NEXT GENERATION INTERNET

Open Call 5

HyPer-5G: Hyper Performance Network Digital Twin for Holistic Management of 5G IoT Edge Network

Deliverable 3: Experiment Results and Final Report

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Deliverable 3: Part I

Analysis, results, and wider impact

1 Abstract

Hyper-5G research project aims at experimenting with a network digital twin (DT), which can process data gathered remotely distributed in EU-US IoT infrastructures and provide closed-loop control to build a common, powerful federated learning model that embeds edge intelligence and twins with an end-to-end (e2e) view of the network. Hyper-5G is a flagship for the 6G vision to connect human, physical, and digital worlds with a set of 6G key enabling technologies. HyPer-5G's broader and primary research goal is to prepare thoroughly and advance current European (and global) understanding and public perception regarding the potential of the digital twins to simplify and streamline the future 5G IoT services and applications and their vital role in transitioning 5G from being a physical network to a metaverse system.

Tallinn University of Technology, the EU partner, is involved in the configuration and deployment of DT services across the GRID5000 and Fit IoT-Lab, and assessment. Vanderbilt University, the US partner, is experimenting with network interconnection, resource configuration, and evaluation of hierarchical federated learning experiments in the Chameleon Cloud. First, IoT devices, gateways, and servers suitable for testing IoT edge networking with small wireless sensor devices and heterogeneous objects are used and evaluated in-house. Second, the generated data is sent to the DT Hub server at Grid'5000. Additionally, we assess different KPIs in the digital twin (bandwidth, latency, energy, and reliability). Finally, we assess distributed scenarios of massive twining services across two cloud infrastructures and evaluate the pub/sub communication, reliability, low latency, high data rate, and ensure data integrity.

2 Project Vision

The Hyper-5G project proposes to experiment with and evaluate a prototype of a Digital Twin network for achieving resilient 5G IoT services by ensuring high availability, openness, and disruption tolerance. The Hyper-5G project connects two geographically dispersed edge-cloud infrastructures, Grid5000 in Europe and Chameleon cloud in the United States, to evaluate the feasibility of deploying new 5G IoT services using the twin. The HyPer-5G research project offers an open European platform for experiments 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 the CHI@Edge IoT testbed, to enable emulating real-world IoT scenarios such as connected robots, smart cities, and smart grids, to name but a few.

This project offers a unique opportunity to build reputations, establish leadership positions in 5G/6G research and teaching, and enable reinforced collaboration and increased synergies between the EU and US partners. This project will then allow for creation of a European 5G testbed to support an ambitious research agenda. Furthermore, the proposed experiments will offer European exceptionalism by enabling and empowering EU citizens to contribute to security and trust data for democratic decision-making. It also makes citizens part of the action and works with other knowledge actors, including citizens, civil society, and end-users, such as in citizen science.

3 Details on participants (both EU and US)

Europe Team at TalTech Estonia

- **Dr. Sadok Ben Yahia** is a full professor of computer science technologies and head of the Data Science group at the Tallinn University of Technology, Estonia. His research interests mainly focus on near-real-time big data management in different use cases, e.g., e-healthcare information systems and sustainable urban mobility in smart cities. Dr. Ben Yahia participates in the project using his long expertise in big data analytics for IoT and distributed systems. He contributes to collecting data analysis and performs different extraction, transformation, and loading operations.
- **Akram Hakiri** is a senior research scientist adjunct at Tallinn University of Technology – TalTech. He has developed strong know-how on programmable networks, blockchain, distributed ledgers, and wireless mobile communication, focusing on using SDN/NFV for resource provisioning and task scheduling in edge computing and IoT systems. His expertise in the project involves the preparation of the network configuration across all distributed testbeds, preparing different communication scenarios, and developing IoT firmware to be deployed inside IoT devices. He is involved in the configuration and deployment of IoT nodes in the EU platform and evaluating different KPIs in remote sites, the configuration of the G5K platform to support different network configurations
    1. Internet-based connectivity through IPv6 network,
    2. SDN-based network interconnection with US ExoGENI testbed, and
    3. Creating and configuring a Virtual Private Network (VPN) between US and EU platforms.

- **Bassem Sellami** Dr. Sadok Ben Yahia and Dr. Akram Hakiri jointly co-supervised her Ph.D. in computer science, which she has held since October 2022. He conducts research on network virtualization, software-defined networking, QoS, resource management in wireless networks,

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artificial intelligence, machine learning, and deep learning. He is working on this project by making reliable machine-learning algorithms for IoT communication.

- **Amani Mtaoua**: is a master's student of computer sciences and cyber-physical systems. She is involved in experiments with the digital twin network on the Grid5000 platform. She is evaluating different Digital Twin platforms on-premises and experimenting with their performance on the EU G5K testbed. She is also experimenting with IoT services through both the Things Board open-source IoT platform and configuring the connection to the Things Network MQTT broker.
- **Nora Themri** is master's student of computer sciences and cyber-physical systems. She participated in Fit IoT-Lab's IoT communication experiments. Remarkably, she will identify the LoRaWAN platforms and implement experiments on their servers and gateways.

US Team at Vanderbilt University

- **Dr. Aniruddha Gokhale** is a Full Professor in the Dept of Computer Science and a Senior Research Scientist at the Institute for Software Integrated Systems (ISIS), both at Vanderbilt University. His primary research interests are blending software engineering principles (e.g., design patterns, modelling) with systems research to address challenging problems in distributed systems. He has been awarded the prestigious NSF Career Award. He has also served as PI/Co-PI on several other projects sponsored by the NSF, DARPA, DoD, and industry. He is a senior member of both IEEE and ACM, and a member of USENIX. In this project, his contribution focuses on addressing diverse challenges in the context of Cloud/Edge Computing and IoT inside the Chameleon Cloud and Edge@CHI platforms.
- **Barve, Yogesh Damodar** is a Senior Research Scientist, at Vanderbilt University, Nashville, TN, USA. In the project, he is involved in WP3 and WP4. Specifically, he brings expertise in systems software, distributed computing, and resource configuration
- **Zhuangwei Kang** is a Ph.D. student and is involved in extending the experiments to other testbeds such as POWDER and Colosseum. While these testbeds are directly involved in the NGI Atlantic, both US and EU teams hope to extend the experiments to other 5G wireless environments.
- **Ziran Min** is a Ph.D. student, and in this project, she is involved in the experimentation and testing of distributed SDN testbeds. The virtualization of the data path between the EU and US distributed platforms. This includes configuring the cross-Atlantic virtual private network between G5K and the Chameleon cloud.
- **Shuang Zhou** is a Ph.D. student, and in this project, she is involved in the experiments and evaluation of hierarchical federated learning experiments in Grid5000 and Chameleon Cloud. This involves deploying FedML experiments in both Edge@CHI in the US and Fit IoT-Lab in the EU.
- **Baxter, Hunter** C. is a Master's student, and in this project, he is involved in the tests of the 5G RAN and UE services into the core 5G-NR. While this part is not directly related to this project, since, in these NGI experiments, we are engaged to perform experiments and tests on both G5K and Chameleon Cloud, the US-EU team hopes to extend these capabilities to other available testbeds such as FABRIC, Powder, and the RENEW testbed.

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4 Results

The Hyper-5G project brings innovative capabilities to allow distributed twins to replicate the 5G IoT network digitally, creates and experiments with cross-Atlantic, large-scale, distributed DT Hubs that gather the trendiest IoT technologies into fascinating and ambitious solutions through disruptive transformation. Such a disruptive transformation contributes to the design of future human-centered networks and built-in trustworthiness in an open society, advancing major societal and economic trends toward 2030 and beyond.
Hyper-5G is a 6G vision flagship that connects the human, physical, and digital worlds through a set of 6G key enabling technologies. The project's broader impact comprises multiple dimensions. In terms of the impact on the discipline, it has the potential to uncover new challenges and inform new solutions, e.g., for distributed heterogeneous operating environments spanning the spectrum of resources from the user to the edge to the cloud and improving the state-of-the-art in rapid learning of accurate models. It also can reveal interesting challenges and solutions to well-known distributed systems problems, such as distributed coordination, consensus, tail latency, and fault tolerance issues, in the context of more significant heterogeneity, scale, and modern settings, such as 5G and beyond (B5G).
The intellectual merit of the proposed research stems from its focus on bringing together different ideas, i.e., the digital twin, the IoT, and the edge cloud, and addressing the key challenges inherent in utilizing these ideas in our context.

4.1 Discussion and Analysis of Results

4.1.1. End-to-end latency

End-to-end latency is critical to many distributed cloud-based applications since it allows for predictable traffic routing. To evaluate the timing performance of our solution, we consider the end-to-end delay as the time duration to send a packet from source to destination. However, the one-way delay measurement is not straightforward because packets experience different network delays, including processing, queuing, transmission, and propagation delays. Thus, we have considered the two-way latency, i.e., the Round-Trip Time (RTT). We then consider a one-way delay as half of the RTT. Furthermore, to evaluate the effectiveness of our approach, we compared the latency results in the two scenarios we have developed.

These criteria have been evaluated in the context of representative application use cases studied in multiple testbeds available to the team, comprising individual institutional testbeds and platforms like Chameleon Cloud and G5K. The first testbed utilizes scaled-down connected and automated vehicles (CAV). The CAV testbed experiment comprises two networked applications: (1) platooning, where vehicles communicate to coordinate their control actions in a fast-moving platoon of closely spaced vehicles, and (2) traffic event information dissemination, in which vehicles relay information in a vehicular network. The former is critical and safety-related, while the latter is for improved situational awareness. Failure of communication links in platooning could result in crashes, while degraded situational awareness could result in less efficient traffic movement. These applications have been tested with a set of scaled-down CAVs equipped with DSRC or CV2X devices operating at scaled-down power. For non-critical applications, where vehicles are not automated, a fleet of actual vehicles can also be used. Network emulators are employed to induce congestion failure, jamming attacks, or intrusions. The

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emulator can also act as a bridge to RSUs, allowing cloud connection and emulation of digital twin and control plane services.

Additionally, bandwidth usage is a concern since our distributed networks must share the same physical infrastructure as other existing applications. Thus, data dissemination in the scenarios described above should be protected against any network fluctuation, such as congestion. To evaluate the usage of the shared links, we consider each application to generate best-effort traffic close to 200 Mbps. We aim to assess whether our approach shows better results in protecting the flow in the face of bandwidth fluctuation. We also compared our approach with the baseline recommendation of the IUT-T.

We conducted several experiments in various nodes on both the EU and US platforms. We have used multiple clusters and many bare-metal nodes inside each cluster, all with different capabilities (i.e., CPUs of 24 cores to 48 cores, RAM of 172 to 250 Go). Furthermore, we used many IoT edge nodes in Fit IoT-Lab (EU) and CHI-Edge (US). Specifically, in CHI edge, we have used Raspberry Pi and Jetson Nano nodes as IoT devices (i.e., which are also the only configuration available in this IoT testbed); in Fit IoT-Lab, we have used many nodes, such as i) LoRaWAN devices to communicate diverse data between IoT gateways and IoT servers, ii) Raspberry nodes for publish-subscribe communication, which are connected to the MQTT broker we deployed inside our G5K servers, and Ditto server nodes deployed inside our Chameleon cloud nodes.

In WP4, we have evaluated the end-to-end performance of wireless links in supporting the increasing number of wireless clients that join the experimentation platform. Our hypothesis is to obtain an optimized bandwidth usage between 80% and 100% of the link capacity. In our experiments, we obtained an overage bandwidth usage of 90%, which conforms with our hypothesis drawn in D1 and D2. For example, for the 25 GB of Ethernet link capacity available on the platforms, at least 20 GB are used for UE-US end-to-end data delivery, which gives us an idea about the reliability (performance degradation) of the wireless links, i.e., the URLLC load (average packets/time slot) determines the impact of URLLC traffic on the eMBB reliability. The results support our hypothesis, as we obtained an average latency of 120 ms, which is less than the threshold value of 150 ms in all scenarios tested. Furthermore, we have repeated the experiments several times and described the jitter (the variation of the latency over the experiments). Therefore, we find that both scenarios' jitter and packet loss satisfy our goals, i.e., both latency and packet loss didn’t significantly affect our experiments.

Regarding mobility and mobility interruption time, the experiments in WP4 involve mobile IoT nodes evolving in the emulated testbed, and we will evaluate the impact of mobility on data quality and network performance (retransmission, congestion). Our derived hypothesis is a delivery rate between 95% and 100% for a velocity speed between 10 m/s and 35 m/s. As expected, we obtained an average delivery rate of 98% across all experiments, which is consistent with our hypothesis because our average rates are consistent with our initial target.

4.1.2. Evaluating the distributed communication based on a decentralized Ledger

we evaluate the performance and scalability of the proposed approach in a blockchain environment. We defined performance as transaction latency and throughput. An IoT transaction is not considered valid until it is committed to the blockchain. These parameters establish an upper bound on transaction throughput. Performance is bounded by a combination of block interval—the time between publishing subsequent blocks—and block size. We define scalability as the blockchain network's ability to improve or degrade workload concerning the number of nodes. We used the Ethereum blockchain to implement a prototype that included 20 nodes that act as blockchain miners, where each node runs the

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leader-election consensus algorithm. Then we compared our solution against well-known baseline consensus algorithms, i.e., Proof of Work (PoW) and Practical Byzantine Fault Tolerance (PBFT). We evaluate the message exchange using different baseline algorithms and compare them against our proposed architecture. We first evaluate the PBFT approach. Next, we discuss the message exchange in POW. Finally, we assess the message exchange in our proposed architecture and compare its overhead against both PoW and PBFT.

4.1.2.1. Message Exchange in PBFT Baseline Algorithm

PBFT was designed to work efficiently in asynchronous systems with low overhead. Specifically, in PBFT, a specific leader proposes the order of the transactions, and then blockchain nodes communicate with each other in several steps to reach an agreement.

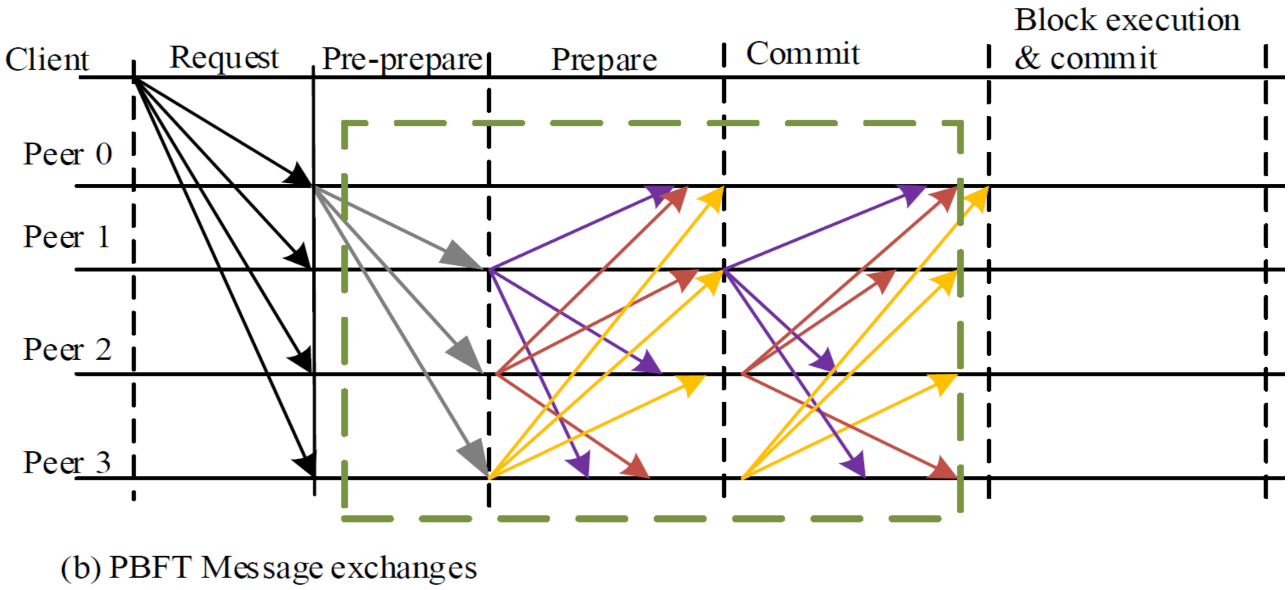

Figure 1: Message Exchange in voting-based PBFT

Figure 1 depicts the message exchange performed by the PBFT voting-based consensus used in the PoW algorithm. The PBFT is introduced to break the performance bottleneck of PoW-based blockchain systems.

4.1.2.2. Message Exchange in PoW Baseline Algorithm

PoW-based consensus does not require a fixed leader to validate the blocks. Instead, a group of leaders competes to validate a block of transactions. First, a node can propose a block of transactions and should solve a PoW (i.e., a mathematical challenge) from the previous transactions to get rewards if that proposal is accepted. Then, the node generates a pseudo-random number, the so-called nonce, which is broadcast to all connected nodes, as shown in Figure 2. After that, nodes compete to become the next leader (i.e., miner) by selecting transactions and generating a hash. The node generating the hash more minor than the nonce value becomes the next leader.

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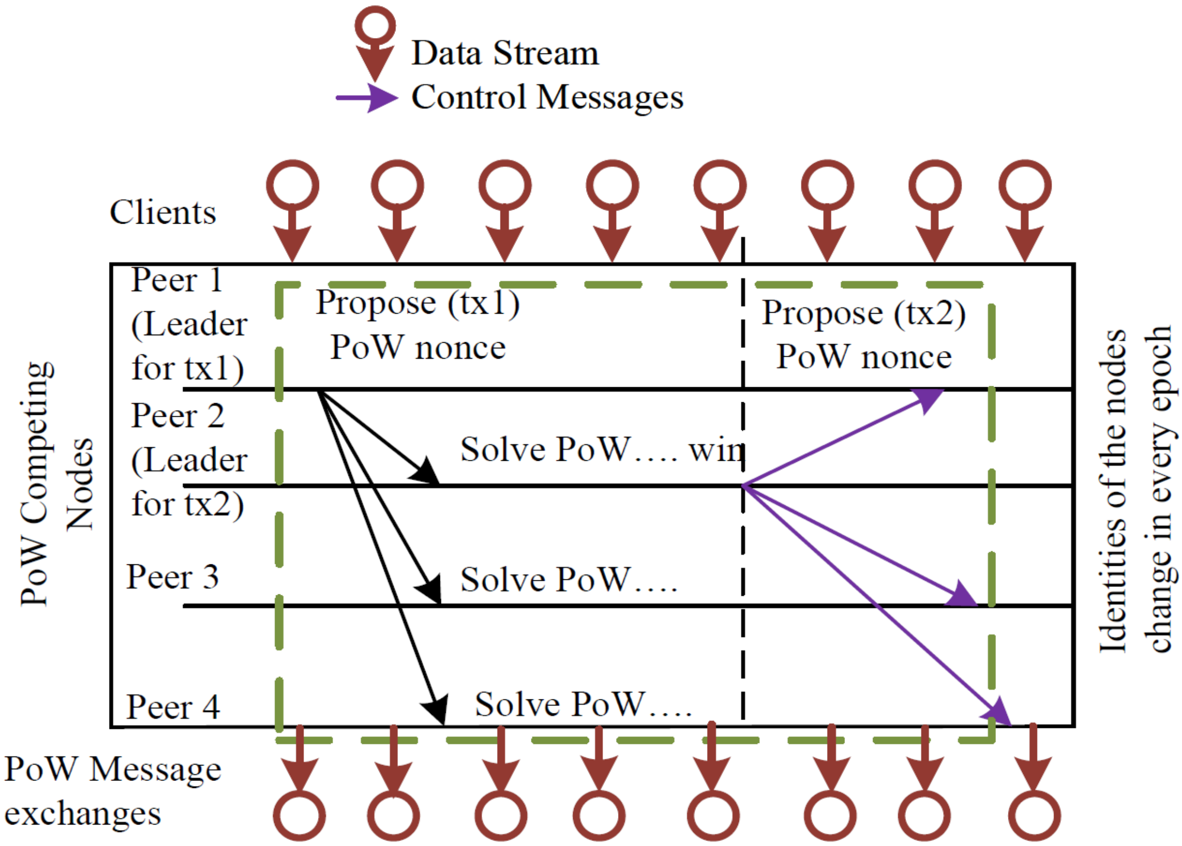

Figure 2: PoW Message Exchanges

Compared to the PBFT-based approach, the PoW algorithm involves less message exchange overhead to validate transactions, as depicted in Figure 2. Specifically, the PoW consensus algorithm requires four message rounds to commit a block. Before a new IoT transaction block is confirmed, most network nodes should verify and approve it. Additionally, in PoW, all unverified IoT transactions are put together in a poll. Then all miners work to check that those transactions are legitimate by solving a complex mathematical puzzle. Thus, the PoW consensus algorithm is the most reliable and secure among the three algorithms.

The problem occurs when more than one node simultaneously solves the mathematical puzzle. In such a situation, a fork operation of the hash chain is triggered and detected by all other connected miners, which leads to an overhead explosion of the message exchange. Such a situation involves the selection of the longest hash chain and takes a long time for each transaction to be validated. It often takes more than six blocks for a transaction to be finalized. The drawback of this approach, the de facto scenario in a distributed blockchain, is the limited number of transactions processed and concluded per second. Thus, scalability becomes an issue because the block size is too small to sustain thousands of transactions, lowering the overall blockchain network's throughput and increasing the energy consumption required to validate these transactions.

4.1.2.3. Message Exchange in Proof-of-Elapsed-Time Algorithm

Proof-of-Elapsed-Time consensus has been introduced to replace PoW with trusted hardware. The PoET is a random leader election consensus introduced by Intel. A separate random timer operates independently at every node to spread the chances of winning equally across network participants. This randomization gives every node the same chance of being the winner. In addition, PoET is coupled with

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the Intel Software Guard Extensions (SGX) trusted execution environment to determine whether a node can verify transactions and create more blocks.

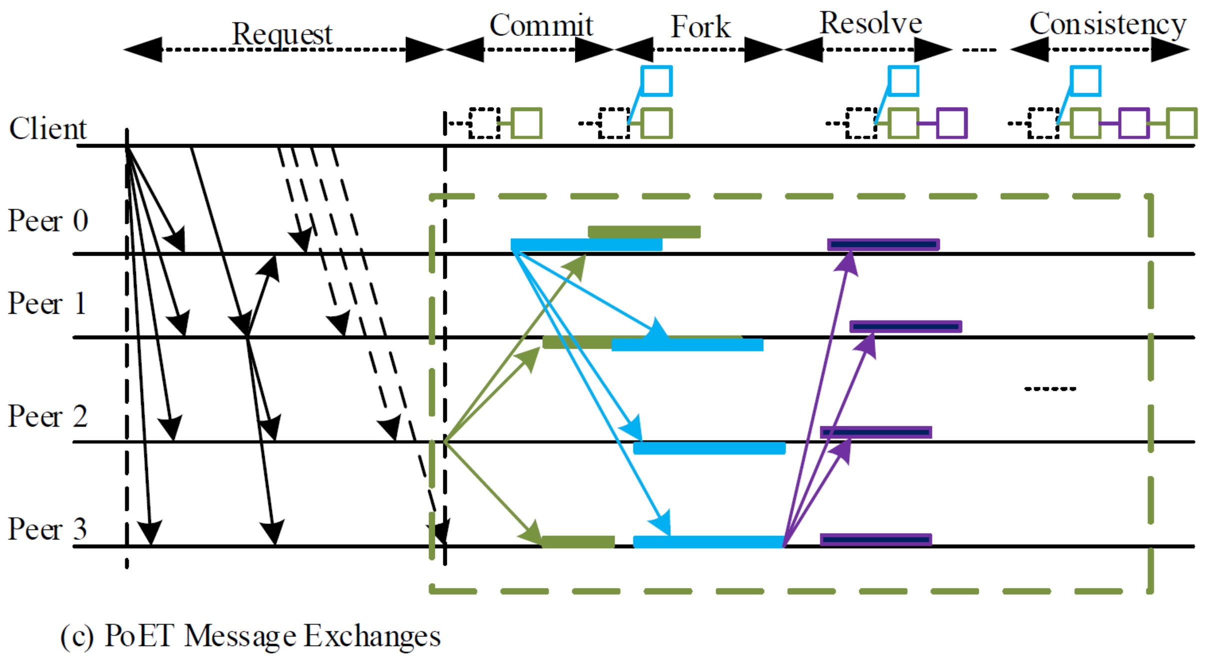

Figure 3: Message Exchange in lottery-based PoET

Figure 3 illustrates the message exchange for an IoT transaction's flow using the PoET consensus algorithm. The PoET lottery-based style of consensus algorithms needs five message rounds—Request, Commit, Fork, Resolve, and Consistency—to validate a block. In addition, the PoET consensus requires a computer running an Intel SGX processor that includes built-in security-specific instructions embedded in the hardware.

4.1.2.4. Message Exchange in our Architecture

A leader node (Authority 0) is shown in Figure 4(a), receiving a client request to validate an IoT transaction block. The leader then sends the block to a group of authority nodes (authority nodes 1, 2, and 3) that have already been approved. These authority nodes validate IoT transactions and add them to the blockchain.

Our validation process, based on the election of an IoT verifier node, shows lower transaction latency than the other consensus algorithms in terms of transaction latency. Our solution approach, in particular, requires only one round to validate and commit a new block to the blockchain. Because our approach relies on PoA, a communication-oriented consensus mechanism that does not involve extensive computation, it assumes bounded transaction latency expressed in terms of time steps. Furthermore, the block is committed at once. Hence, the transaction latency in terms of the number of message rounds is one.

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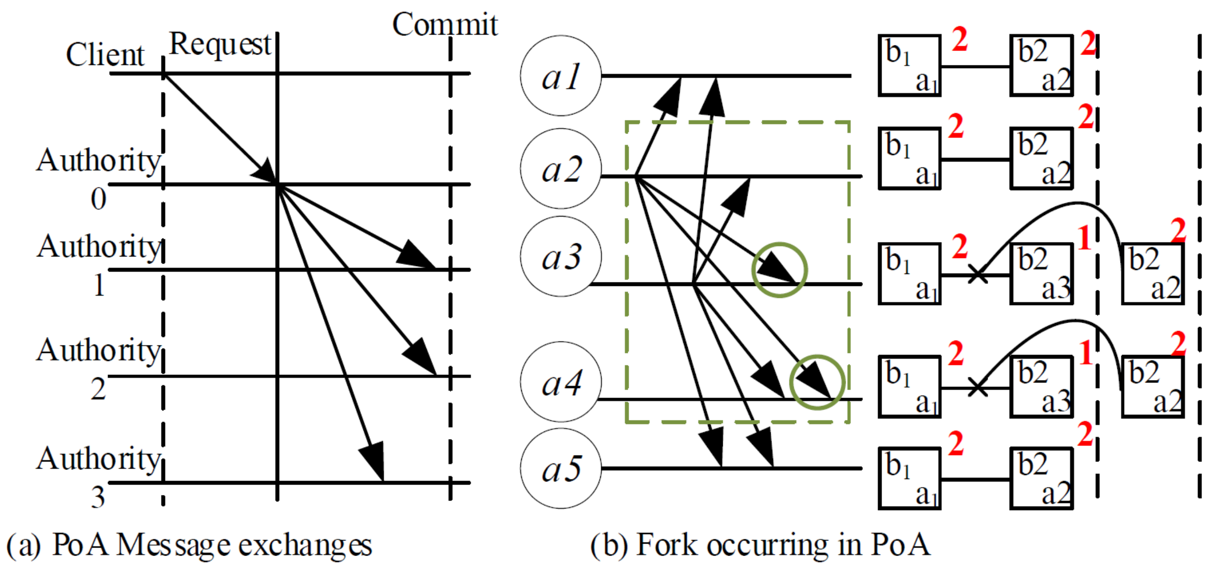

Figure 4: Latency during Message Exchange in our proposed approach based on the PoA

Figure 4(b) depicts a specific scenario in which a leader node a2 broadcasts a new block b1 to the blockchain while another non-leader authority node a3 simultaneously broadcasts another block b2. The first newly created block, b1, which precedes block b2, reaches nodes a1 and a5 before b2 arrives at these nodes. However, b2 reaches nodes a3 and a4 before they receive the first created block, b1.

The right side of Figure 4(b) shows a fork operation performed by each node in the blockchain when blocks from different miners become misaligned, and the network becomes desynchronized. Authority nodes "a3" and "a4" decide to continue using block b1 as the first block, reference it as a previously reacted block, and refer to block b2 as the next arriving block.

From the above discussion, we argue that our approach based on Proof-of-Authority (PoA) outperforms both PoW and PBFT and improves the performance of the blockchain IoT network.

As expected from our hypothesis, our approach selects representative mining nodes based on their reputation. Once the reputation system is built, preselected nodes have the authority to propose new transactions and notify others of the results. For IoT scenarios like IoVs, the Roadside Units (RSUs), the representative mining nodes, are preselected, trusted, and deployed by the IoV service providers, who assume they are not motivated to build up their reputation and then corrupt the entire system. Any malicious nodes can be easily detected and blacklisted based on their IDs, i.e., their physical or local addresses. In addition, other nodes about which we have doubts about their behaviour can be greylisted and cross-checked against their respective IDs.

4.1.2.5. Transactions Latency

In contrast to the transaction latency that involves the commitment of subsequent blocks, a.k.a., confirmation block, and the safety check against double-spending to ensure that the transaction will be irrevocable within the chain at least for the subsequent six mined blocks, the blockchain network latency is the time delay for the first confirmation of acceptance of a transaction by the network.

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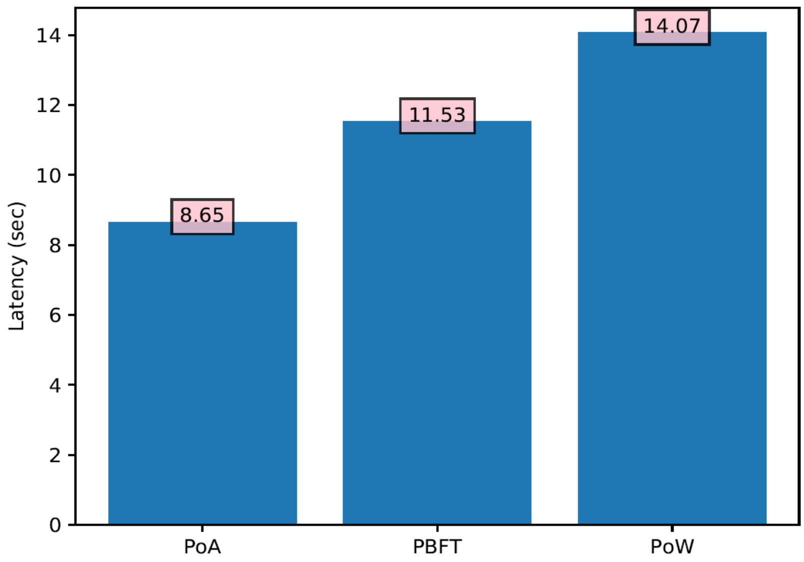

Fig 5: Latency of different consensus algorithms: our approach (PoA) versus PoW and PBFT over time

The implementation of our solution for three types of consensus (PoW, PBFT, and PoA) is depicted in Figure 5 in terms of network latency. Our experiments show that PoW consensus's latency is higher than other consensus algorithms. Indeed, PoW consumes substantial computational resources to confirm a block. Similarly, although practical Byzantine fault tolerance (PBFT) achieves lower latency than PoW (because it gives equal importance to all the participating nodes of the peer-to-peer network), it shows a higher latency than our approach, which implements the PoA consensus.

Specifically, our approach achieves an average latency of 8.51 seconds for confirming an IoT transaction. In addition, the voting-based PBFT consensus achieves an average latency of 12.09 seconds to validate a transaction. Finally, the PoW consensus validates a new IoT transaction with an average time delay of 14.35 seconds. Therefore, our approach outperforms these approaches and archives better network latency.

4.1.2.6. Transactions Throughput

There are two subcategories of blockchain throughput: read throughput and transaction throughput. The former measures the rates at which data are read, i.e., the number of reading operations completed in a given period, formally expressed in the number of reads per second (RPS). However, read throughput is often not considered a critical metric to evaluate the quality of service in a blockchain network because blockchain nodes typically achieve a significantly higher read and query efficiency than blocks' write operations in the ledger. The latter is a transaction's throughput, which measures how fast the blockchain can process incoming IoT transactions, expressed in transactions per second (TPS).

The blockchain network throughput is not measured at a single node, but reflects the overall performance across all nodes. The blockchain network throughput is defined as the ratio of total valid transactions over time in seconds.

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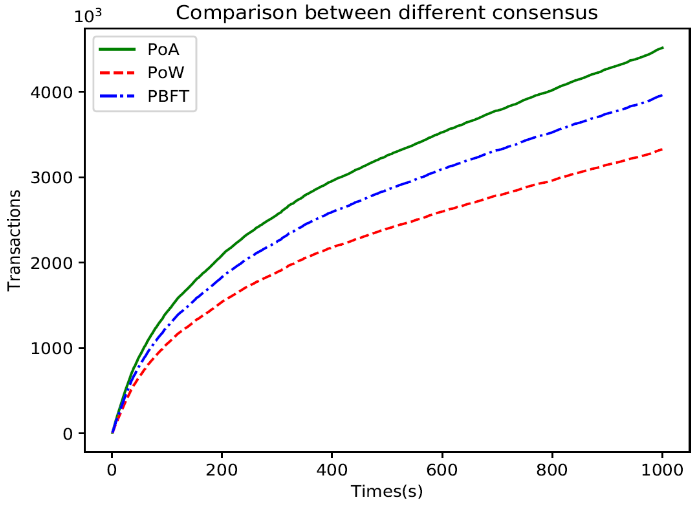

Figure 6: The proposed approach's transaction rate (TX/sec) against the PoW and PBFT algorithms.

Blockchain energy consumption has received much attention because the blockchain may be cost-ineffective due to the significant amount of computing power required. The cost of making transactions trustable can be the very wastefulness of mining. Mining involves competition against other miners, where all blockchain nodes race for a cryptographic lottery, which consumes considerable energy and computation resources.

4.1.2.7. Energy Consumption

Blockchain energy consumption has received much attention because the blockchain may be cost-ineffective due to the significant amount of computing power required. The cost of making transactions trustable can be the very wastefulness of mining. Mining involves competition against other miners, where all blockchain nodes race for a cryptographic lottery, which consumes considerable energy and computation resources.

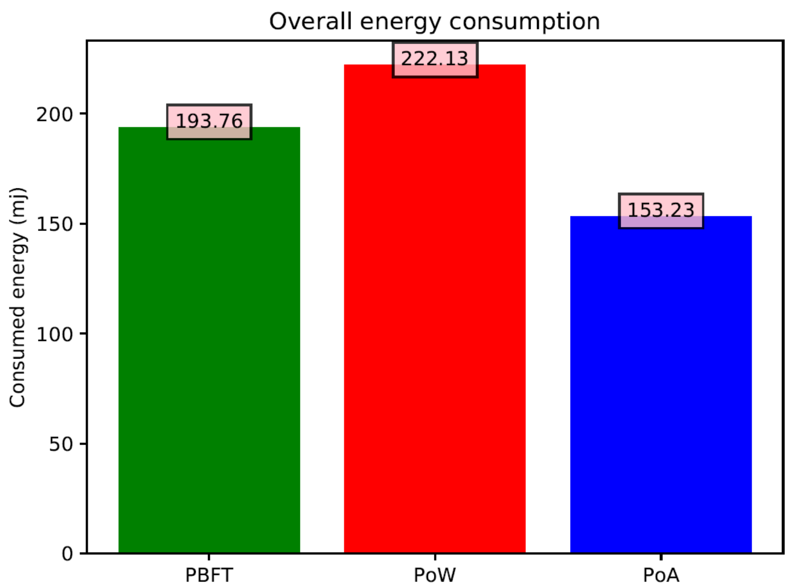

Figure 7: Evaluating the energy efficiency in battery-powered IoT nodes.

As shown in Figure 7, we have evaluated the energy efficiency of the proposed approach. Figure 7 illustrates that the PoW consensus algorithm performs worst as the battery capacity runs out after processing, conforming, and validating 18×106 transactions. Similarly, the PBFT approach performs

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slightly better than the PoW, as it can process and confirm an average of 280×106 transactions before running out at low levels.

Our approach, which leverages the PoA algorithm, achieves more than 100% better energy efficiency than the PoW approach and over 50% better energy savings than the PBFT. As a result, our approach ensures that excessive resource utilization and energy consumption are avoided. Furthermore, it helps to optimize the system's energy efficiency and intelligently allocate computational resources.

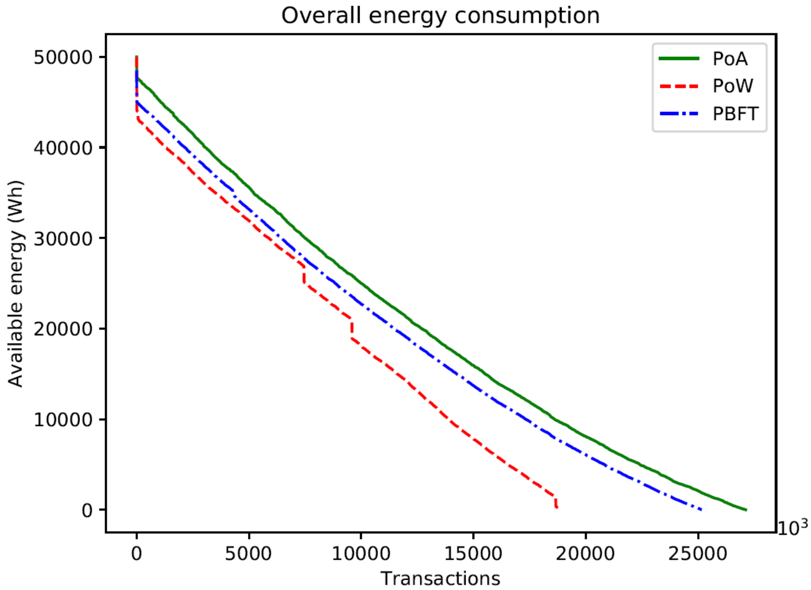

Figure 8: Comparison of the energy consumption of the proposed architecture with the PoW and PBFT baselines.

To further investigate the most energy-efficient blockchain consensus algorithm, Figure 8 illustrates the overall energy consumption of each approach. The PoW approach is energy-intensive, substantially consuming 222.13 MJ to deter frivolous or malicious attacks. Similarly, the PBFT consumes 193.76 MJ without conducting complex mathematical computations like in PoW. Finally, our approach based on PoA outperforms both approaches, as the energy consumption is around 153.23 mJ.

4.1.2.8. CPU Resource Utilization

Resource usage is a critical aspect of the blockchain to determine how distributed peer-to-peer (P2P) network nodes run smoothly. CPU resources are essential in blockchain communication since they dictate how many transactions can be validated, engaged in a block, and added to the blockchain.

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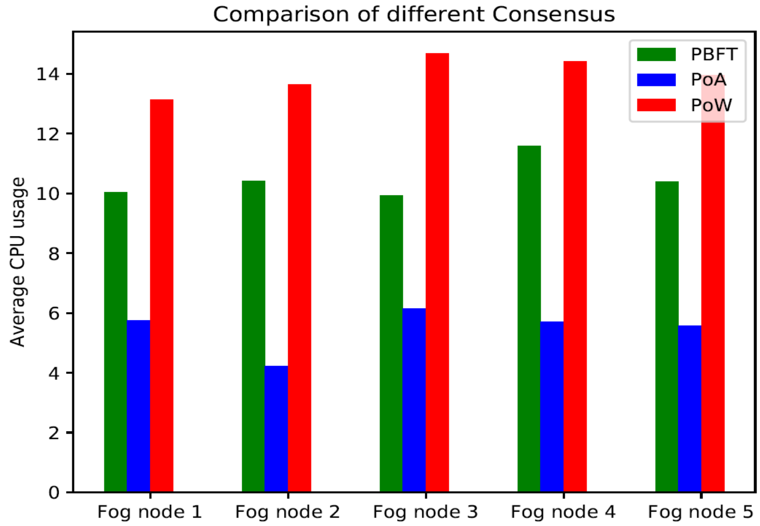

Figure 9: CPU usage: Our approach is based on PoA versus PoW and PBFT.

Figure 9 depicts the CPU usage of all approaches. Although the PoW CPU usage is around 14%, which is under the 50% required in the blockchain to validate a block, it is still high enough that straightforward tasks could have become laboriously slow. The PBFT consumes around 10% of CPU resources on different nodes. Finally, our approach outperforms both approaches with a 5% CPU usage. Our approach is not based on the computational power to validate IoT transactions; instead, the CPU computation is used only for fog nodes to process incoming requests. Our approach benefits from the election-based consensus algorithm used to preselect blockchain validator nodes. Such a process is not CPU-consuming; hence it outperforms the baseline consensus algorithms.

5 Present and Foreseen TRL

As described in our implementation plan in WP3 (i.e., prototyping) and WP4 (i.e., test and validation), we have some functioning instances of DT software (Eclipse Ditto) that we used to implement and evaluate a prototype. In particular, Eclipse Ditto supports different programming languages such as Java, Go, and Python, making it pluggable with existing IoT devices supported in our experimental platforms (e.g., Raspberry Pi) and with 3D modelling frameworks like Unity. It also supports open data formats like JSON, which makes it interoperable with existing IoT protocols (e.g., WoT, COAP, MQTT, Web Sockets), servers, and gateways, such as The Things Network (TTN) and ThingsBoard platforms, which are also supported by our IoT edge testbeds. Reusability also comes into play in favour of the Ditto framework, as DT services can develop in the form of microservices operating with Docker, Kubernetes, Helm, and OpenShift, which are DevOps solutions that can simplify the deployment of applications and services using lightweight containers and CI-CD pipelines.

Furthermore, Ditto can be deployed on-premises or in the cloud, which is ideal for our cloud platforms, which support both on-premise servers (such as Grid5000) and cloud services (such as our Chameleon cloud). Similarly, for DT modelling, Ditto can use Eclipse Vorto to define twin specifications and automatically generate code. Besides, 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 the AMQP messaging bus for a particular tenant, which sends

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IoT data retrieved from the registered and authorized devices to Ditto. Each DT is represented as a thing entity in Ditto using a simple text format and a JSON-based description language.

To manage and operate multiple things connected to it, Ditto introduces the concept of Features to collect all the 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 correspond to different contexts or aspects of a thing. Furthermore, Ditto provides a 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) use 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 uses 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 the MongoDB database service to store the latest states of the sensor values of the digital twin and connects to InfluxDB via the Apache Kafka service to keep track of all historical data used for big data analytics, stream processing, and feeding machine learning models. Above the Ditto digital twin layer, Eclipse Vorto provides a language-independent description of devices for modelling the digital twin. It enables the design of information models and function blocks for modelling the information models, reducing development and coding time, and simplifying the integration of physical assets in the digital twin. Finally, the Hyper5G project uses the 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.

Therefore, HyPer-5G evaluates a networked digital twin's experimental proof of concept to evolve from TRL2 (Potential Application Validated) towards TRL3 (Proof-of-Concept Demonstrated experimentally). The proposed experiments achieved in this project open doors to moving the proposed concept toward TRL 4.

6 Exploitation, Dissemination, and Communication Status

This project offered a unique opportunity to build reputations, establish leadership positions in 5G/6G research and teaching, and enable reinforced collaboration and increased synergies between the EU and US partners. In particular, in collaboration with our US partner (Vanderbilt University), we will organize the 26th IEEE ISORC2023 (https://isorc.github.io/2023/) international conference in Nashville, TN, USA, on May 23–25, 2023. In addition, we will organize the 1st International Workshop on Digital Twins for Next Generation 5G IoT and Beyond (DT4NG-IoT) in conjunction with the 26th International Symposium on Real-Time Distributed Computing, IEEE ISORC 2023, Nashville, Tennessee, 2023.
During the project performance period, we have successfully organized the BIOC'22 workshop (https://www.dymaxion-mfssia.com/ieee_bioc_2022_workshop/) and the 1st international IEEE IGET Blockchain conference (https://get.blockchain.ieee.org/) on blockchain and IoT. Besides, we have

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submitted two journal papers and expect to submit a conference paper to be published at IEEE ISORC 2023. Furthermore, during the project period, two master's students completed their studies, and their defence is scheduled for December 16, 2023. Finally, we have received a notification of acceptance of our special issue proposal on the digital twin.
Furthermore, we expect to realize financial sustainability through this project, as we will be submitting on December 22, 2022, a joint EU-US collaborative Research project proposal to NSF CNS CSR medium 2022, titled "***Enabling Distributed Edge Intelligence for Resilient Internet of Things,***" to address the future towards developing augmentation and adaptation techniques for secure and resilient 5G operations in the edge to core continuum.

- **Presentation of papers** on Digital Twin for IoT on the 2022 IEEE 1st Global Emerging Technology (https://get.blockchain.ieee.org/widgets/cfp/workshops)
  - the conference has been successfully organized in hybrid mode (remote and in-person). 1777 registration, 200 speakers, 5 days of actions (over 12 hours each day), 382 distinct agenda items, and 90 hours of recorded sessions.
- Refereed **journal articles** on Digital Twin for submission on top-rated periodic (e.g., IEEE Access, Computer Network (Elsevier), Future Generation Computer Systems (FGCS) (Elsevier), Digital Communications and Networks (Elsevier), targeting fellow researchers across multiple computer sciences disciplines.
  - **submitted journal papers**: Akram Hakiri, Sadok Ben Yahia, Aniruddha Gokhale, Nedra Mellouli Nauwycnk. *Digital Twins: New Frontiers in the IoT Industry: A Comprehensive Survey.* Future Generation Computer Systems (FGCS) Journal. Editor: Elsevier. Manuscript number: FGCS-D-22-02150. Impact factor: 7.187
  - **Conference organization:** the 26th IEEE International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing. Nashville, USA. May 2023. roles: Aniruddha Gokhale (Vanderbilt, USA): Conference Co-chair Akram Hakiri (TalTech, EU). Web chair (https://isorc.github.io/2023/)
    - Communicates with EAI Community Manager, who gives access to a ready-made conference website
    - Works closely with all chairs to make sure the Website is correct and updated at all times
    - Is responsible for all the changes and content updates made to the conference website
    - Publishes all newly confirmed information, mainly:
  - **submitted conference paper**: Akram Hakiri, Sadok Ben Yahia, Aniruddha Gokhale. *Cross-Atlantic Digital Twin Testbed for Next Generation 5G IoT Networks and Beyond*. The 26th IEEE International Symposium on Real-Time Distributed Computing (ISORC).
- An Open-access **project website** (https://hakiri.github.io/Hyper5G/) disseminates select project research outcomes and investigates their marketing potential, targeting academics, standardization bodies, competence centers, and Public bodies.
- Organization of **thematic sessions on seminars** (or webinars) to share knowledge with the scientific community related to standardization in the areas of "Internet of Things" (IoT) and

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"Digital Twin" technologies. Consideration will be given to emergent trends and the future work program concerning these technologies and some of their applications.

- The EU (TalTech) and US (Vanderbilt) partners have successfully organized the 5th Workshop on Blockchains for Inter-Organizational Collaboration (BIOC'22) in conjunction with the 2022 IEEE 1st Global Emerging Technology (https://www.dymaxion-mfssia.com/ieee_bioc_2022_workshop/). Two invited speakers and 4 original papers were presented during a half-day workshop with internationally recognized researchers and scientists from different countries. Over 40 participants attended the workshop.
- The EU (TalTech) and US (Vanderbilt) partners expect to organize a Workshop on Digital Twins and the Internet of Things in conjunction with the ISORC2023 Conference:
    - The 1st International Workshop on Digital Twins for Next Generation 5G IoT and Beyond (DT4NG-IoT) will be held in conjunction with the 26th International Symposium On Real-Time Distributed Computing, IEEE ISORC 2023, Nashville 23-25, 2023.

- **Special journal issue** on Digital twin and metaverse for 5G and beyond (e.g., FGCS, IEEE TSNM, IEEE IoT, IEEE Communication Magazine)
    - **We have received a notification of acceptance for our Special Issue proposal, which will be published in the top-rated FGCS journal**: Akram Hakiri, Sadok Ben Yahia, Aniruddha Gokhale, Nedra Mellouli Nauwycnk. *Journal: Special Issue on Digital Twin for Future Networks and Emerging IoT Applications. Accepted in Computer Science Journal Special Issues and Conference Proceedings Proposals.* Manuscript number: CSSI-PROCS-D-22-00982
- To strengthen the Hyper5G project's online presence, we identified three open-source collaboration Digital Twin developers' community interactions that will accelerate the adoption of digital twin-enabling technologies and solutions (e.g., DT consortium, FIWARE, and DigitalTwin.io), as well as Facebook groups (e.g., Digital Twins Professionals Network) and LinkedIn groups (e.g., Digital Twin Engineering) that will aid in disseminating our findings and receiving feedback. .
    - HyPer5G LinkedIn page:
        - https://www.linkedin.com/company/hyper5g/

7 Timeline

Figure 5 shows the progress of the work until the submission of this deliverable. All the work packages have been achieved successfully, which complies with the fixed objectives. Furthermore, WP4, which involves the preparation of EU and US testbeds, has made significant progress in the past month. Thus, the progress of the project has evolved as expected.

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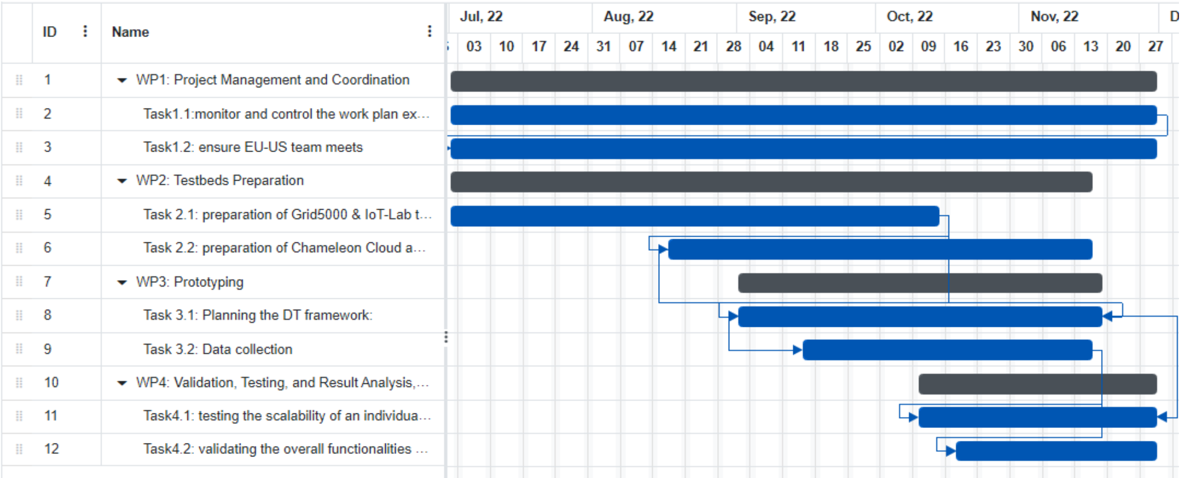

Figure 5: Gantt diagram showing the progress of the tasks for the last deliverable D3

8 Impacts

Impact 1: Enhanced EU – US cooperation in Next Generation Internet, including policy cooperation.

The project will enable US researchers to collaborate with multidisciplinary EU teams experienced in diverse large-scale platforms, including Grid5000 and IoT-Lab. Likewise, the EU team will perform experiments on US testbeds, such as NSF PAWR program-sponsored testbeds, and bring its competence in digital twins (DT) to help US partners build DT Hub capabilities to control and manage IoT. Simultaneously, the US team will provide expertise in artificial intelligence and machine learning that will empower the DH Hubs and provide expertise to the EU team to conduct experiments on US testbeds. This is a win-win partnership in which both partners mutually benefit from their respective expertise, nurture their existing relationship, and forge a strong alliance that promises to drive further future collaboration. Furthermore, the US and EU will experiment with diverse protocols in terms of capabilities (e.g., LPWAN, Optical/cellular and mobile, SDR, O-RAN). We will also explore other testbeds, such as the US-based NSF Chameleon Cloud and CHI@Edge, building upon new functionalities for managed distributed federated learning, edge computing, cybersecurity, zero trust, big data analytics, and data visualization. Both partners will benefit from the complementary know-how and the volume of knowledge that they will share to realize such cross-Atlantic experimental setups.

The project offers an invaluable and truly unique opportunity for developing collaborative EU-US experimentally driven research on resilient NGI services on trans-Atlantic testbeds. This is a unique opportunity for the EU partners to experiment with their prototype on one of the largest and most advanced wireless testbeds, ensuring interoperability between US and EU platforms. Furthermore, the Hyper-5G project will reinforce cooperation for better future EU-US relations. Their active collaboration has already created a fruitful relationship in developing the future standard for IEEE P1930.1, called SDN-MCM—SDN-based Middleware for Control and Management of 5G multi-RAT Networks.

Impact 2: Reinforced collaboration and increased synergies between the Next Generation Internet and Tomorrow's Internet programmes.

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The project brings together Dr. Hakiri and Dr. Ben Yahia from the EU and Prof. Gokhale and Aniruddha S from the United States. Dr. Hakiri has developed strong expertise in distributed networks, SDN/NFV, and IoT communication and has worked on several R&I projects, including H2020 SmartNet, IPERCITIES, and ANR projects such as ADN, SATCOM, SMART4ALL, SAFEST, and FORESIGHT. Prof. Ben Yahia leads the Data Science Group at Taltech and has worked on diverse research topics, including big data analytics, data mining and visualization, information extraction, and ontology. He also led a team that developed robot-human collaboration and the Internet of Things in industrial processes. At Vanderbilt, Prof. Gokhale has worked on over 25 NSF and DoD-DARPA projects, including the NSF Convergence Accelerator, the NSF Smart and Connected Communities Pilot Project, the AFOSR Dynamic Data-Driven Applications Systems (DDDAS) program, the NSF US Ignite program, the NSF CAREER and many more. Prof. Gokhale is interested in solving systems problems involving a variety of quality of service and data consistency issues through effective resource management, particularly in cloud computing, Cyber-Physical systems, and the Internet of Things.

Furthermore, EU-US teams have recently submitted a joint research project in the NSF Convergence Accelerator program for realizing secure end-to-end flows in 5G networks. They had also previously submitted a proposal titled "RINGS: Resilience using Distributed Digital Twins." The EU-US partners have participated in and chaired numerous international conference venues and edited top-rated international journals. Therefore, this project will reach numerous well-established communities and an extensive social network from industry and academia, spanning North America, the EU, and Asia. The project reinforces the chances of collaboration and increases synergies between Next-Generation and Tomorrow's Internet programmes.

Impact 3: Developing interoperable solutions and joint demonstrators, contributions to standards.

The project's main idea is to develop an interoperable network of digital twins in which DT hubs from the EU and US can exchange data across unified, large-scale, distributed wireless edge-cloud testbeds spanning two continents, which will offer a unique opportunity to develop interoperable solutions and joint demonstrations. Different heterogeneous technologies and protocols in terms of capabilities (e.g., LPWAN, SDN/OpenFlow, 5G-NR, MQTT, Docker, Kubernetes, etc.) that fit different standards (e.g., IEEE, 3GPP, ONF, etc.) are expected to interoperate and contribute toward standardization efforts on digital twins, i.e., by defining scope and terms, working on concepts and vocabulary, on use cases, policies, life-cycle issues, virtual systems, devices, and sensors, to include digital twins on a reference architecture. This NGI Atlantic Hyper-5G project will identify possible partnerships and joint activities within other standardization bodies and working groups within ISO and IEC. Our previous collaboration has also contributed to developing the IEEE P1930.1 standard. We expect this NGI project to create a working group to create and write a new standard on digital twin architecture for 5G and beyond (B5G).

Impact 4: An EU - US ecosystem of top researchers, hi-tech start-ups / SMEs, and Internet-related communities collaborating on the evolution of the Internet

The PIs of the project already has a combined academic and professional network, including many start-ups and SMEs. For example, Prof. Ben Yahia and Dr. Hakiri actively participate in joining academia-industry European research projects. Prof. Ben Yahia has also contributed to several joint

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projects with start-ups in France, Germany, and Estonia, many government agencies in Tunisia, and NGOs in Europe. Prof. Gokhale and Dr. Hakiri have been the Ph.D. advisers of Dr. Prithviraj Patil, who is leading a team at MathWorks, Boston, USA, specializing in AI and DevOps for cloud and IoT. They also collaborate with Radisys, an industrial partner specializing in containerized 5G software stacks, on "NSF Convergence Accelerator 2022: Joint NSF/DOD Phases 1 and 2 for Track G: Securely Operating Through 5G Infrastructure." Prof. Gokhale has an ongoing industrial partnership with Siemens on 5G networking for factory automation systems and preliminary discussions with RadiSys, an industrial partner specializing in a containerized 5G software stack. Prof. Gokhale also participated at Vanderbilt in numerous mentoring graduate, undergraduate, and high school students over the years. The EU and US partners actively contribute to the EU-US research project with Siemens Technology, USA, specializing in AI for automation and drive technology. In addition, they are contributing to Public-Private Partnership programmes such as NSF Convergence Accelerator 2022 and Joint NSF/DOD "Track G: Securely Operating Through 5G Infrastructure.

We expect valuable business relationships will be formed with SME/hi-tech start-ups and Internet-related communities collaborating on the evolution of the Internet. Additionally, the project ideas can be extended beyond enterprise-wide area networks. The findings of this project may also help foster future collaborations with the healthcare industry to disseminate remote robot surgery techniques. The PIs will organize a workshop on immersive technologies, which will be held in conjunction with the 2022 IEEE 1st Global Emerging Technology Blockchain World Forum (07-11 November 2022, Southern California, USA). The workshop will be a unique opportunity to create and grow the community around the project activities and foster interactions with other initiatives for further collaboration, discussion, project development, scaling up, best-practice exchange, and experience sharing. The findings of this project may also help foster future collaborations. We expect to enable several joint activities, continue publishing at top-rated scientific events, build reputations, and establish leadership positions in 5G research and teaching. We expect this project will permit the development of many projects that will join NSF and US Ignite projects, co-supervise two Ph.D. theses, and jointly publish in top-rated leading journals, such as IEEE Access and IEEE IoT journals. Finally, the project PIs are also professionally connected to the "Taltech Start-up Centre" initiative to facilitate the exploitation and sustainability of the project outcomes, exploring and suggesting new business models.

9 Conclusion and Future Work

The HyPer-5G project proposes to experiment with and evaluate a prototype of a Digital Twin (DT) network for achieving resilient 5G internet services, and interconnecting two geographically distributed edge-cloud infrastructures, i.e., Grid5000 and Fit IoT-Lab in Europe and Chameleon Cloud and CHI-Edge in the US, to assess the feasibility of deploying new 5G services using the twin. We have surveyed a wide range of recent and state-of-the-art projects, software implementations, and standardization efforts in the realm of the digital twin. We discovered that most researchers believe that current digital architectures require additional research efforts to provide a unified framework that can ensure interoperability between different industrial applications, allow diverse domains that can benefit from DT, and ensure secure data dissemination at scale among potentially distributed industrial IoT systems.

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We have identified Eclipse Ditto, an open-source framework for creating, managing, and controlling digital twins, as the DT service that represents the devices and their properties (e.g., temperature and humidity). Ditto fits all the criteria for building distributed DT hubs. We have implemented an API that allows our framework to distribute data across trans-Atlantic cloud servers we have provisioned in both cloud platforms, i.e., Grid5000 in France (Europe) and Chameleon Cloud in Texas (USA). 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 evaluated the proposed solution in the cross-Atlantic testbeds and shown the effectiveness of the proposed solution in achieving low latency and guaranteeing end-to-end QoS parameters on different platforms.

We have realized that the end-to-end QoS parameters can be generally respected, such as a maximum delay of 130 ms, below the threshold of 150 ms. Additionally, since both the EU Grid5000 and the US Chameleon Cloud platforms support high-speed optical fiber at 10 Gb/s, the end-to-end bandwidth is also guaranteed during all the experiments. We find that scenario 2 in our experiments has more significant latency; we can explain this variation by the time required to create, establish, maintain, and release the resources at the endpoints of each router on different platforms.

We have not studied an exhaustive list of opportunities in the Hyper-5G project. Although several opportunities for DT exist, they also pose a set of challenges that should be addressed, which will require coordinated attention from the research community for its success and wide acceptance. We argue that the widespread use of digital twins in Next Generation IoT applications beyond 5G poses many challenges that will necessitate coordinated effort from the research community to ensure their success and widespread acceptance. While these research efforts are essential, they need to occur in the context of common, standardized, and openly abstracted APIs that can forecast future use cases. We believe additional challenges and opportunities for research exist along a broad spectrum, ranging from composable DT solutions to be used in the upcoming 5G network and beyond to high-fidelity formal data modelling, knowledge data mapping, and blockchain-based security models to improve the trustworthiness of the DT-based solutions.

We have assembled a convergent team comprising researchers and practitioners from academia, industry, and government. Our team comprises participants from academia (Vanderbilt University, Tennessee Technological University, Florida International University, Meharry Medical College, Tallinn University of Technology, TalTech Estonia) and industry (Siemens Technology). We have had preliminary discussions with a US National Institute for Standards and Technology (NIST) team about cooperating on this project. We will work with NIST researchers on technology transition and standardization activities. In addition, we are in discussions with the Intel Smart Edge platform team about using their experience kits to evaluate our ideas. Finally, our team will also consist of graduate students from different academic institutions involved in the prototyping efforts. We are preparing a joint EU-US proposal to submit to the NSF CNS CSR medium in 2022 to address the open and challenging issues we have identified through our work on the Hyper-5G project. We will also forge international collaborations and projects with European partners through programs like the Horizon Europe program and the Lead Agency. NSF-ANR as ANR, as team members from the University of PAU and Pays de l'ADOUR in France, show interest in developing scalable and elastic cloud computing platforms that enable the integration and smart management of objects, services, resources, data, and people.

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11 Glossary (preferably in tabular form, like below)

5G	Fifth Generation (mobile/cellular networks)
NGI	Next Generation Internet
DT	Digital Twin
SDN	Software Defined Network
IoT	Internet of Things
VNF	Virtual Network Function
WIT	Waterford Institute of Technology (Coordinating Partner)
TalTech	Tallinn University of Technology
Vanderbilt	Vanderbilt University
ISIS	Institute for Software Integrated Systems
VPN	Virtual Private Network
G5K	Grid 5000
Edge@CHI	Edge IoT testbed at Chameleon CHI

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