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Towards Automation of Configuration Management for Multi-Research Infrastructure Experiments

Gehrke, Oliver; Vogel, Steffen; Widl, Edmund; Rajkumar, Vetrivel Subramaniam ; Pham, Minh Cong Pham; Tran, Quoc Tuan ; Paludetto, Gabriele; Montero, José López ; Kamsamrong, Jirapa ; Arhum, Mohammad

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Towards Automation of Configuration Management for Multi-Research Infrastructure Experiments

Oliver Gehrke
Technical University of Denmark
Roskilde, Denmark
olge@dtu.dk

Steffen Vogel
RWTH Aachen University
Aachen, Germany
svogel2@eonerc.rwth-aachen.de

Edmund Widl
Austrian Institute of Technology
Seibersdorf, Austria
Edmund.Widl@ait.ac.at

Vetrivel Subramaniam Rajkumar
Delft University of Technology
Delft, The Netherlands
V.SubramaniamRajkumar@tudelft.nl

Minh Cong Pham
CEA-Liten, INES
Le Bourget du Lac, France
minh-cong.pham@cea.fr

Quoc Tuan Tran
CEA-Liten, INES
Le Bourget du Lac, France
quoctuan.tran@cea.fr

Gabriele Paludetto
RSE
Milan, Italy
gabriele.paludetto@rse-web.it

José López Montero
Tecnalia
Donostia-San Sebastian, Spain
josea.lopez@tecnalia.com

Jirapa Kamsamrong
OFFIS
Oldenburg, Germany
jirapa.kamsamrong@offis.de

Mohammad Arhum
OFFIS
Oldenburg, Germany
mohammad.arhum@offis.de

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***Abstract*—The complexity and dynamic nature of laboratory configurations pose a challenge when undertaking joint experiments, involving multiple Research Infrastructures (RIs). In this context, this paper presents an approach towards the automation of Configuration Management (CM) for joint experiments between multiple labs. The objective is to develop a CM workflow, based on the automated generation of individual local signal configurations from a single global experiment configuration. For this reason, a global experiment configuration file which defines signals, their exchange patterns between RIs, and the data transport packages used for the actual exchange is created. Furthermore, typical use cases based on static and dynamic lab configuration are defined and demonstrated using the proposed approach.**

***Index Terms*—configuration management, distributed experiments, multi-research infrastructure, global configuration, coupling tool.**

I. Introduction

A. Context and Motivation

Conducting distributed experiments involving multiple Research Infrastructures (RIs) as in Figure 1 presents a significant challenge, owing to the intricate and ever-changing nature of laboratory configurations [1]. Reproducibility and replicability of experiments rely heavily on the ability to maintain identical configurations of systems and components. However, research laboratories are inherently dynamic environments characterized by continuous work-in-progress. As a consequence, standard parameters are subject to modifications, and the physical layout of equipment and software is frequently subjected to re-locations, updates, or replacements. In this context, the ERIGrid 2.0 project, building upon the experiences of its predecessor, ERIGrid, seeks to address these configuration-related complexities and uncertainties to enhance the robustness and efficacy of distributed experiments across RIs. During the ERIGrid's demonstration phase, the practical application of closed-loop interconnections involving RIs across distinct organizational boundaries provided valuable experimental insights. A pivotal observation emerged, revealing that a significant proportion of the encountered challenges were rooted in non-technical aspects, primarily arising from the convergence of heterogeneous organizational structures, disparate procedures, and divergent underlying assumptions. While the overarching concept of RI interconnection was successfully demonstrated within the context of ERIGrid 1.0, a structured framework for the systematic establishment of experimental configurations across organizational boundaries was not explicitly formulated. Instead, ad-hoc adjustments and adaptations were predominantly deployed in response to arising needs. This pragmatic, de-facto approach gave rise to a series of obstacles that manifested during the experimentation phase and were further compounded by the necessity to coordinate laboratory time allocations among multiple collaborating organizations and personnel.

Therefore, the primary objective of the work in this paper has been to explore methods for automating Configuration Management (CM) in the context of distributed multi-RIs experiments. The aim is to minimize the need for manual intervention, while ensuring the feasibility of implementation within the project's existing resources. This paper outlines the efforts made toward achieving this objective, focusing on the following aspects:

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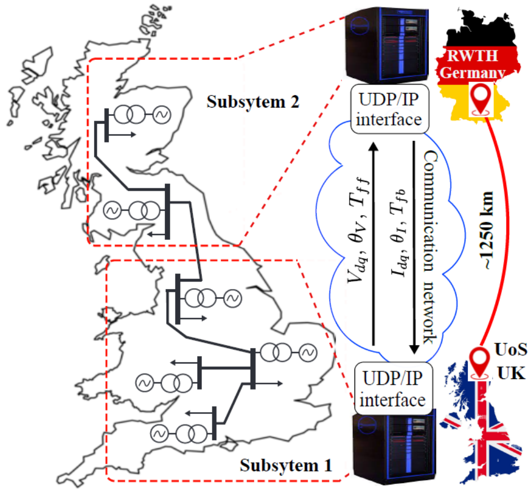

Fig. 1: An example of distributed experiment for frequency support, involving multiple RIs in the ERIGrid 2.0 project [2].

- *The development and selection of configuration management use cases*: The study found two main CM use case categories: static configuration, for knowledge sharing of existing facilities , and dynamic configuration, for tracking changes over time. One use case was chosen for practical implementation across partner institutions, centered on automating data exchanges between RIs using a global signal configuration approach.
- *The development of an automating configuration management workflow*: Iterative collaboration among ERIGrid 2.0 developers established a flexible workflow, accommodating diverse deployment structures (centralized, peer-to-peer, federated) and automating local signal configuration from a unified global experiment setup for seamless data exchange among packages.
- *The definition of a standardised description of data exchanges between RIs*: A machine-readable global experiment configuration has been developed in Yet Another Markup Language (YAML), containing detailed specifications of signals, their exchange patterns between RIs, and the specific data transport packages employed for data exchange.

B. Outline of the paper

This paper is structured as follows: In Section 2, an exploration of configuration classification and CM potential use cases is expounded. Section 3 presents the proposed configuration management approach for achieving automated data exchange in multi-RI experiments. For a comprehensive understanding of configuration management in the scope of ERIGrid 2.0, Section 4 includes detailed architectures about the existing laboratory coupling tools applied in CM process. Finally, Section 5 presents the conclusions drawn from this study.

II. Use Cases for Configuration Management

In the initial phase of this work, it was determined that the aforementioned issue related to CM in section 1 were too abstract to suggest practical solutions. As an intermediate step, a series of case narratives were formulated to provide a tangible representation of the problem. Therefore, the CM challenges were categorized into two scenarios:

- The management of static configurations, aimed at conveying established knowledge about a facility (such as a connectivity model).
- The management of dynamic configurations, designed to monitor the changing configuration elements of a system (for instance, identifying the specific segment of the grid to which a device was connected at a particular moment).

Based on these two scenarios, the configuration classification and potential use cases for CM are proposed in the next subsections.

A. Configuration classification

In this subsection, two types of configuration for the distributed test are identified and introduced by the working group in the ERIGrid 2.0 project: static and dynamic configuration.

1) Static Configuration: The static configuration narratives encompass the following scenarios:

- An experiment conducted within the RI_1 yielded measurement data. Over time, RI_1 underwent expansions and modifications. To utilize the recorded data, a future researcher at RI_2 needs a comprehensive understanding of RI_1's physical configuration during the measurements. This knowledge is crucial for accurately interpreting the data, including vital details like the spatial coordinates of 'measurement point ABC123' and the grid connection's impedance at the specific recording time.
- A researcher in RI_1 developed an adaptive state estimator for testing across multiple RIs (RI_2 ... RI_n). The manual configuration process for RI_2 ... RI_n is laborious and error-prone. Adopting an automated approach is recommended to enhance efficiency and reliability during test execution.

2) Dynamic Configuration: The dynamic configuration narratives are as follows:

- In multi-RI experimentation, RI_1 has a mobile load unit connected to various points within its grid. RI_2 remotely operates RI_1, conducting tests with the mobile unit connected at different grid points. Post-testing data evaluation reveals anomalies, leading RI_2 to seek validation for the mobile unit's adherence to the testing plan.
- A researcher in RI_1 developed an adaptive state demand response controller for diverse load portfolios. The controller is tested at RI_2, where the configuration changes dynamically during run time by adding or removing load units from a base setup. To ensure the controller's accurate response, real-time information about the configuration changes is communicated to the controller.

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B. Potential Use Cases

After that, the narratives provided above served as input and lead to the following use cases below.

1) Global signal configuration: This use case automates signal setup and properties for seamless data exchange among multiple RIs. It combines an offline component defining global data flows and an online component automating the mapping process. The online component converts the global data description into localized signal maps, auto-configuring all relevant components involved in data exchange.

2) Automated recording and restoration of laboratory configurations: This use case focuses on automated recording and restoration of laboratory configurations for improved experiment repeatability. It involves systematic capture of experiment configurations and execution data to enable precise replication of conditions. To achieve this, a mechanism is developed to extract configuration data from laboratory equipment and reconfigure it accordingly. Considering the varied automation levels and platforms in RIs, the system emphasizes high modularity to accommodate procedures ranging from fully automated to fully manual.

3) Experiment sequencing: The experiment sequencing use case involves coordinating experiments across multiple RIs. It comprises two components: an offline element for advance experiment description and an online component for synchronizing experiment events, phases, or states among RIs and recording them for documentation. This seamless synchronization enables a unified and structured approach, enhancing experiment reproducibility and systematic documentation.

Due to software resource limitations, Use Case 2 was unfeasible due to partner-specific back-end development needs. Conversely, Use Case 3 aligned better with distributed middleware goals. Use Case 1 was selected for practicality, requiring minimal expertise and aligning with the Universal Application Programming Interface (uAPI). Subsequent sections detail the chosen solution approach for Use Case 1.

III. Configuration Management Approach

In this section, only Use Case 1 in the previous section, which lies in the automation of data exchange for multi-RIs experiments, is selected for illustrating the configuration management approach in this section. This proposed CM strategy comprises two key components:

- An offline global configuration or a description that encompasses data flows between the participating RIs.
- An online automated process that maps local RI signals to data channels during the experiment, relying on the information provided by the global description.

The chosen CM framework is presented in Figure 2, demonstrating its application in a joint experiment involving two example RIs. To facilitate such collaborative experiments, dedicated laboratory coupling tools, such as the Virtually Interconnected Laboratories for Large Systems Simulation/Emulation (VILLAS) Framework, Joint Test Facility for Smart Energy Networks with Distributed Energy Resources (JaNDER), or Lablink, are employed as intermediaries for data exchange between the RIs. Nevertheless, as mentioned in the above section, the configuration process of these tools is complex, manual, and susceptible to errors. In order to address this challenge, a CM tool is proposed with the primary objective of automating the data exchange configuration process for experiments involving multiple RI. This is achieved by devising an offline global configuration or description that outlines the intended data flow among the participating RIs. Furthermore, an online automated mapping is established, which facilitates the association of local RI signals with data channels during the experiment, guided by the information provided in the global description. By adopting this approach, the CM process can be significantly streamlined, resulting in simplified and reproducible multi-RI experiments. The workflow to apply the proposed CM tool is outlined in Figure 3. More details about the Global Configuration and the RIs Local Configuration are presented in the next subsections.

A. Global Configuration

The global experimental configuration, as its name suggests, is a document that outlines the global aspects of a multi-RI experiment. It stands as a crucial element in automating multi-RI experiments, structured as a machine-readable file detailing various facets of the experiment, such as a list of channels, Signal list, and Type of transport. Furthermore, this document can encompass additional relevant experimental details, including but not limited to the involved RIs, laboratory arrangements, and various experiment variables. With a comprehensive and standardized global experimental configuration file in place, the automation process gains enhanced efficiency and efficacy, thereby enabling smooth and dependable data interchange among the diverse RIs engaged in the experiment. Moreover, the global experimental configuration file serves to support experiment reproducibility, offering a precise and comprehensive account of the experimental arrangement and parameters. Consequently, this file simplifies the setup of collaborative experiments among the participating RIs.

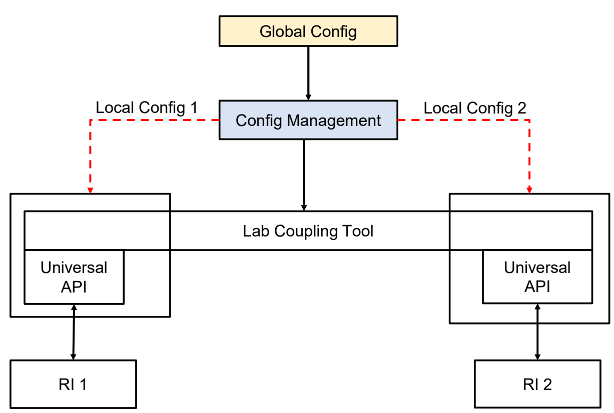

Fig. 2: Overview of the proposed configuration management automation strategy.

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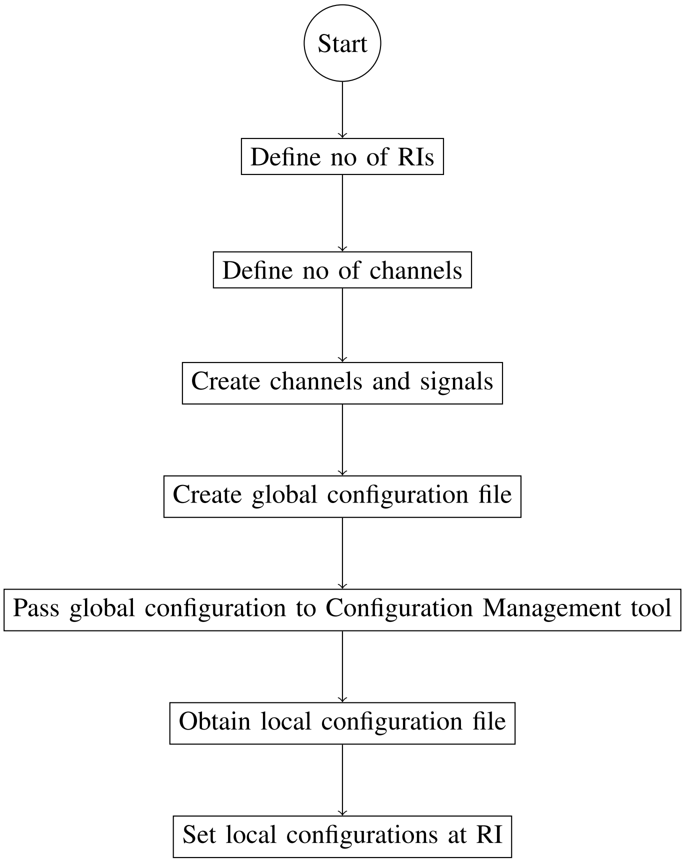

Fig. 3: Configuration management workflow.

```yaml
nodes:
  rwth:
    description: RWTH Aachen University

    uapi_endpoint: http://uapi.dtu.dk:8080/v2 # Optional

    channels: # This node provides (sources) these channels
    - id: rwth::busbar1:v
      unit: V
      rate: 100.0

    - { id: rwth::ch1.v, unit: V, rate: 100.0 }
    - { id: rwth::ch2.v, unit: V, rate: 100.0 }

    transport:
      type: jander

      # All following attributes are specific to the type of transport
      # and not covered by the global config schema.
      redis:
        host: 10.10.2.1
        port: 123
        username: erigrid
        password: wdsjfsd

  ait:
    transport:
      type: lablink

        # All following attributes are specific to the type of transport
        # and not covered by the global config schema.
        client-type: opal-rt

        mapping:
        - channel: rwth::busbar1:v
        simulink_signal_name:

connections:
- from: rwth::busbar1:v
  to: dtu
- from: rwth::busbar1:v
  to: ait

ri_adapters:
- type: syslab

  nodes:
  - ait
  - rwth
```

Fig. 5: An example of the global configuration YAML file.

To define a global CM file as in Figure 4, the document requires the following parts:

- RI Nodes: Listing RIs and specifying devices and points (channels) used.
- Devices: List devices used in the scenario; optional due to implicit channel naming conventions.
- Channels: In line with uAPI, list channels (measurements, setpoints, states, commands, events) identified by IDs, grouped by RIs, potentially including additional details.
- Transports: Define RI transport, leveraging uAPI for universal understanding or RI-specific options like VILLASframework, JaNDER, Lablink, with essential communication details.
- Data Flow: Define connections and directions among RI channels, allowing samples to be redirected and setpoints exchanged; outline permitted RIs' access to specific channels. Transport and data specifics are irrelevant; this maps channels between RIs, granting permissions.

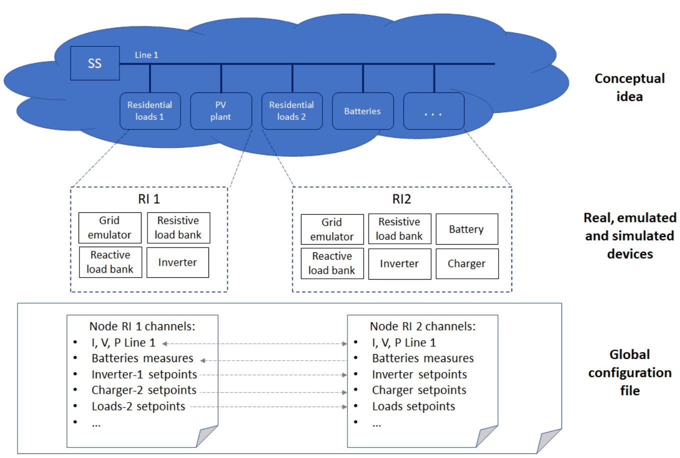

Fig. 4: Global configuration management file creation example.

An example global configuration Yet Another Markup Language (YAML) file for automating CM test between Austrian Institute Of Technology (AIT) and RWTH Aachen University is described by the code snippet in Figure 5.

B. *Local RI Configuration*

The global configuration file serves as an input for each individual RI's local configuration, establishing the parameters required for application execution, configuring their transports, and preparing the communication networks.

1) Application Configuration: The internal test infrastructure's channels and transport sections are obtained by the RI from the global configuration file for preparation purposes:

- Retrieving the transport method employed by the RI,
- Acquiring and reserving all designated (input) ports for message reception by the RI,
- Setting up the channels for data transmission, encompassing endpoints, ports, credentials, and more,

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- Mapping the (input/output) channels to the internal infrastructure such as channels and databases,
- Establishing the flow of channels by configuring routing paths.

2) Communications Setup: The RI's responsibility includes establishing bidirectional data communication with other RIs. This involves port activation, IP/DNS access authorization, and cybersecurity measures like credentials and certificates, as stipulated in the global configuration file. The collected input and output channel data from this communication informs RI cybersecurity policies and rules:

- Authorize data transmission (addresses, ports, and protocols) to other RIs,
- Enable data reception from RIs (ports and protocols) through the RI's application/transport,
- Restrict access to RIs not engaged in communication with this RI as defined in the global configuration.

IV. Laboratory Coupling Tools

As can be seen in Figure 2, the lab coupling tools play a very important role in automating the CM process as they work as intermediaries for data exchange among RIs. Thus, in this section, some of the existing laboratory coupling tools applied in the ERIGrid 2.0 project for CM will be introduced in this section. Some typical examples for the demonstration of these tools are [3] [4] for VILLAS, [5] for JaNDER and [8], [9] for Lablink.

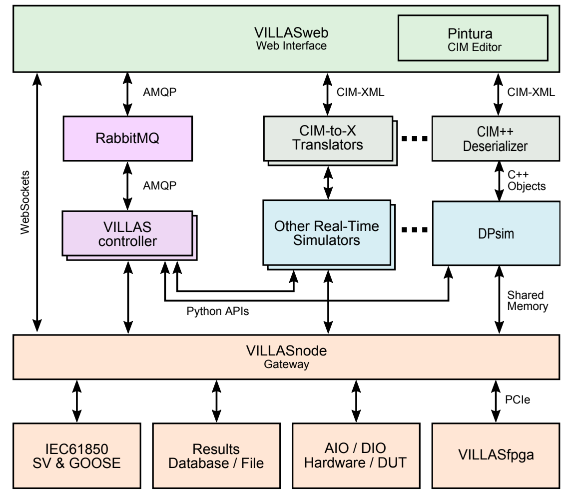
A. VILLAS

The VILLASframework presented in Figure 6a, developed by RWTH Aachen University's Institute for Automation of Complex Power Systems (ACS) [7], is a toolset for Geographically Distributed Real-Time Simulation (GDRTS). Its core components include:

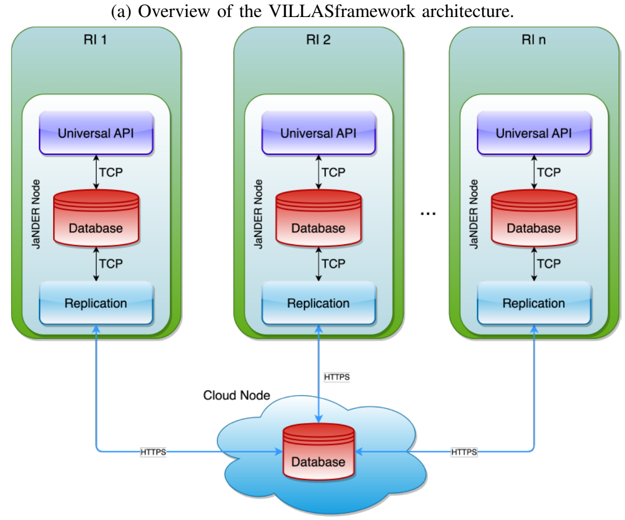
- VILLASnode: Serves as a gateway linking RI components like simulation equipment, databases, and web services. Developed in low-level C code with real-time capabilities, it supports various protocols.
- VILLASfpga: Connects simulators and devices for Hardware-in-the-Loop (HIL) using real-time interfaces. It integrates with VILLASnode via PCIexpress and Direct Memory Access (DMA) transfers.
- VILLASweb: Offers real-time visualization and control of experiments, allowing variable monitoring and interaction.
- VILLAScontroller: Provides a unified Application Programming Interface (API) for managing RI components, utilizing Advanced Message Queuing Protocol (AMQP) to transport JavaScript Object Notation (JSON)-encoded objects. VILLAScontroller is implemented in Python with the Kombo messaging package.

B. JaNDER

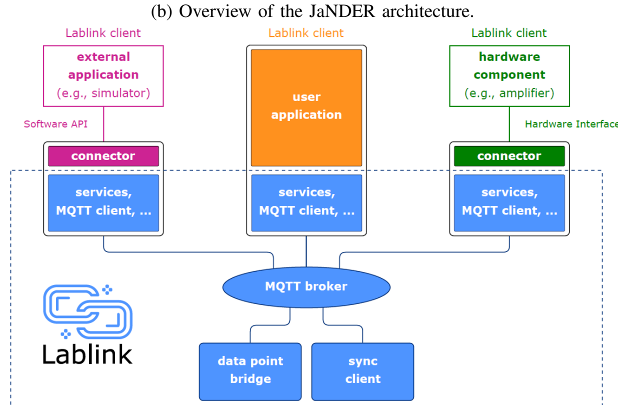
JaNDER, a product of the ERIGrid project, enables data exchange across RIs. Key attributes encompass secure HTTPS connections, easy installation, and modularity. JaNDER's core role is replicating infrastructure data through a cloud node. Data recorded locally mirrors in the cloud and vice versa, without structural interpretation. Components of JaNDER illustrated in Figure 6b are:



(a) Overview of the VILLASframework architecture.



(b) Overview of the JaNDER architecture.



(c) Overview of the Lablink architecture.

Fig. 6: ERIGrid's Lab Coupling Tools.

- Cloud Node: A cloud-based Redis database serving as a hub for RI node data exchange. Access is secure through

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- certificates and HTTPS, bridging different RI instances' local nodes.
- RI Database: A local Redis database at the facility, serving as a data endpoint for reading and writing. Running replication software syncs data between the cloud and local nodes.
- Replication Software: Created in Golang, this software securely connects local Redis and cloud nodes. Data replication occurs by subscribing to Redis keyspace notifications and intercepting updates matching patterns. It enables bidirectional replication.

Furthermore, a data model layer above replication software enables accessible measurements, mapping model instances to suitable database structures. The current API supports channels, samples, and events. JaNDER operates across diverse infrastructures, with compatibility and interaction with various transport services in progress.

C. Lablink

Lablink is an open-source middleware platform developed at the Austrian Institute of Technology (AIT) that manages and transfers data between distributed clients. It provides seamless integration of various laboratory instruments and devices, allowing users to control and monitor them remotely. Lablink offers a variety of clients designed specifically to access hardware (e.g., laboratory equipment) and software (e.g., simulation tools) often found in HIL and CHIL testbeds. It also provides various auxiliary tools, e.g., for logging and visualizing data or for synchronizing the execution of clients. Lablink has been successfully used for implementing HIL and CHIL test setups not only for applications in the smart grids doamin [8], [9] but also in the thermal domain [10] and for integrated energy systems [11].

Figure 6c shows a schematic representation of the basic architecture concept of Lablink. For implementing bindings to hardware or software targets, clients extend the functionality provided by the Lablink core library (data-driven event handling, connection to transport layer, etc.) to support various popular open standards, e.g., OPC UA [12], FMI [13], or the uAPI. Lablink offers a communication platform that enables the exchange of data between distributed clients through the data routing and encoding functionality implemented by its core library. In its current implementation, Lablink relies on MQTT for messaging between clients over standard TCP/IP connections.

V. Conclusion

This paper outlined and proposed a configuration management framework for distributed experiments involving multiple laboratories. This framework incorporates the utilization of a global experiment configuration file, serving as a semi-automated mechanism for facilitating configuration management in multi-research infrastructures experiments. The details of this *yaml* file alongside the introduction of three existing laboratory coupling tools was discussed. Consequently, this approach notably advances the documentation and reproducibility of joint multi-RI experiments.

VI. Acknowledgement

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