DOI 10.5162/iCCC2026/P34

A 5G power-hardware-in-the-loop testbed for smart low-inertia power systems applications

Rolando Cortés Martínez[1], **Nandavardhan Reddy Ramireddy**[2], **Eric William Zurita**[1], **and Johannes Schiffer**[1,3]

[1]Control Systems and Network Control Technology Group, Brandenburg University of Technology Cottbus-Senftenberg (BTU C-S), 03046 Cottbus, Germany
[2]Institute for Computer Science, Brandenburg University of Technology Cottbus-Senftenberg (BTU C-S), 03046 Cottbus, Germany
[3]Fraunhofer IEG, Fraunhofer Research Institution for Energy Infrastructures and Geotechnologies, 03046 Cottbus, Germany

Correspondence: Rolando Cortés Martínez (cortesma@b-tu.de)

Abstract. The use of 5G communication technologies is broadly expanding in different areas. Power systems are a highly promising area of application, where the advantages of 5G can play a significant role. Some of the 5G outstanding features are good reliability, low latency, and low jitter, among others. However, there is a challenge in incorporating new technologies into highly complex and extremely crucial infrastructures. In this work, we present a testbed that tackles this problem by combining a power-hardware-in-the-loop environment with a 5G communication network. We present preliminary results that validate the approach by showing relevant performance indexes around 5G.

1 Introduction

The increased addition of renewable energy sources (RES) into the electrical grids has yielded the need for experimental facilities that allow exploring the new control paradigms involved in such low-inertia power systems (see e.g., Krishna et al. (2022)). For such purposes, power-hardware-in-the-loop (PHIL) testbeds offer good flexibility and safety, making them ideal for testing a variety of scenarios found in the industry before real implementation. Thanks to the use of PHIL facilities, many scenarios can be reproduced under controlled conditions. A natural capability is to emulate the mechanical and electrical dynamics of RES (see e.g., Fadaeinedjad et al. (2008), Chiniforoosh et al. (2010)).

Typical communication solutions in real power systems consist of using large wired cables based on industrial Ethernet or costly optical fiber. However, Porcu et al. (2021) show that to improve flexibility and reliability, the industry is exploring the use of 5G technology, which also offers a good range of coverage and massive device capacity. Xu et al. (2020) emphasize the characteristics that make 5G ideal for these applications, such as reliability, low latency, massive capacity in terms of the number of nodes, high transmission speeds, and edge computing, among others. Porcu et al. (2022) propose a scheme to emulate distributed generation control with 5G communication. For this, a grid emulator (GE) is connected to other power sources to contribute to the balance of frequency and power supply. The sensor and actuation signals from one RES can be flexibly shared with the operator control station.

The current PHIL laboratories lack 5G technology (e.g. von Jouanne et al. (2023)). However, this is crucial to incorporate it since the stability of the testbed is affected by the presence of time delays and jitter in the communication link. With this need in focus, we modify the PHIL testbed developed at the Control Systems and Network Control Technology department at the Brandenburg University of Technology (BTU), Cottbus-Senftenberg, Germany (see Krishna et al. (2022)). The purpose of this setup is to establish a controlled experimental environment for evaluating 5G communication in power network applications, where the PHIL platform emulates the electrical grid and assess the system's behavior under 5G operation. We present the following contributions: 1) We design the architecture to set up the testbed for incorporating 5G devices into the PHIL laboratory, 2) we measure key performance indicators (KPIs) of every 5G equipment to show its status, and 3) we show the capabilities of the testbed by running the 5G and PHIL combined for future applications.

2 Design of experimental setup

2.1 PHIL testbed

The PHIL facilities used in this work consist mainly of four distributed generation units (DGUs), one grid emulator (GE) unit, a power line emulation cabinet, a control supervisory computer and the input grid of the University (see e.g., Krishna et al. (2022)). The system has a total power of 110 kW and can convert the 230/400 AC 50 Hz three-phase input power to variable AC or DC voltages with output frequencies from 0 to 400 Hz. Each DGU is controlled by a real-time computer (RTC), which runs embedded code generated under the Matlab/Simulink environment. Thus, each RTC can be used to emulate different electrical dynamics (e.g., storage elements, RESs, virtual synchronous generators, controllers, etc).

2.2 5G and PHIL integration

In this work, we use the 5G HAT SIM8200EA-M2 kit by Waveshare. We refer to this single equipment as a 5G user equipment (5G-UE). This is integrated by a Raspberry Pi 4 (RPi) as an embedded computer, a Raspberry HAT that incorporates the 5G modem SIM8200EA and five antennas. It supports 5G/4G/3G and stand-alone (SA) and non-stand-alone (NSA) networks. The kit features Ethernet and USB ports, as well as general-purpose input/output (GPIO) ports. The combined capabilities of PHIL hardware and the 5G hardware (5G-PHIL) is shown in Fig. 1. The 5G-UEs are connected through a dedicated local Ethernet network to the PHIL hardware. An Ethernet interface is combined with the user datagram protocol (UDP) as a transport layer. The 5G connectivity is provided by a private stand-alone (SA) 5G network in the frequency band n78, with the server antennas located inside the PHIL laboratory.

The use of Ethernet as a local network in addition to the 5G network does not compromise any of the advantages of the 5G network, as Ethernet, combined with the UDP protocol, offers lower delays and faster transmission speeds than 5G radio signals. The proposed interconnection aligns with real-world scenarios, where power systemd hardware can commonly communicate using standard protocols, such as IEC 61850, PMU IEEE C37.118, DNP3, SCADA DNP3, Modbus, CAN (see e.g. von Jouanne et al. (2023)). The main difference, and for the convenience of the laboratory, is that we provide a single local network for all the power devices. The topology in the local network, however, is configured such that only one 5G-UE is paired with one corresponding DGU or GE hardware. The pairing is achieved by identifying and matching the IP addresses during transmission.

On the radio signal side, every 5G-UE is configured to have a fixed IP address for sending and receiving data with other 5G-UEs. In Fig. 1, each 5G-UE has two fixed IP addresses, one for the Ethernet interface and the other for the 5G interface.

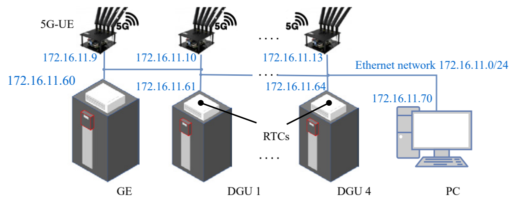

Figure 1. General diagram of the 5G-PHIL setup.

Application communication protocol. Ethernet and 5G constitute the physical communication layers while UDP is the transportation layer, however for the definition of the user data packages we use the message queuing telemetry transport (MQTT) protocol. MQTT is easy to implement and offers flexibility in the definition of the network topologies. In this way, it is possible to turn on and off each one of the links in the network, which is important to test stability conditions in the network. It operates under a *client*, *topic*, *subscriber*, and *publisher* scheme, where the number of clients in the network can be easily scaled up.

2.3 Mode of operation

The testbed has the capability of testing the communication part with or without utilizing the PHIL hardware. This feature facilitates debug processing. During the debug process, instead of connecting all the RTCs to the 5G-UEs, the 5G-UEs can be connected to a single computer in the Ethernet network. This operation, however, lacks real-time capabilities. This computer also serves for editing and development of the codes inside the 5G-UEs. During this process, the computer utilizes the secure shell (SSH) protocol over Ethernet to access the Linux system remotely from other systems, such as Windows.

When the 5G-UEs are paired with the GE and the DGUs, the main function of the PC is to edit, upload, and execute code dedicated to each RTC and its corresponding power system device (see, e.g., Krishna et al. (2022)).

The MQTT client publishes its own set of *topics* related to the physical measurements of the DGU (e.g., voltages, currents, frequency, control variables, etc.), the names of the *topics* follow the form *cliXX_Y*, where *XX* is the number of the MQTT client and *Y* is the number of the *topic* related to that client. For the MQTT broker, which can also act as a client, the *topic* name is *broker_Y*. The name of the *topic* is not transmitted through the UDP-Ethernet to maintain simplicity in this stage. For these reasons, a predefined number of *topics* and a relationship between signals and *topics* are

DOI 10.5162/iCCC2026/P34

necessary. An example of the system sending a signal from the RTC of the GE to the RTC of DGU 1 is shown in Fig. 2. The data, which could be an electrical measurement of the emulated Grid, is sent by Ethernet UDP to the RPi of the 5G-UE 1. Then, the data is transformed into MQTT *topics* and is published using the 5G network. Any RPi subscribed to the published *topics* (RPi 2 in Fig. 2) receives the data and packs it to send it again through the Ethernet UDP network to the target RTC.

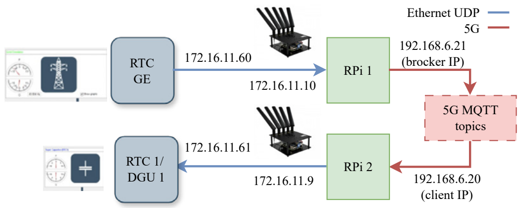

Figure 2. Example for sending information from one RTC to another through 5G-UEs.

Software layer. The five RPis work with the Ubuntu 20.04 server version, with the robotic operating system (ROS) 2 foxy as middleware, the Paho MQTT libraries, and the SIM8200 driver. Our main application code is made in Python language under a ROS 2 node. To understand the internal process of the 5G-UEs in example shown in 2, consider the diagram in Fig. 3. The RPi 1 receives the UDP stream and splits it into individual floating-point values. Then it publishes them into *topics* using multiple threads. This parallelizes the process, where every publication implies a transmission time delay. The RPi-2 subscribes to the *topics*, packages, and streams them over Ethernet using UDP. The pro-

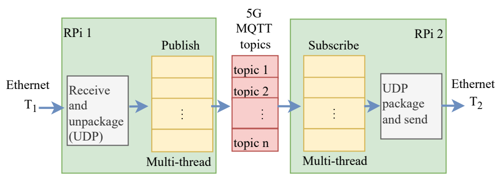

Figure 3. MQTT *topics* publication-subscription process.

cesses are event-handled (as soon as a new UDP package is detected, concurrent MQTT *topics* publication is done). Analogously, as soon as new data arrives in a *topic*, the subscription to it ensures immediate reception of the information to proceed to send it through UDP. On the RTC's side, the process of sending and receiving UDP packages is repeated at regular periods $T_1 = 10$ ms and T_2 = 1 ms, respectively. These values are selected to avoid buffer overflow.

The full or partial set of MQTT *topics* is available to every MQTT client. The client only needs to subscribe to the target *topics*. Thus, the active subscriptions define the topology of the communication. In this way, the 5G-PHIL operator can choose to simulate any kind of topology, such as

Table 1. Ethernet RTCs network configuration (IP address[1]):(port).

Flow	RTC 1	RTC 2	RTC 3	RTC 4
Send	10:7000	11:7000	12:7000	13:7000
Receive	10:8001	10:8002	10:8003	10:8004

[1] Network 172.16.11.0

directed, undirected, connected, strongly connected, etc. To automate the subscriptions based on the desired topology, an initial *topic* publication containing the topology information can be shared through the whole network.

3 System performance analysis

The purpose of this analysis is to assess the 5G performance and to show its suitability for power grid applications. Table 1 shows the configuration of the IP addresses and ports for the RTCs. Every 5G-UE is bound to every RTC by using the same respective pair (IP, port). For convenience, every receiving port is different from each other to maintain compatibility during the communication debug process (Matlab/Simulink supports only one port bound to a single IP address).

The list of *topics* comprises 20 elements with names from *broker_1* to *broker_4* and *cli20_1* to *cli24_4*. Every client is subscribed to all the *topics* in the list except for its own *topics*. Every *topic* corresponds to a Matlab/Simulink variable of type *single* (floating-point value, or four bytes).
To evaluate the performance of the 5G-UEs, we use radio signal measurements such as reference signal received power (RSRP), reference signal received quality (RSRQ) and signal-to-noise ratio (SNR) as well as network measurements such as the round trip time (RTT) between the edge 5G server and the 5G-UE, and the jitter (variation in the RTT). Additionally, by using application-layer data, we measure the latency in the transmissions under the normal PHIL operation mode. The RTT and jitter are obtained during a test carried out during one hour for the five 5G-UEs, a one-minute sample for one device is presented in Fig. 4, and Table 2 summarizes the average values obtained for all devices during the test. As can be seen, the values are consistent with those reported in the literature for indoor environments (see e.g., Singh et al. (2024)) Note that an RTT between UEs is twice the RTT w.r.t. the 5G server.
On a second test, we measure the downlink and uplink throughputs under different communication tasks (see Fig. 5). During the intervals t_1=(17:38, 17:46) and t_2=(17:46, 17:50), ping tasks with periods of 0.1 s and 0.01 s were executed, respectively. In a third test, we measure the 5G-PHIL latency between two RTCs (e.g., Fig. 2). To simplify the task, we utilize a single RTC. A signal $s_t(t) = \text{ramp}(t)$ is transmitted from RTC 1 and received as a delayed sig-

DOI 10.5162/iCCC2026/P34

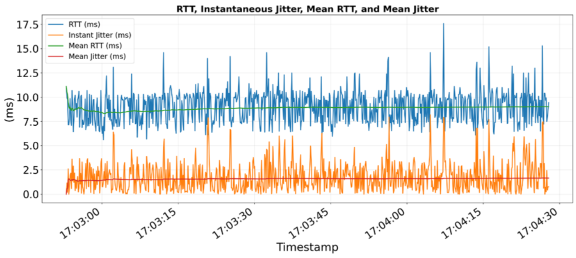

Figure 4. RTT and jitter for the MQTT broker.

Table 2. Network and radio signal KPIs (dB) in the five 5G-UEs.

KPI	broker	client 20[1]	client 22[1]	client 23[1]	client 24[1]
RTT	9.01	9.17	9.25	8.57	9.46
Jitter	1.66	1.56	1.58	1.53	1.71
RSRP	-64	-65	-70	-65	-66
RSRQ	-11	-11	-11	-11	-11
SNR	40	40	40	33.5	36.5

[1] The numbers correspond to the MQTT client identification, same as its 5G IP address and same as *topic* names.

nal $s_r(t) = s_t(t - \tau(t))$, where $\tau(t)$ is the accumulated time-varying delay from: publication from RPi 1, subscription in RPi 2, back publication in RPi 2, subscription in RPi 1, and UDP transmission to the original RTC. The latency measured under this scheme is shown in Fig. 6, with a mean value of $\bar{\tau}(t)$ =91.3 ms. The mean of the effective delay between RTCs is then $\bar{\tau}(t)/2$ =45.7 ms. Such a delay is still acceptable for several real-time power system applications compared to traditional wired solutions, where the delays can go from 50 ms to 130 ms (e.g., Zacharia et al. (2020)).

4 Conclusions

The integration of 5G technology with the PHIL facilities into the 5G-PHIL is a promising approach for representing power system scenarios in a more realistic environment where 5G communication can be effectively implemented. The KPI measurements obtained are consistent with the existing literature. Moreover, radio signal measurement levels such as the signal power, signal interference, and noise ratio are within an excellent range of operations.

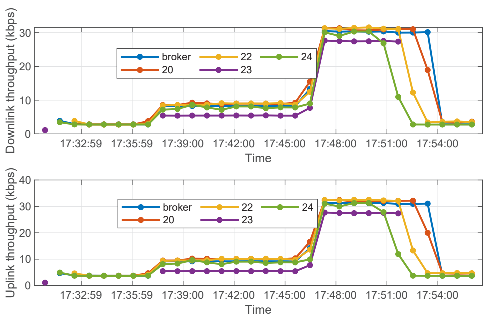

Figure 5. Throughput for uplink and downlink during second test for the five 5G-UEs (MQTT clients 20, 22, 23, and 24).

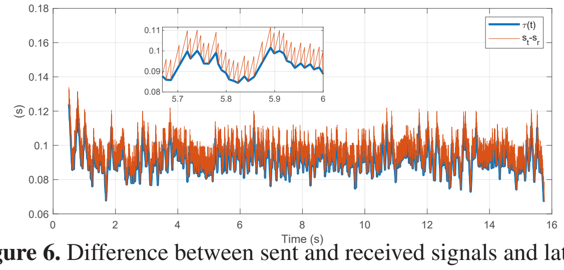

Figure 6. Difference between sent and received signals and latency

References

Chiniforoosh, S., Jatskevich, J., Yazdani, A., Sood, V., Dinavahi, V., Martinez, J. A., and Ramirez, A.: Definitions and applications of dynamic average models for analysis of power systems, IEEE Transactions on Power Delivery, 25, 2655–2669, https://doi.org/10.1109/TPWRD.2010.2043859, 2010.

Fadaeinedjad, R., Moallem, M., and Moschopoulos, G.: Simulation of a wind turbine with doubly fed induction generator by FAST and simulink, IEEE Transactions on Energy Conversion, 23, 690–700, https://doi.org/10.1109/TEC.2007.914307, 2008.

Krishna, A., Jaramillo-Cajica, I., Auer, S., and Schiffer, J.: A power-hardware-in-the-loop testbed for intelligent operation and control of low-inertia power systems, at-Automatisierungstechnik, 70, 1084–1095, 2022.

Porcu, D., Chochliouros, I. P., Castro, S., Fiorentino, G., Costa, R., Nodaros, D., Koumaras, V., Brasca, F., Di Pietro, N., Papaioannou, G., et al.: 5G communications as "enabler" for smart power grids: the case of the Smart5Grid project, in: IFIP International Conference on Artificial Intelligence Applications and Innovations, pp. 7–20, Springer, 2021.

Porcu, D., Castro, S., Otura, B., Encinar, P., Chochliouros, I., Ciornei, I., Hadjidemetriou, L., Ellinas, G., Santiago, R., Grigoriou, E., et al.: Demonstration of 5G solutions for smart energy grids of the future: a perspective of the Smart5Grid project, Energies, 15, 839, 2022.

Singh, B. C., Diaz, R., and Shetty, S.: Evaluating the Performance of 5G NR in Indoor Environments: An Experimental Study, Procedia Computer Science, 241, 16–23, 2024.

von Jouanne, A., Agamloh, E., and Yokochi, A.: Power hardware-in-the-loop (PHIL): A review to advance smart inverter-based grid-edge solutions, Energies, 16, 916, 2023.

Xu, D., Zhou, A., Zhang, X., Wang, G., Liu, X., An, C., Shi, Y., Liu, L., and Ma, H.: Understanding operational 5G: A first measurement study on its coverage, performance and energy consumption, in: Proceedings of the Annual Conference of the ACM, pp. 479–494, 2020.

Zacharia, L., Asprou, M., and Kyriakides, E.: Measurement Errors and Delays on Wide-Area Control Based on IEEE Std C37.118.1-2011: Impact and Compensation, IEEE Systems Journal, 14, 422–432, https://doi.org/10.1109/JSYST.2019.2918841, 2020. 60