Hyper-5G: A Cross-Atlantic Digital Twin Testbed for Next Generation 5G IoT Networks and Beyond

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***Abstract*—This paper introduces the Hyper-5G research project, which aims at developing and evaluating an experimental proof of concept of a cross-Atlantic Network Digital Twin for the future wireless mobile 5G and beyond (B5G). Hyper-5G project brings innovative capabilities to allow distributed twins to replicate the 5G IoT network infrastructure digitally. Hyper-5G project interconnects two geographically distributed edge-cloud infrastructures, i.e., Grid5000 in Europe and Chameleon cloud in the US, to assess the feasibility of deploying new 5G IoT services using the twin. Hyper-5G offers an open European platform to experiment with different IoT scenarios, ranging from smart agriculture to healthcare, connected cars, etc. In the USA, Hyper-5G deploys the DT Hub inside the Chameleon cloud, connected to CHI-Edge IoT testbed, to enable emulating real-world IoT scenarios such as connected robots, smart cities, and smart grids, etc.**

***Index Terms*—Digital Twin, Real-Time IoT, Federated Learning, Mobile Edge, Predictive Analytic.**

I. INTRODUCTION

The emerging 5G network is expected to bring instantaneous connectivity to billions of IoT devices to enable the digital transformation of Industry 4.0 for companies, customers, and investors. According to recent report [1], 85 percent of IoT platforms will contain some form of digital twinning by 2025 driving projections of market growth from $3.1 Billions today to $48.2 Billion in the next five years. Digital Twins (DT) are envisioned to replicate physical entities to their virtual entities [2], maintain a device twin for every connected device [3] and enable synchronization between them to achieve real-time replication.Typically, digital twin systems are generated and then synchronized using data flows in both directions between the real-world physical components and their virtual replica counterparts. Nowadays, the concept of DT is used in a wide variety of domains such as manufacturing, smart cities, smart grids, etc. to enhance the performance, enable proactive maintenance to extend the physical system's life, increase productivity, and innovate smarter and faster at reduced costs. Furthermore, a digital twin is expected to enable continuous prototyping, and testing on-demand, without interruption, assuring and self-optimizing the forthcoming 5G network and beyond [4].

Despite the benefits of digital twinning in different domains, there are several barriers towards its adoption at scale. First, digital twins require continuous interaction between real-world objects and their virtual representation in real-time and with reliable two-way communications [5]. However, due to the dynamic behavior and frequent changes in the network environment, it becomes challenging to ensure strict reliability, low latency, and real-time requirements. Indeed, due to the distributed nature of the digital twin systems and the variation of the network delay, it becomes challenging to keep network digital twins in sync or auto-sync between the physical network and digital twin network [6], i.e., reflecting the changes in the physical entities to their virtual replicas in real-time can be even more hard. Hence, the lack of real-time data feeds from local edge nodes to the digital twin to perform custom closed-loop control limits the continuous real-time interactions between physical IoT objects and their virtual replicas, which represent a key barrier towards the adoption of federated learning in digital twins.

Additionally, diverse connectivity protocols have been made during the past decades to enable the connectivity in different industrial sectors, ranging from wired data acquisition and control networks, such as the OPC Unified Architecture (OPC UA) [7], Time Sensitive Networking for Industrial Automation [8], and many more other solutions that provide deterministic low latency, reliable access, desired flexibility, and differentiated QoS services required by future IoT systems (e.g., industrial IoT, AR/VR). However, the heterogeneity of standards, protocols, and technologies further exacerbates the problem of understanding, finding, accessing, and extracting relevant data needed for use case-dependent applications. Consequently, depending on the scope and scale of the industrial domains, digital twins should integrate with existing networks and cater to the diversity of all these connectivity protocols.

Therefore, we argue that further investigations are needed to empower the Next Generation Internet (NGI) with digital twins to optimize the structure of industrial IoT systems and improve their real-time communication and energy efficiency. To address these limitations, this paper introduces the Hyper-5G project, which aims at enabling cross-Atlantic experimental validation of the distribution network digital twin model to make NGI more robust in various events, outbreaks, and down-

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time, by interconnecting both European testbeds (Grid5000 and FIT IoT-LAB) to the US testbeds (Chameleon Cloud and CHI-Edge). Second, the project forecasts the future Internet architecture evolution towards better efficiency, scalability, security, and resilience, leveraging network digital twin to provide reliability, fault tolerance, and auditability to create highly available, resilient, and robust internet infrastructure components.

II. RELATED WORK

The concept of Digital Twin has gained much popularity recently, which make is poised to make drastic changes in the future of IoT industrial environments. We have seen an increasing research efforts by academia and industry for facilitating the transition to digital twin. Schleich et al. [9] surveyed the recent advances on DT, its enabling technologies (e.g., edge and cloud computing, CPS, AI data mining, etc.) and showcased different use cases across the product lifecycle, involving the design, manufacturing, use, and recycling phase. Wu et al. [10] surveyed the recent research and technological development in the area of DT and the DTN (Digital Twin Network) deployment in different application domains. In particular, the authors provide key features and definitions of DTN. They elaborated the technical challenges in DTN implementation, and investigated potential addressing approaches. Finally, they showed promising application paradigms, technology evolution trends and open research issues related to DTN.

Khan and al. [11] argue that in order to enable the future Internet of Everything (IoE) in the forthcoming 6G network, there is a need for a novel framework that can be used to manage, operate, and optimize the wireless network infrastructure and its underlying IoE services. Lu et al. [12] introduce the Digital Twin Wireless Networks (DTWN) by incorporating digital twins into wireless networks, to migrate real-time data processing and computation to the edge plane. Then, they propose a blockchain empowered federated learning framework running in the DTWN for collaborative computing, which improves the reliability and security of the system, and enhances data privacy by formulating an optimization problem for edge association and exploit multi-agent reinforcement learning to find an optimal solution to the problem. Numerical results on real-world data-sets show that the proposed scheme yields improved efficiency and reduced cost compared to the benchmark learning method.

IoT-NGIN [13] focuses on implementing Meta-Level Digital Twins that allows on-usage interpretation and application of data and information and delivers improved efficiency and traffic congestions, in human centered twin smart cities. IoT-NGIN supports novel digital twins' functionality to enable high-availability and what-if scenarios. The 5G-DIVE [14] project is devoted to the development of 5G connectivity solution that supports distributed edge computing use cases such as deep AI/ML twinning for replica of a robotic arm for teleoperation [15], Zero Defect Manufacturing (ZDM), Massive Machine-Type-of Communication (mMTC), Drone Collision Avoidance System (DCAS) and Intelligent Image Processing for Drones (IIPFD), etc. Compared against IoT-NGIN and 5G-DIVE projects, Hyper-5G creates and experiments a large-scale distributed network DT Hubs that gather the trendiest technologies (e.g., federated learning, metaverse, augmented reality, tiny AI, etc.) into fascinating and ambitious solutions (e.g., self-assembling robots, mixed holographic reality, cellular-connected drones, autonomous supply chain) through disruptive transformation.

III. TOWARDS A NOVEL DT ARCHITECTURE FOR IOT 5G

In this section, we describe the proposed architecture of our Hyper-5G project [1], which aims at enabling network digital twin and supporting distributed DT hubs. We first describe the architectural design of the proposed solution and then delve into the technological choices that motivate our design.

A. Architectural Overview of Hyper-5G

The Hyper-5G project (Figure 1) proposes to experiment and evaluate a prototype of Digital Twin (DT) network for achieving resilient 5G internet services by ensuring high availability, openness, and disruption tolerance. The proposed DT creates a virtual replica of the current IoT network state to simplify the deployment and management of new 5G IoT services at scale. In our prototype, we interconnect two geographically distributed edge-to-cloud infrastructures, i.e., Grid5000 [16] in Europe and Chameleon cloud [17] in the US, to assess the feasibility of deploying new 5G services using the twin. Furthermore, we deploy DT Hubs that interconnect with existing IoT platforms in both regions.

In Europe, we interconnect Grid5000 cloud to Fit IoT-Lab [18], an open European platform for experiments with different IoT scenarios, ranging from smart agriculture to healthcare, connected cars, etc. In the USA, we deploy the DT Hub inside the Chameleon cloud, which is connected to the CHI-Edge [19] IoT testbed, to enable the emulation of real-world IoT scenarios such as connected robots, smart cities, and smart grids.

We use virtual tunnels to interconnect EU and US infrastructure. Furthermore, Hyper-5G makes use of a secure, high-performance, publish-subscribe, event-based middleware to provide i) real-time connectivity to IoT interfaces and digital twin Hub services at scale, ii) interconnect the edge network to the DT Hub services together to perform real-time analytics, iii) build scalable, modular, and reliable DT micro-services for real-time streaming sensor data, and iv) offer adaptive network control and service provisioning to support horizontal and vertical full automation at scale. As illustrated in Figure 1, Hyper-5G controls edge testbeds (i.e., EU FIT IoT-Lab and US CHI-Edge) by performing custom closed-loop control to build a common, powerful federated on-device (local FedML in Figure 1) machine learning model that embeds edge intelligence and twins with an end-to-end (e2e) view of the network, including radio access networks and edge to cloud networks.

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[1] https://ngiatlantic.eu/funded-experiments/hyper-5g

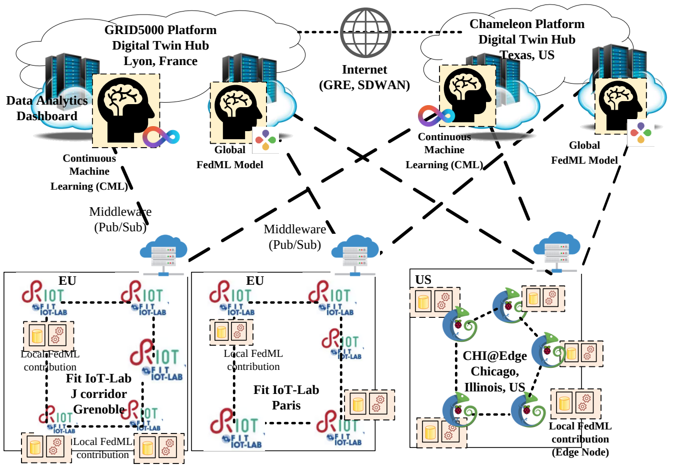


Fig. 1. Architectural Overview of the proposed solution

The asynchronous distributed (federated) model learning and inferencing on heterogeneous edge devices (i.e., including different hardware accelerator technologies) consumes substantially less computing power and less energy. Furthermore, to produce immediate analysis from static or streaming data of any size, the project uses continuous machine learning (aka. MLOps) to perform simulations, auto reports for ML experiments and predictions, and create recommendations. It expects to benefit from these real-time insights and intelligence to create an accurate and up-to-date network view and autonomously learn and adapt as new data comes in. Hyper-5G uses data analytics tools (e.g., based on Spark and Elasticsearch) to operate on those data and extract insights from testbed platforms to help predict future behavior, simulate different scenarios, and other analytics tasks. Hyper-5G interacts with data analytics to present results and findings through visualization tools to offer a timely decision process.

Hyper-5G improves both maintainability and deployability. For maintainability, it enables i) flexibility by supporting the efficient deployment of upgrades in case of disastrous system failures, performance degradation, and changes in workload, ii) Hyper-5G is equipped with periodic self-test procedures to track system integrity and immunity against malicious attacks, and iii) the Hyper-5G digital twin enables auditability and responsiveness to change conditions of 5G services. For deployability, Hyper-5G allows i) to quickly and instantly switch back and forth between different versions of software and dependencies, ii) to easily distribute and combine new technologies to deploy them and make appropriate modifications at run-time, iii) a coordinated approach to realize the required deployments and upgrades on the NGI infrastructure for solving scalability issues, increasing reusability of efforts, and sharing of knowledge beyond the project lifetime, and vi) ensuring resiliency, reliability, trustworthiness, and sustainability of the NGI, as well as increasing the responsiveness and availability of the Internet towards future 6G services.

B. *Supporting Network Digital Twin*

We aim to assess digital twin networks for mission-critical applications, such as cross-Atlantic robot remote surgery, as depicted in Figure 2. Such operations require ultra-low latency, reinforced security, and high-level reliability. The system comprises connected robots in CHI-Edge connected to the 5G mobile network.

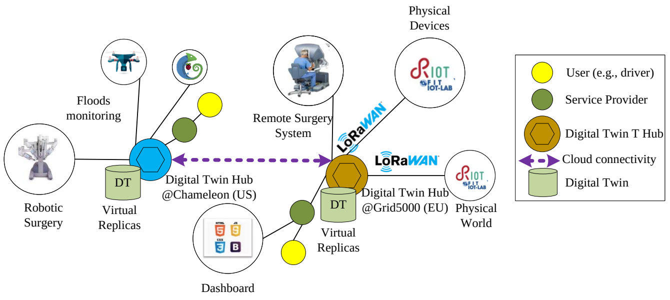


Fig. 2. Simplified view of distributed Digital Twin Hubs

Hyper-5G implements and evaluate a proof of concept of two DT Hubs: EU DT hub to create a virtual representation of IoT-LAB (e.g., LoRaWAN nodes and environmental sensors) and send data to a remote US DT hub via secured Internet gateway, and vice versa. We integrate Big Data Analytic tools (e.g., elastic search, Kibana) for continuous machine learning in the digital twin, implement straightforward monitoring and supervision (using Kibana front-end) to visualize the data, and enforce real time, scalability and reliability using Kafka stream processing for interconnecting DT Hubs. Data analytic algorithms and visualization tools (e.g., dashboard) are tested inside the European Grid'5000 platform as well as the US-based Chameleon Cloud platform, which allows monitoring the collected data and visualizing the interaction with the DT hubs in real time.

C. *Implementation Details*

Figure 3 shows the implementation details of the Hyper5G Framework. As discussed in Section III, Hyper5G connects different digital twin hubs located in Europe and USA. Each DT hub provides a broker platform with real-time and historical data storage made available from and to IoT devices deployed between different platforms (IoT-Lab and CHI-Edge).

As shown in Figure 3, the authentication of the registered devices uses OpenID Connect (OIDC), which adds login and profile information about the IoT devices. Each device in a tenant has a unique identifier (ID) that can be used for device authorization grant, as described by RFC8628 [20]. Edge devices do not require two-way communication with OAuth clients. Instead, Eclipse Hono approves the access request for the underlying sensor devices.

Eclipse Hono creates the connection with both the digital service in Ditto and the authorized IoT devices and allows creating of tenants and registering IoT devices on these tenants. Then, Hono uses device information to determine whether a device belonging to specific tenants is allowed to connect to the protocol adapters or needs an additional

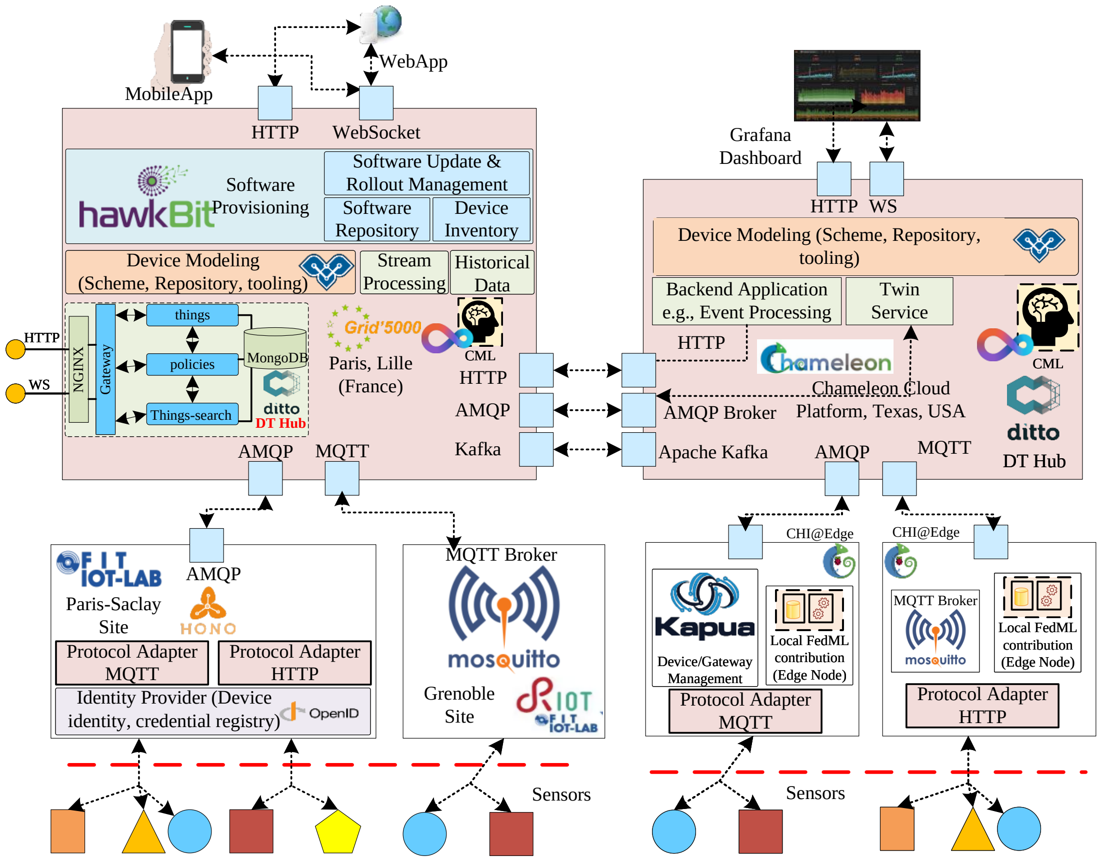


Fig. 3. Hyper5G Framework: Implementation Details

authentication procedure to join the twin platform. Currently, three protocol adapters are supported, i.e., AMQP adapter, MQTT adapter, and HTTP adapter. AMQP API allows IoT devices to exchange messages with Hono tenants through an AMQP client, which connects to Hono to invoke operations of the API. MQTT provider allows lightweight publish-subscribe message exchange between the underlying physical assets (i.e., IoT devices) and Hono using limited bandwidth. HTTP protocol adapter enables CoAP-enabled (Constrained Application Protocol) to retrieve data from IoT devices following the ETSI M2M architecture. To this end, a hierarchical containment tree where each node in the tree represents an IoT resource is invoked to pull different data and measurements of IoT devices and their associated attributes. These attributes include the resource's description in the form of meta-data that provides information about the resource creation, access rights, creator of the resource, content size, creation time and date, etc.

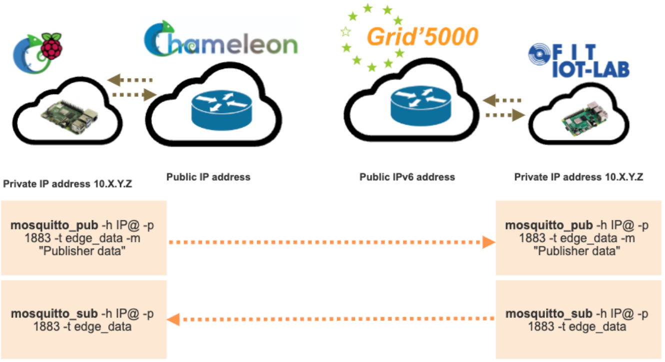
Eclipse Ditto provides a device as a service and allows the creation of the digital twin of registered things in Hono once the connection is established through the protocol adapters. Ditto connects to Hono through AMQP messaging bus for a particular tenant, which sends IoT data retrieved from the registered and authorized devices to Ditto. In Ditto, each DT has represented as a *Thing* entity via a simple text format JSON-based description language. To manage and operate multiple things connected to it, Ditto introduces the concept of *Features* to collect all data and functionality of a Thing that can be clustered in a specific context. Different features represent states and properties of things and DT functionalities for different contexts or aspects of a thing. Furthermore, Ditto provides both REST-like HTTP API to manage DTs and communicate with their real-world counterparts. Client Software Development Kit (SDK) API implementations in different programming languages (Java, JavaScript, and Python) uses the Ditto protocol to exchange messages between the physical assets and their virtual replicas in the DT. A built-in search engine, so-called things-search, finds things and a predefined policy system to configure fine-grained access control. Physical assets (aka, *Things entity*) can update their states and values by sending commands to the DT via Hono. If a command is successful, the states of the thing entity are updated, and a new event is generated.

Ditto uses MongoDB database service to store the latest states of the sensor values of the digital twin, and connects to InfluxDB via Apache Kafka service to keep track of all historical data that is used for big data analytics, stream processing and feed machine learning models. Hyper5G framework brings together MLOps, Continuous ML, and AutoML to deploy and maintain machine learning models in production reliably and efficiently. Above the Ditto digital twin layer, Eclipse Vorto provides a language independent description of devices for modeling the digital twin. It allows reducing the development and coding time and simplifying the integration of physical assets in digital twin by enabling the design of information models and function blocks for modeling the information models. Finally, Hyper5G project uses Eclipse HawkBit back-end framework for deploying firmware updates to edge devices, controllers, and gateways connected to the Internet. The connection of the different objects to the HawkBit solution can be done directly through optimized interfaces or indirectly through device management servers, depending on the chosen architecture.

D. Experimental scenarios

We have developed two connectivity scenarios to interconnect the remote testbed. As both CHI-Edge and IoT-Lab platforms are connected to chameleon cloud and Grid5000 testbeds, respectively, we can run experiments on these edge IoT platform and using the developed scenarios we can achieve end-to-end communication between them.

1) Scenario 1: Interconnection over public IPv4 : Figure 4 illustrates the first scenario, which makes use of public IP addressing available on the US chameleon cloud to connect to the European Grid5000 Platform. In this scenario, we lease remote machines on Grid'5000 and Chameleon Cloud (cloud server). Then, we lease IoT devices, i.e., Raspberry Pi 3 nodes, in FIT IoT LAB and CHI-Edge (edge device). Next, we deploy MQTT broker and run deep Learning application on the cloud server for AI inference. Thereafter, we deploy MQTT client on the Raspberry Pi to send images feeds from connected cameras to the cloud server.

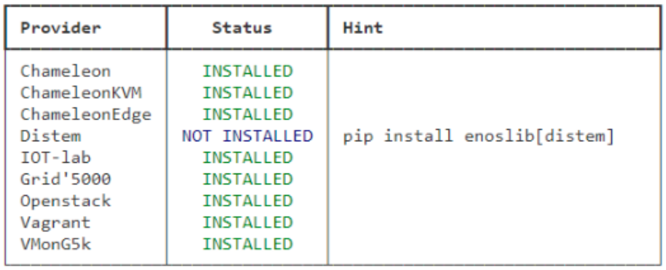


```
mosquitto_pub -h IP@ -p 1883 -t edge_data -m "Publisher data"
mosquitto_pub -h IP@ -p 1883 -t edge_data -m "Publisher data"
mosquitto_sub -h IP@ -p 1883 -t edge_data
mosquitto_sub -h IP@ -p 1883 -t edge_data
```

Fig. 4. MQTT messaging between G5K and CHI using public IPv4

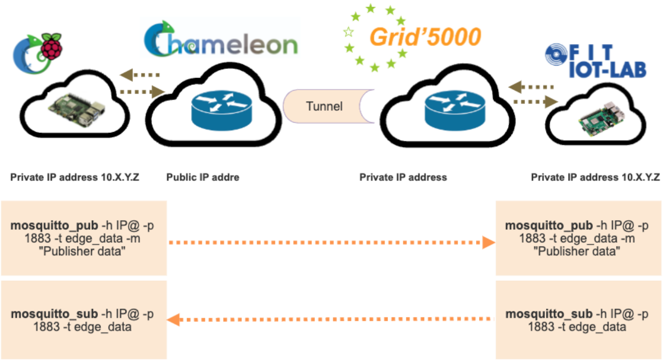
Figure 5 illustrates the status of the configuration on all EU and US platform. We can notice that all the platforms are correctly connected, their software and hardware dependencies are met.

2) Scenario 2: Interconnection over Virtual Private Network: in this scenario, we use Grid'5000 Virtual Private Network (VPN) for connecting our local workstation or personal computer to Grid'5000 network, while preserving security. When connected to Grid'5000 VPN, our local machine is considered *inside* the Grid'5000 network, thus it won't be required to perform several SSH hops or tunnels to access Grid'5000 nodes, since direct connections are possible. Figure 6 describes our approach of using Grid5000 VPN to connect remote Chameleon cloud and CHI-Edge.



Provider	Status	Hint
Chameleon	INSTALLED	
ChameleonKVM	INSTALLED	
ChameleonEdge	INSTALLED	
Distem	NOT INSTALLED	pip install enoslib[distem]
IOT-lab	INSTALLED	
Grid'5000	INSTALLED	
Openstack	INSTALLED	
Vagrant	INSTALLED	
VMonG5k	INSTALLED	

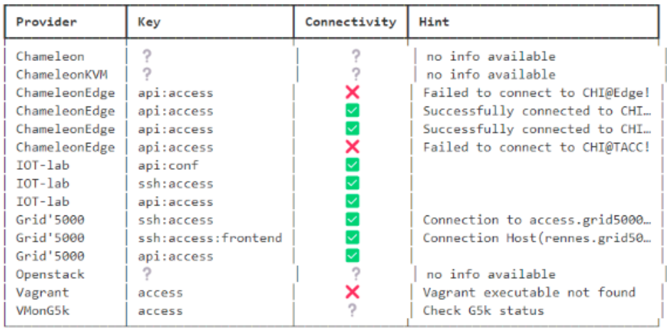
Fig. 5. dependencies check in all experimental platform



```
mosquitto_pub -h IP@ -p 1883 -t edge_data -m "Publisher data"
mosquitto_pub -h IP@ -p 1883 -t edge_data -m "Publisher data"
mosquitto_sub -h IP@ -p 1883 -t edge_data
mosquitto_sub -h IP@ -p 1883 -t edge_data
```

Fig. 6. Using Grid'5000 VPN to connect remote Chameleon cloud

Similarly, we show in Figure 7 the status of the connectivity between all the platforms, i.e., the European test beads are connected to the US testbed during the experiments. Some experiments in Figure 7 show hint messages saying that no information was available, this is because we are not using the specific hardware and software equipment's available on these equipments. For example, chameleon KVM is tool used to create specific cluster nodes to enable infrastructure as a service (IaaS) on the US testbed. However, these experiments are not the scope of this project and keep them as



Provider	Key	Connectivity	Hint
Chameleon	?	?	no info available
ChameleonKVM	?	?	no info available
ChameleonEdge	api:access	✗	Failed to connect to CHI@Edge!
ChameleonEdge	api:access	✓	Successfully connected to CHI…
ChameleonEdge	api:access	✓	Successfully connected to CHI…
ChameleonEdge	api:access	✗	Failed to connect to CHI@TACC!
IOT-lab	api:conf	✓	
IOT-lab	ssh:access	✓	
IOT-lab	api:access	✓	
Grid'5000	ssh:access	✓	Connection to access.grid5000…
Grid'5000	ssh:access:frontend	✓	Connection Host(rennes.grid50…
Grid'5000	api:access	✓	
Openstack	?	?	no info available
Vagrant	access	✗	Vagrant executable not found
VMonG5k	access	?	Check G5k status

Fig. 7. Connectivity Check in all EU and US testbeds

E. Monitoring and Data Collection

We have used several methods to monitors the information collected in all the testbed in which we have performed the experiments. First, in IoT-Lab, we have used web interfaces to configure different profiles and define the KPI we want to supervise during the experiments. For example, in addition to the web portable that enables us to monitor the experiments in real-time (as shown in Figure 27) we have created profiles to monitor the radio communication for wireless nodes: Figure 28 shows the RSSI parameter that identifies the quality of the transmitted and received signals through the wireless channels. Figure 29 illustrates the Radio Sniffer monitoring, which allows us to capture the exchanged packets on the fly and analyze the traffic exchanged in real-time. We can also use the capture files that include the exchanged data between the senders and receivers and analyze them with Wireshark tool. The advantage is that this packet analyzes can be performed offline and can be copied to different machines for further investigation and reproducibility. We have also monitored the energy consumption as shown in Figure 30.

IV. CONCLUSION

This paper delves into the architectural design of Hyper-5G project, which implements an digital twin API to distribute data across Atlantic cloud servers and assess the feasibility of deploying new 5G IoT services using the twin. Besides, we introduced Device as a Service by offering a high-level abstract API (realized as a REST API) to access remote devices, a state management service for event notification of state changes in the DT, and digital twin management by offering a meta-data scheme for searching and selecting digital twins. We have implemented the proposed solution in the cross-Atlantic testbeds and shown its effectiveness in achieving low latency and guaranteeing end-to-end QoS parameters on different platforms.

Although several opportunities for DT exist, they also pose a set of challenges that should be addressed, such as the need for common standardized and open abstracted API, which will require coordinated attention from the research community for its success and wide acceptance. We believe additional challenges and opportunities for research exists along a broad spectrum, ranging from composable DT solutions to be used in the upcoming 5G network and beyond, to high-fidelity formal data modeling, knowledge data mapping, and blockchain-based security models to improve the trustworthiness of the DT-based solutions, which present our future research direction.

ACKNOWLEDGMENT

This work was funded by EU-H2020 under the NGI Atlantic Program, Grant Agreement number: 871582. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of NGI or H2020.

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