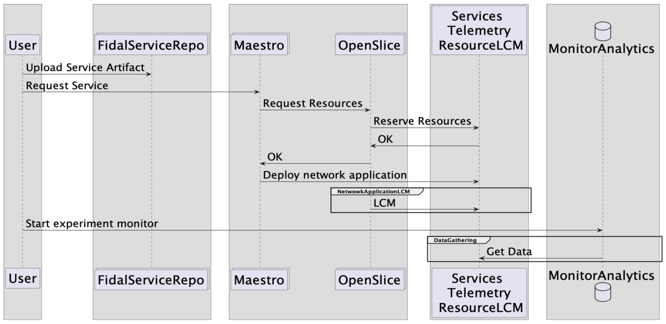

Fig. 1. Experiment flow

environment for 5G and IoT applications, in essence a 5G playground. This advanced testbed incorporates both open-source and commercial solutions, featuring dedicated components and services to support a wide array of 5G and IoT scenarios. Key capabilities of the Patras5G testbed include:

- Support for both containerized and virtualized deployments, spanning from 5G RAN to 5G Core.
- Implementation of 5G standalone (SA) setups.
- Integration of IoT gateways.
- Provision of necessary cloud and SDN fabric to host and test various services
- User and application access facilitated by the open-source Operations Support System (OSS) Openslice [7].

In the Patras5G testbed, OpenSlice is the main entry point for all operations. Any user that experiments there can select an appropriate service from the provided service catalog. Once all the elements are selected, like 5G network capabilities, gNodeB to be used, etc., OpenSlice will provision and orchestrate the deployment of all components providing a ready to use private 5G network for a specified time period.

Telemetry and monitoring tools are integrated across all layers of the experimental workflow in Patras5G testbed, providing detailed metrics from Radio Access Network (RAN) measurements to cloud-related data. Prometheus [8] is utilized for data storage, persistence and to provide access to the gathered monitored data. Additionally, custom-built data collectors are deployed in the lab infrastructure that gather specific metric. One example is the collection of RAN related metrics from the deployed gNodeBs. The gathered data can be accessed either by the parties involved in the experiment, either visually or by the use of appropriate APIs from other interested entities, like analytics Platforms or AIaaS solutions, for post processing and further assessments. This flow can be seen in Figure 1.

In Patras5G testbed, we delpoyed, tested and validated various PPDR related UCs which are presented in detail in the section IV.

B. Preparation

The validation process in the Patras5G Test-Lab followed a systematic approach: the first step was discussions between testbed owners and UC owners resulting in a detailed breakdown of each UC into its constituent elements. This process defined how various parts of the UC could be represented within the testbed environment. Key considerations included (but not limited to): (i) User Equipment (UE) requirements: Addressing the integration of non-5G capable devices through CPEs or tethered 5G devices; (ii) UC Traffic requirements: Identifying uplink or downlink needs for correct 5G network configuration; (iii) Network application requirements: Determining Virtual Machine (VM) specifications, quantity, and GPU needs and (iv) Potential simulation solutions: Exploring software deployment options for efficient testing in the absence of physical devices.

Once the constituting elements of each UC were identified the configuration phase for these UC would follow. VM would be deployed in Patras5G testbed according to the UC requirements (specs, network access, GPU access, etc.). Such VMs would also be deployed to be used as simulated 5G UEs to facilitate and expedite the testing process. The above elements would be interconnected through a 5G network as can be seen in Figure 2.

C. Testing Approach

The Patras5G Test-Lab employed a hybrid testing methodology to comprehensively validate the PPDR use cases within the 5G environment. This approach combined remote testing with on-site physical testing, optimizing the use of lab resources.

1) Remote Testing: The validation process began with remote testing, where UC owners received secure access to the testbed environment. This allowed them to install and configure their applications on VMs set up to meet specific requirements. Testbed owners then configured a 5G network to simulate various conditions, enabling performance assessments across different scenarios. During this phase, UC owners connected to their VMs while testbed personnel managed the network infrastructure and any physical devices. Any issues encountered were documented, and collaborative troubleshooting sessions were held to address them. This iterative process continued until all major issues were resolved, preparing the use cases for physical testing.

2) Physical Testing: Once remote testing was successful, physical on-site testing validated the use cases under real-world conditions. The Patras 5G Test-Lab was exclusively reserved for each use case during testing sessions, with the 5G network tailored to specific requirements. UC owners brought all necessary equipment, including specialized AR/VR devices. The presence of both UC owners and testbed personnel enabled real-time adjustments and prompt problem-solving. Predefined test scenarios were executed to assess performance under normal and edge-case conditions.

IV. Use Cases

A. Cloud-native XR PPDR application for first-aid responders

Overview. Surgeons should play a central role in disaster planning and management due to the overwhelming number of physical injuries that are typically involved during most forms of disaster. In fact, various types of pre-hospital emergency treatment, such as soft tissue wounds, orthopaedic trauma, abdominal surgery etc. [9], must be provided to injured patients on-site, by emergency medical teams before their transfer to a hospital. It is well known that pre-hospital treatment is a very critical phase for an emergency injury. It is a fact that in most cases the surgical knowledge of first-aid responders' is relatively minimal and that medical experts are usually located in hospitals, leading to leaving many incidents uncured till the patient reaches the hospital. In this UC, on-site first-aid responders are equipped with untethered AR Head-Mounted Displays (HMDs), significantly enhancing their assistance capabilities by following real-time instructions from medical experts located in hospitals, who are equipped with VR HMDs. This interaction is facilitated within a blended XR scene [10], [11] where both the responders and medical experts co-exist and collaborate virtually.

Solution. Three primary components (shown in orange in Figure 2) cooperate to achieve this distributed XR solution : i) a thin application running on the XR HMD that receives, decodes and projects the video stream, ii) a remote rendering network application (RRS) that renders the scene and iii) a network application (PhyS) [12] that acts as a dissected physics engine for this rendering pipeline.

Lab Trials. Lab experimentation was conducted at the Patras5G testbed, with a variable number of users and network configurations. Due to space limitations, we present metrics for a single experiment involving three users (2 AR and 1 VR). A Meta Quest-2 HMD was used for VR, while for AR we used a Meta Quest-3 and a Quest Pro. Each AR device was connected to the 5G network via a WiFi hotspot provided by a discrete 5G-enabled phone, while the VR device was connected via a CPE 5G router. Metrics collected from the phones are shown in Table I (the network consumption was mainly downlink to the headset). The QoE assessment was positive, with no problems detected and a good image quality of the video (framerate averaging at 50 frames per second).

B. Cloud-native AR PPDR Application for Law Enforcement Agents

Overview. Augmented Reality (AR) and Artificial Intelligence (AI) can significantly enhance Law Enforcement Agent (LEA) operational capabilities, in the event of a critical terrorist incident [13]. In particular, such technologies harnessed together can provide real-time annotations of potential threats, enabling officers to assess and respond to dynamic situations quickly, enhancing their situational awareness and ensuring more effective and timely responses.

Solution. For leveraging LEAs situational awareness the AR application discussed in [14] has been further developed so as to facilitate 5G network infrastructure. The computer vision and decision-making components of the application have been implemented as a Network Application running on the edge or cloud. This allows the most computationally intensive parts of the application to be offloaded, enabling a more accurate and efficient analysis of the users' field of view. The Network Application comprises several components. The AR Video Annotator (ARA) component needs to be running on an AR headset and is responsible for streaming the video and acquiring digital information entailed by the scene analysis. The Video Receiver (VR), the Video Analyzer (VA), and the Decision Maker (DM) components which are responsible for the video stream analysis and the provision of digital information in the form of annotations. These components are being deployed on the edge/cloud. Specifically, the VR component captures the video stream from the HUDs that is streamed over the 5G network, while the VA component employs Machine Learning (ML) based Computer Vision (CV) algorithms for analyzing the stream and identifying objects or persons of interest (e.g., guns, injured people, etc.). The DM component filters the provided cues to prioritize information that is most relevant and helpful for the officers operating on the field and creates a JSON file containing this information, returning it back to the ARA, over a 5G connection.

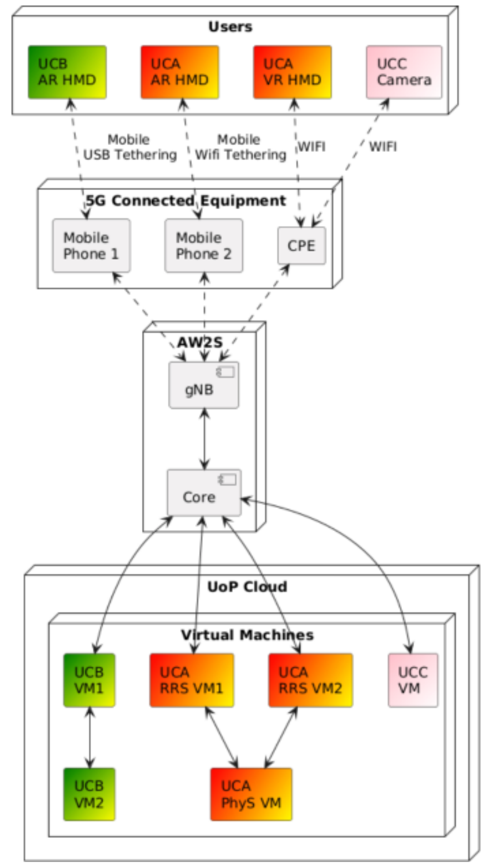

Fig. 2. Component Diagram of all UCs at Patras 5G testbed. Components of the same color correspond to components of the same UC.

Lab Trials. We tested several configurations to optimize system performance in our recent lab tests at Patras5G. We employed multiple setups involving AR glasses (Magic Leap 2) connected with the Network Application in two ways: via USB tethering to a 5G smartphone and a Huawei CPE

5G Router. Two virtual machines running the remote scene analysis and AR annotation Network Application components supported each setup. In addition to these configurations, we experimented with various image types because each type requires different amounts of data to be transferred: RGB with 3 channels, RGBA with 4 channels (adding transparency), YUV separating luminance and chrominance, and Grayscale with only one channel. Also, we tested various streaming protocols, TCP and RTSP. Metrics, such as frame per second, latency, and throughput, were collected. The best-performing metrics from the experiments, shown in Table I, were achieved when the AR glasses were connected to a CPE router and streamed grayscale images using the TCP protocol — a frame rate of 34 FPS was achieved.

C. Digital Twin for first responders

Overview. Climate change has led to more frequent and severe wildfires in many parts of the world. First responders in wildfire situations face a large spectrum of challenges in disaster environments including environments with low visibility and hidden hazards. Managing fires under these evolving climate conditions requires adaptive strategies and a comprehensive understanding of fire behaviour time. Timely identifying the onset of a wildfire and alerting first responders is critical to successfully minimizing the relevant impact while also making efficient use of the available resources.

Solution. 5G technology offers several advantages in the context of forest fire management. It enables high-speed and low-latency communication, allowing for real-time data transmission. With 5G, high-definition video streaming becomes feasible in remote areas. This allows for live video feeds from surveillance cameras, and other monitoring devices installed in forests. Emergency responders can remotely monitor the fire's progression, identify potential hazards, and make informed decisions in real time, improving situational awareness. Additionally, 5G networks provide reliable and high-bandwidth communication channels for emergency responders, enabling seamless communication among firefighters, incident commanders, and other stakeholders. They can exchange critical information, coordinate efforts, and respond effectively to evolving situations. This use case will demonstrate the capabilities of the 5G technology and the advantages it provides to the forest fire detection and management domain.

Lab Trials. A small-scale version of the use case has been deployed and evaluated into the 5G infrastructure that is provided by the Patras5G testbed. A preliminary series of tests has been organised, evaluating the performance of the solution. Within these tests, the capabilities of the solution and the 5G infrastructure have been validated. A camera sensor was used, providing input to the analytics modules of the solution through the 5G infrastructure. Several metrics, such as latency, and throughput, were collected. These metrics are mentioned in Table I (the network consumption was mainly uplink, from cameras to the network application). During these tests, the mean end-to-end delay of the process (from the camera on the field to the completion of the analytics process) was around 1 second, while multiple high-resolution cameras were able to be used simultaneously. The QoE assessment yielded positive results, with no issues identified and the video displaying good image quality, maintaining an average framerate of 30 frames per second.

	UC A	UC B	UC C
Network Consumption (Mbps)	23.2 /user	81 /user	14.2 /camera stream
Application Latency (msec)	60.5[1]	34[1]	62.5[2]

TABLE I
PRELIMINARY REPORTS OF NETWORK CONSUMPTION AND APPLICATION LATENCY FOR EACH UC. ALL METRICS WERE OBTAINED AT THE PATRAS5G TESTBED. LATENCY FOR UC'S WAS MEASURED AT APPLICATION LEVEL. [1]: INCLUDES 5G AND MOBILE WIFI-HOTSPOT LATENCIES, [2]: INCLUDES 5G ROUTER LATENCY.

V. RESULTS & PREPARATIONS FOR LARGE SCALE TRIALS

The conducted small-scale lab trials helped identify and resolve various issues between components before the large scale field trials. Specifically, for UC A, results indicate that a good QoE can be achieved for both AR and VR users. It was confirmed that latency levels are sufficient to preserve user immersion, and network configurations supporting these round-trip times were identified. Additionally, it was demonstrated that XR HMDs, lacking a 5G interface, can effectively connect to a 5G network via a WiFi hotspot on 5G-enabled mobile phones; such a setup will be used in the upcoming large scale field trials.

For UC B, optimal combinations for performance and reliability were also identified. Challenges in recognizing standing individuals were addressed by updating the recognition model and adopting YOLOv5 for its speed and accuracy. Implementing YOLOv5 improved recognition capabilities, reduced latency, and increased processing speed, resulting in more precise and efficient outcomes.

Lastly, for UC C, this preliminary small-scale test revealed the capabilities of the 5G infrastructure in near-real conditions. The network's delay and bandwidth were found to be sufficient, though this depends on deployment scale. Additionally, 5G network density is crucial, as most wildfires occur in rural or wilderness areas where 5G antenna density is typically lower than in urban environments.

During the lab trials of each presented UC at the Patras 5G testbed, metrics for bandwidth consumption and application-level latency were obtained (see Table I). Comparing these metrics with the capabilities of the testbed (see Table II), provides insights into the potential performance of field trials, where multiple concurrent users will coexist on the network.

Throughout our experiments, the best performance was almost always achieved when legacy user equipment without 5G support, such as AR/VR headsets or cameras, was connected to the corresponding application via a dedicated 5G device. This setup typically involved a mobile 5G phone using WiFi/USB tethering or a 5G router. This configuration consistently provided superior connectivity, lower latency, and more stable performance, ensuring optimal operation of the PPDR applications compared to scenarios where multiple such devices used the same 5G device as a gateway. Future tests involving 5G native HMD are expected to have better performance in both metrics and Quality of Experience. The use of a unified slice for both AR and VR users is anticipated to optimize bandwidth usage and significantly reduce latency.

VI. Lessons Learned and Challenges

The experiments conducted within the 5G testbed provided valuable insights into the performance and challenges associated with deploying 5G networks for PPDR applications. One notable finding was the identification of a tradeoff in network configurations. Some setups were optimized for either uplink or downlink bandwidth, while others achieved a balanced configuration that limited the total bandwidth available. This tradeoff underscores the need for a careful selection of network settings based on specific application requirements. A promising potential solution is the implementation of two separate networks—one optimized for uplink and another for downlink—to maximize performance in both directions.

Our trials confirmed that 5G networks can deliver low-latency, high-quality augmented reality (AR) and virtual reality (VR) experiences for up to three concurrent users. Notably, no increase in latency was observed as the user count scaled from one to three, suggesting minimal antenna interference and a positive outlook for scaling these applications in real-world scenarios. However, it is essential to conduct further testing with larger user groups to ensure performance remains consistent under heavier loads.

A significant challenge faced during the trials was the inherent limitation of AR/VR head-mounted displays (HMDs), which typically lack built-in 5G support, such as SIM card slots or 5G dongles. To address this, we explored two alternative approaches: using dedicated 5G routers and employing 5G smartphones equipped with USB tethering or WiFi hotspots. Both methods proved functional; however, using smartphones with WiFi hotspots emerged as the most effective solution. This approach allowed for greater user mobility beyond the fixed range of a router and successfully overcame the limitations associated with USB tethering on certain headsets.

Overall, these experiences not only highlighted the capabilities of 5G technology in supporting critical applications but also illuminated the challenges and considerations that must be addressed to optimize performance and scalability in real-world deployments.

VII. Conclusion

In this work, we present the first promising experimentation results of the demanding, use case network applications, towards validating B5G networks during the FIDAL project lifecycle. We present the 5G testbed and the testing methodology used, as well as detailed descriptions and results from the corresponding use cases.

These results were obtained in a research-level 5G infrastructure, using open-source solutions and components. In this setup, high quality results were delivered for limited number of users. As we envision large scale trials within the FIDAL project, commercial 5G network equipment will be employed to fully exploit the capabilities, in terms of bandwidth and latency, that only 5G and beyond networks can deliver.

The aim is to increase the number of concurrent experiments that can be executed in the testbed whilst also increasing the number of connected devices for each experiment to create a realistic real-life scenario. To this end, an evaluation of the testbed has been performed, the results of which can be seen in Table II. This, when combined with the performance and requirements of each use case, allows for better dimensioning and resource management, thus leading to more efficient deployment of both 5G networks and use cases.

Throughput			
Mean Value (Mbps)		DL Configuration	UL Configuration
Downstream	TCP	429.31	141.65
	UDP	688.91	80.25
Upstream	TCP	68	256.77
	UDP	62.62	254.67

TABLE II
PERFORMANCE METRICS OBTAINED ON NETWORK LEVEL

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