

A tutorial for using the RT simulators EXataCPS and HYPERSIM OPAL RT

Author: Mekkanen Mike

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1 Overview

Goals	To accelerate on starting with Real time simulation Keysight EXataCPS and HYPERSIM OPAL RT
Pre-reading material	1- L. Zhang, S. Li, L. Wihl, M. Kazemtabrizi, S. Qaseem, J. Paquin, S. Labbé," Cybersecurity Study of Power System Utilizing Advanced CPS Simulation Tools",
Main material resources	<p>1- https://wiki.opal-rt.com/display/DOCHS/Getting+Started,</p> <p>2- IEC 61850 IEC Just Published Just Published, IEC Webstore</p> <p>3- https://wiki.opal-rt.com/display/DOCHS/HYPERSIM+User+Documentation</p> <p>4- https://wiki.opal-rt.com/display/DOCHS/EXata+CPS+%7C+Installation+and+License+Request</p> <p>5- SCALABLE EXataCPS1.1 Documents</p>
Done by	Mike Mekkanen

2 Introduction

Real-time simulation, a more sophisticated simulation technique, simulates the behavior of numerous systems or components that interact with one another to improve CPS security testing. Simulation can be used to model interactions between a CPS's physical (OT) and cyber (IT) systems as well as those between the CPS and its environment in the context of cybersecurity for cyber-physical systems (CPS). This can be helpful for determining vulnerabilities, gauging the security of the CPS, and evaluating the effectiveness of different security measures. While the CPS simulation's real-time interactions with the outside world will demand that the simulator execute/solve all computations and provide output precisely within the simulation time step (t_s). In order to use all the various hardware in the loop testing scenarios, this simulation time step needs to be synchronized to run in universal time, (e.g., C-HIL, P-HIL,...)as illustrated in Fig (1), [1-2].

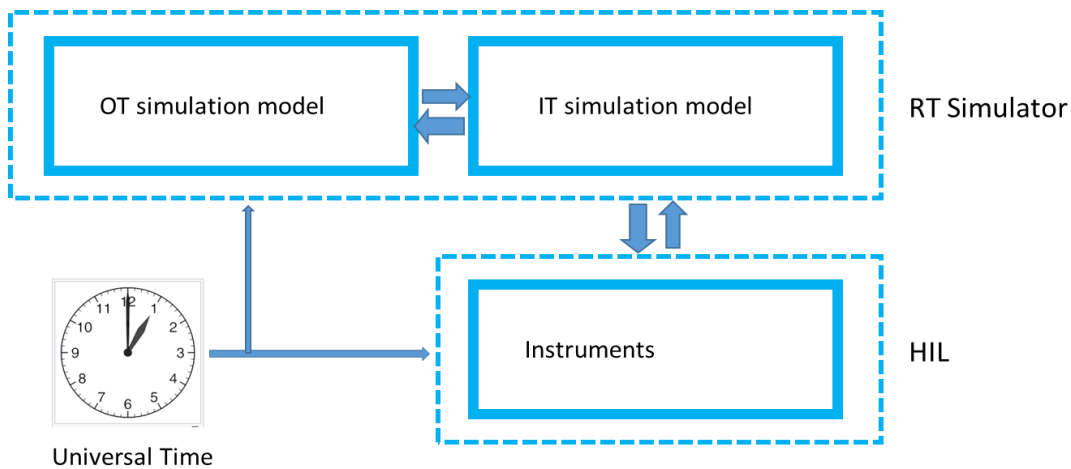


Figure 1: CPS RT co-simulation synchronized with the Universal time

3 EXataCPS and OPAL-RT Principles

3.1 SCALABLE EXataCPS:

Keysight Network Technologies is the leading provider of live, virtual, constructive communications networking modeling and simulation tools across all domains (undersea-to-space). Where EXataCPS is one of these Network Technologies offered by Keysight with a high fidelity network simulation/emulation tool used to test the performance and scalability of the communication networks. It allows users to simulate different network conditions and test the behavior of various network protocols, as well as enables to identify and address potential issues before they affect real-world network performance based on various operational scenarios “what if”, including cyber-attacks. The simulation/emulation run in real-time and models connections, computers, protocols, firewalls and other defenses. New advance EXataCPS tool is integrated with OPAL-RT within the HYPERSIM software GUI running in one physical target simulators. This advance new solution allow both software to share the available resources e.g., CPU cores, virtual and physical I/O etc., in order to reduce cost, simplicity, smoothly-internally exchanging real-time data via virtual adapters as well as more effectively identify and visualize the impact of cyber-attacks on OT systems. [3]

3.2 OPAL-RT

Opal RT Technologies is a pioneer in the development of real-time digital simulation software and engineering services for power system and electric drive research, testing, and validation, as well as high-performance, real-time digital simulators. Their solutions are used in a wide range of applications, such as power system stability and control, renewable energy integration, and electric vehicle charging and grid integration. The simulator hardware and the associated software platform HYPERSIM comprise the overall setup. The simulator's operating system is a proprietary version of Linux known as OPAL-RT Linux [4].

OPAL RT and SCALABLE are working together and have integrated EXataCPS and HYPERSIM within the same simulator as illustrated in Figure (2). Both software can execute on the simulator operating system and distribute processes on multiple CPUs to achieve parallel computation. The connection between the two software is virtual Ethernet links, but the data are still transmitted as standard communication protocols. This solution makes it possible for the communication emulator and the physical system simulator together executed on the same machine that hosted and controlled by individual host machine.

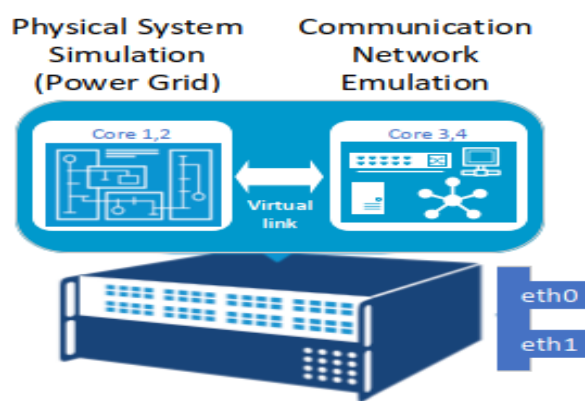


Figure 2: OPAL RT HYPERSIM and SCALABLE EXataCPS integrated at one RT simulator

4 Design Principles

HYPERSIM is a standalone software that been used for simulating three-phase electromagnetic and electro-mechanical transients. User is able to design-create simulated models by using the rich component library of more than 300 validated power system components and controllers. Users also can import ready models directly from MATLAB Simulink [4]. In order to simulate/test physical cyber security application for power systems SCALABLE EXataCPS and HYPESIM need to be installed at the Host machine usually a Windows PC or virtual machine, as illustrated in Figure (3).



Figure 3: HYPESIM and EXataCPS GUIs

From Figure (3) the primary power system model (OT) is developed in HYPERSIM environment while the communication system (IT) model is developed in EXataCPS. Therefore in order to design a complete model the following steps can serve as a starting point:

- 1- Define the scope and objectives of the simulation, clearly define the problem that the simulation is intended to solve
- 2- Identify and list all the IT/OT systems components
- 3- Clearly define the specifications, characteristics, and operating conditions of both systems components defined in step 2.
- 4- Design and create the model using the components defined in step 2 along with their operation conditions specified in step 3 in order to accurately construct overall systems.
- 5- Set the simulation parameters, including the starting time, time step, simulation length, solver etc.,

- 6- Analyze, compile and execute the simulation, then using the visualization and analysis tools to help interpret the simulation results
- 7- Validate and verify the accuracy of the model by comparing its results to real-world measurements or other data

The process flow for predefined real-time simulation creating model steps using EXataCPS and HYPERSIM is illustrated in Figure (4).

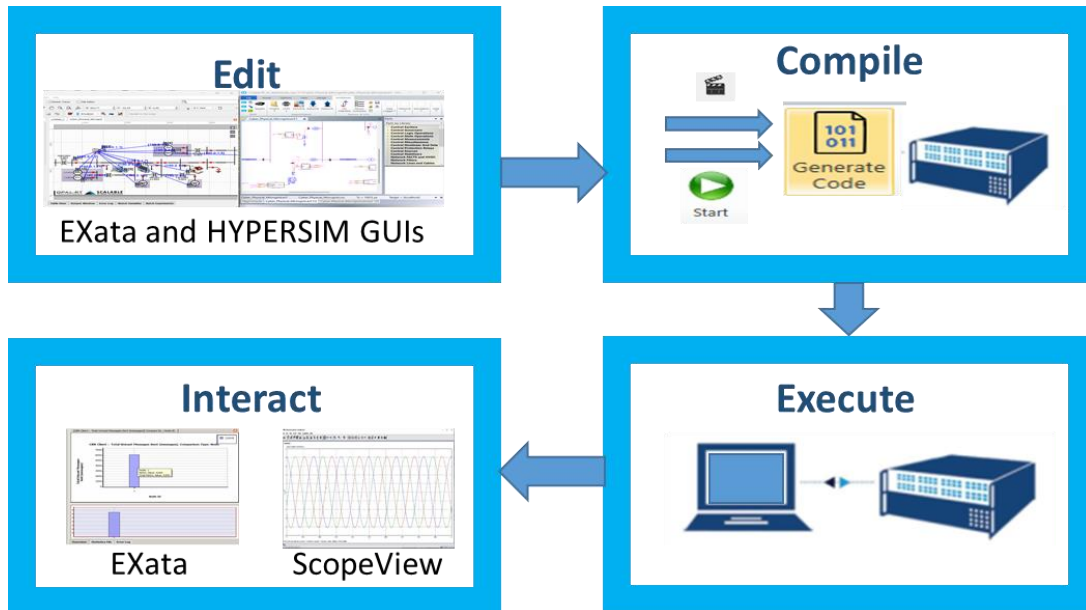


Figure 4: Process flow for creating model steps using EXataCPS and HYPERSIM

5 Conducting RT CPS model

Creating a model within the OPAL RT CPS environment requires to gather knowledge of both HYPERSIM to model power system (OT) and EXataCPS to model the communication system (IT) as well as some specific communication protocols that widely used to connect the electrical units [3] e.g., IEC 61850 [5]. This combination of multidisciplinary different systems will make the task more challenging. For simplicity and for the first starting step is to start with pure HYPERSIM and pure EXataCPS models is recommended. This first step will help the user to familiarize himself with the software characteristics, and operating conditions. There is two option to start with, either using the available demo examples within the software provided library or by creating model from scratch. Both options need to be finalized by interacting with the running model using different analyzation and visualization tools. At HYPERSIM GUI for example is integrated a “Scopeview”, which is analyzing and visualizing tool. The “Scopeview” role is to gather all the measurements from different sensors that initiated within the designed model and analyzed/visualized these measurements within a sub-window as illustrated in Figure (5).

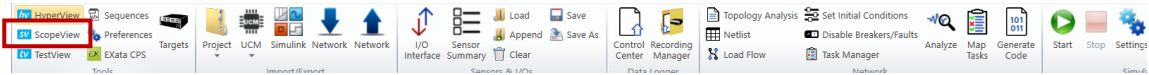


Figure 5: HYPERSIM GUI and Scopeview tool

While at EXataCPS GUI, within the components toolbar there is four components, one from them is “Analyzer” component, which is used for analyzing and visualizing the simulation results.

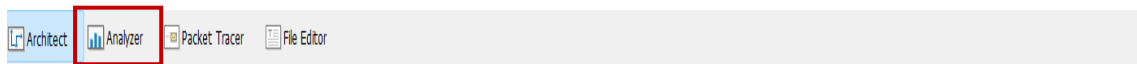


Figure 6: EXataCPS GUI and “Analyzer” component

6 Hands-on with EXataCPS and HYPERSIM

This section explains step by step how to design, simulate and implement a model. Because our primary goal is to provide cyber security for power system training based real time simulator, authors present here a combined EXataCPS and HYPERSIM software model. Then subsequently the generated codes from both software are individually transferred and run in the real-time OPAL-RT simulator.

6.1 Installation

To start with the CPS model, SCALABLE EXataCPS newer version 1.1 or latter and OPAL RT HYPERSIM newer version 2022.2 or latter is required. These two software need to be installed in to the host-machine. OPAL-RT and SCALABLE provides detailed step by step guide for software installations, [6], [7]. Before proceeding further, it is worth mentioning that even EXataCPS software are integrated in to the HYPERSIM GUI, however the EXataCPS software can be run as standalone software and has individual GUI.

6.2 Developing a model from scratch

Starting with HYPERSIM at the beginning.

6.2.1 OPAL RT HYPERSIM

At the desktop of the host machine navigate to HYPERSIM icon, right click on it and chose the “Run as administrator” from the selection window, since HYPERSIM needs administrator privileges.

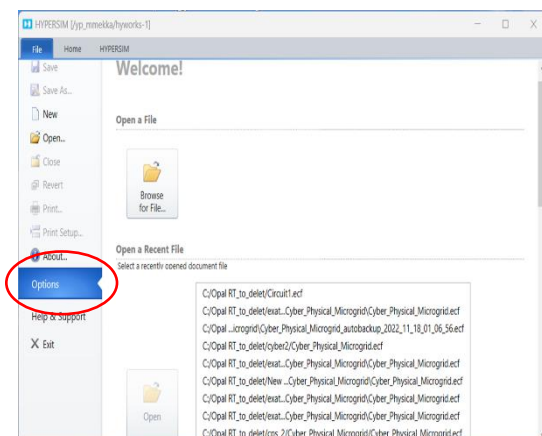


Figure 7a: option window

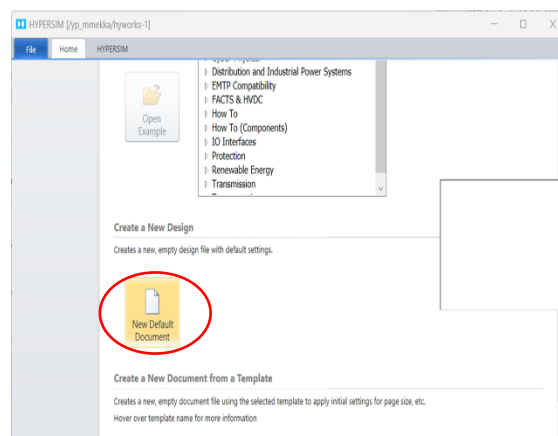


Figure 7b: New Default Document

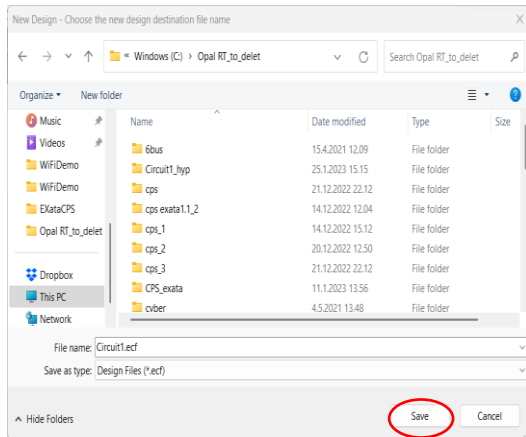


Figure 7c: Saving option window

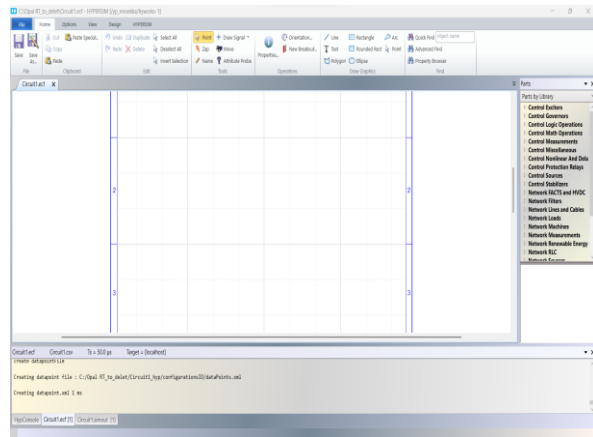


Figure 7d: Full HYPERSIM GUI

- Step 1: the option window will pop up (Figure 7a)
- Step 2: from the option window chose “New Default Document” under “Creat New Design” section (Figure 7b)
- Step 3: Saving option window pops up, name new design file and save it to the work space directory within a predefined project folder (Figure 7c)
- Step 4: Full HYPERSIM GUI pops up (Figure 7d)
- Step 5: Create new model as per guidelines provided in OPAL-RT HYPERSIM manual [6]. The examples provided can also be used as a platform to build or develop advance new model.

6.2.2 SCALABLE EXataCPS

To start the EXataCPS on Windows host machine, do one of the following either starting as standalone software by right clicking at the EXataCPS icon located at the desktop of the host machine and chose the “Run as administrator” from the selection window, since EXataCPS needs administrator privileges, or from the HYPERSIM GUI by clicking on the EXataCPS button as illustrated in Figure (8). At this point CPS training second option has been explained here. Since within the first option user need to develop the EXataCPS environment manually by creating name space and assign eno2 (physical adapter used by EXataCPS) for it using command prompt, whereas for the second option HYPERSIM did the task internally.

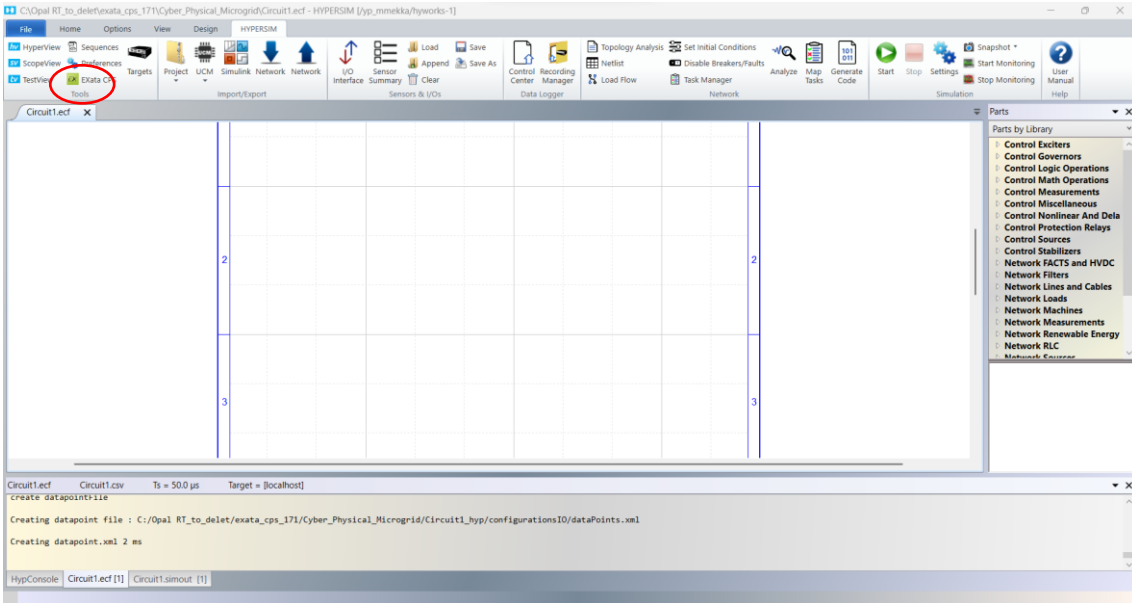


Figure 8: HYPERSIM GUI with the integrated EXataCPS starting button

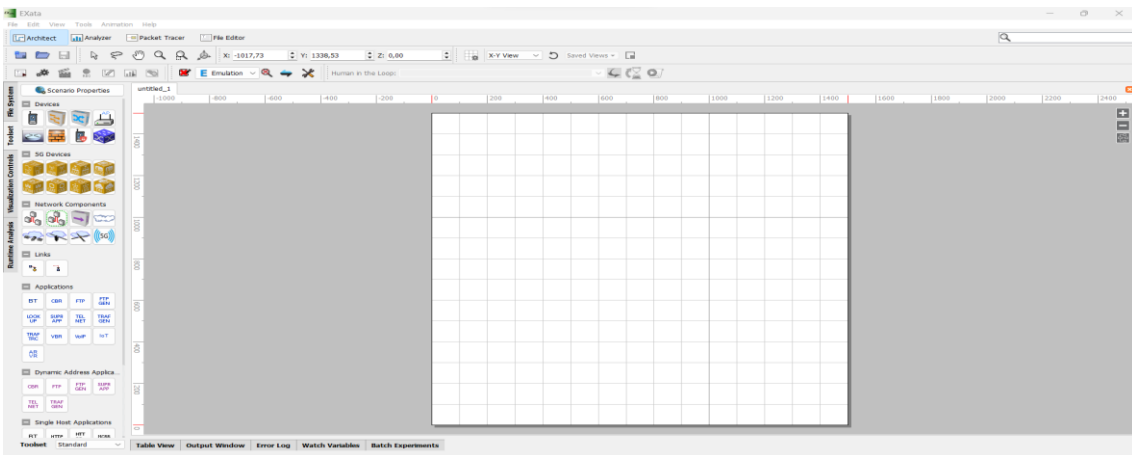


Figure 9: EXataCPS GUI starting by default with new design mode

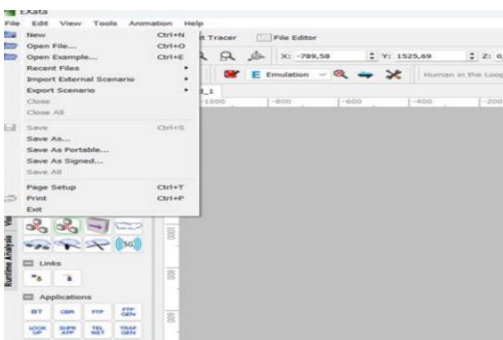


Figure 10a: new design file window

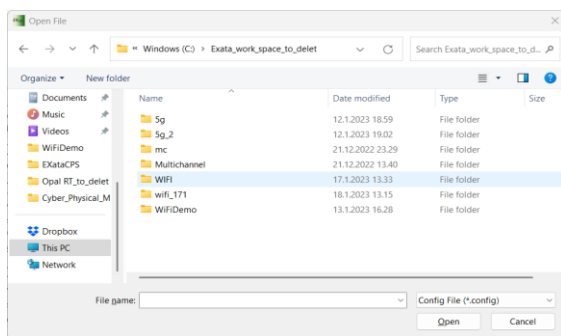


Figure 10b: file Explorer window

- Step 1: EXataCPS GUI window will pop up--> do one from the following (Figure 9)
- Step 2: File --> New --> new design file will open (Figure 10a)
- Step 3: File --> Open file --> new file Explorer window will pop up to navigate to existing design file (Figure 10b)
- Step 4: File --> Open Example --> a new file Explorer window will open, and the user should navigate to the SCALABLE examples folder. Other options are available under the File toolbar menu, which the user can explore.
- Step 5: after user open one from the above, at the open canvas user may create a model accordance with the guidelines provided in the SCALABLE EXataCPS "Product Tour" documents. The examples provided can also be used as a platform for developing a new model.

6.3 Executing a model in Real-time

6.3.1 OPAL RT HYPERSIM

After building the model in HYPERSIM, show the selected/assigned sensors by clicking at "Sensor Summary" located at the HYPERSIM ribbon "Sensor and IOs" section. It is worth mentioning here that sensors play two roles: first, they allow monitoring of the various signals across the model by transferring the selected measurements to "ScopeView" in order to visualize them. Second, they can be used to configure analog and digital I/O as well as communication protocols as illustrated at Figure (11).

Selected	Category	Type	Device	Name	Description	Unit	Base Factor	Base Unit	I/O Type	I/O Number	I/O Factor	Record	Group	Trigger
<input checked="" type="checkbox"/>	Math Operations	Input	Add8	u2			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	Math Operations	Input	Add8	u3			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	BESS1_Meas	P			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	BESS2_Meas	P			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	BESS3_Meas	P			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	Switches and Breakers	Output	CBLD3	STATEa		Logic	1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	Switches and Breakers	Output	CBLD4	STATEa		Logic	1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	CHP_Meas	P			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	Target Inputs and Outputs	Input	Connected	u1			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	DEV21	Output			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	DEV22	Output			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	DEV23	Output			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	DEV24	Output			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>
<input checked="" type="checkbox"/>	SubSystem	Output	DEV25	Output			1.0		0	1.0		<input type="checkbox"/>	SIGNAL_GROUP_1	<input type="checkbox"/>

Figure 11: Sensor Summary window

Name / IP	Description	Active	Running Version	License		
			Architecture	Build	Protocol	(days)
localhost		<input checked="" type="checkbox"/>	Windows	2022.2.1 c305	3.0.0	∞
192.168.5.171	target	<input checked="" type="checkbox"/>	linux-optirous3-64	2022.2.1 c305	3.0.0	∞

Figure 12a: target Manager window

Simulation Settings - Cyber_Physical_Microgrid (3)

General

Target Configuration

Target: 192.168.5.171 - target Architecture: linux-optirous3-64

Simulation mode: Real-time

Simulation

Time step: 100e-6 s Performance factor: 1 Processor load level: 0.8

Code directory: C:\henrygy_mmmakur\HPEPO\Mcode\2022.2.1 c305\gy_mmmakur\5594624a3c9132c04dc89719

Enable simulation logging

Nonlinear elements iterative method

Activate iterative method Maximum iterations: 5 Apply to all nonlinear elements

Model sensors

Default sensor file name: C:\Opal_RT_to_delete\exata_cps_171\Cyber_Physical_Microgrid\Cyber_Physical_Microgrid.csv

Automatically open sensor file with design

Load flow

Frequency: 50.0 Hz Power base: 100.0 MVA PQ tolerance: 5 MVA

Max iterations: 60 Deceleration factor: 1.0

Perform load flow and set initial conditions at simulation start

Figure 12b: file Explorer window

cording anager
ger

Analyze Map Tasks Generate Code Start Stop Settings User Manual Help

Network Simulation

Parts

Parts by Library

- Control Exciters
- Control Governors
- Control Logic Operations
- Control Math Operations

Figure 12c: Simulation Start button

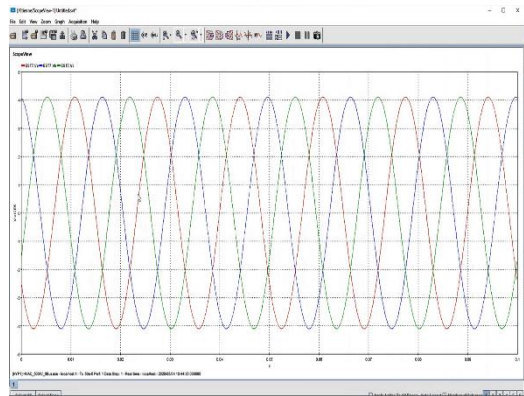


Figure 12d: ScopeView window

Running the model at real-time requires the following steps,

- Step 1: Targets --> click (+) sign to add target

- Step 2: Add New Target --> pops up window, define IP address for the target and name, --> ok target will appear at the target Manager window (Figure 12a)
- Step 3: Simulation Settings --> Target Configuration --> chose the target, and at the "Simulation mode" chose "Real-time" (Figure 12b)
- Step 4: Start --> the tasks are mapped automatically to the various cores, the code is compiled and the simulation starts running. (Figure 12c),
- Step 5: ScopeView--> visualize the simulation results (Figure 12d),

6.3.2 SCALABLE EXataCPS

To run the model in real-time after it has been built in EXataCPS, the model must be transported to the OPAL-RT real-time simulator, where initialization and execution can begin as follows;

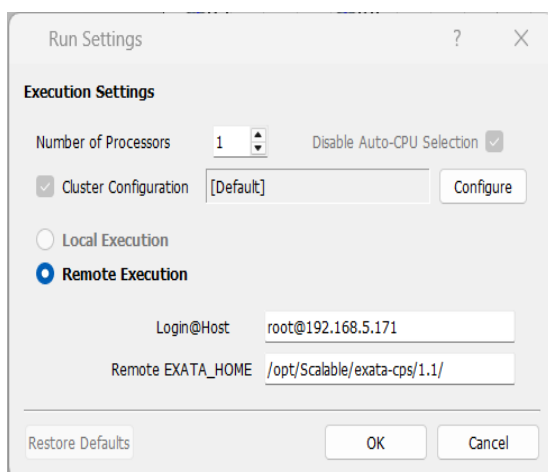


Figure 13a: Run Settings

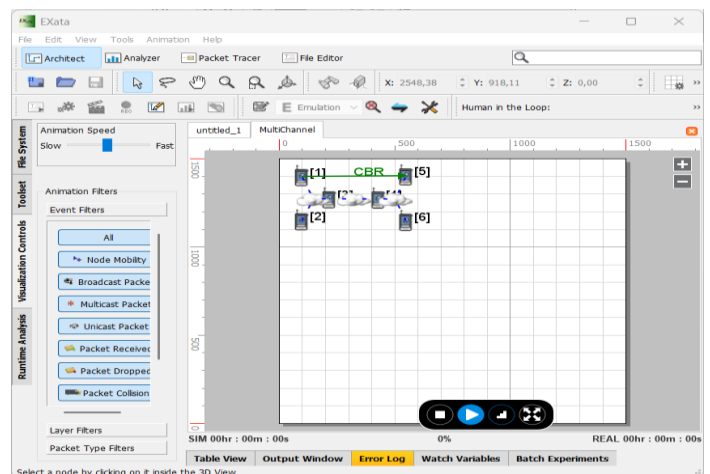






Figure 13b: visualise mode

- Step 1: click Run Settings  --> pops up window of Run Settings, make the admin SSH access to the target and define the directory for the execution folder at the target --> ok (Figure 13a)
- Step 2: select execution mode --> Target Configuration -->
- Step 3: click  Initialize Simulation --> pops up window, ask user to save example scenario
- Step 4: A copy of the scenario is saved --> the design mode will change to visualize mode (Figure 13b)

- Step 5: Click play button  --> to run the scenario in real-time (Figure 14a)
- Step 6: Click the Analyze Results button  --> simulation results in EXataCPS Analyzer (Figure 14b)

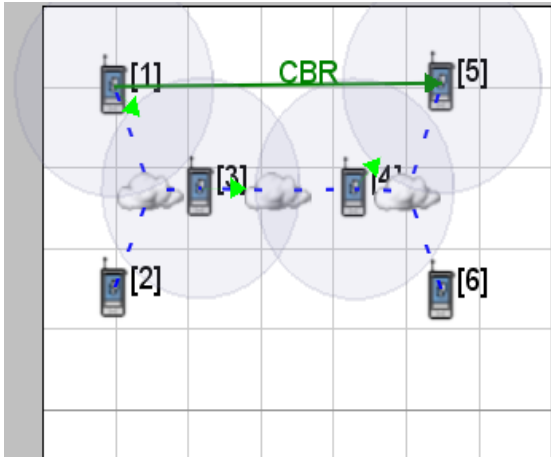


Figure 14a: simulation is running,

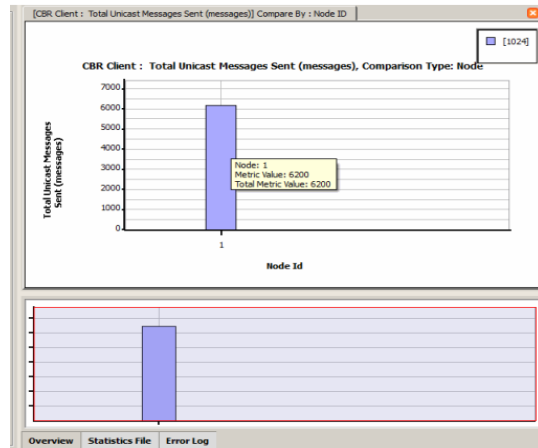


Figure 14b: simulation results

At Figure 14a when a node transmits a packet, green arrows representing successful packet reception whereas the circles representing radio transmissions boundaries.

References

- [1] C. Rehtanz und X. Gillaud, „Real-time and co-simulations for the development of power system monitoring, control and protection,“ in 2016 Power Systems Computation Conference (PSCC), 2016.
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- [5] IEC 61850 IEC Just Published [Just Published | IEC Webstore](#)
- [6] OPAL RT, [Online], <https://wiki.opal-rt.com/display/DOCHS/HYPERSIM+User+Documentation>
- [7] OPAL-RT,[Online], <https://wiki.opal-rt.com/display/DOCHS/EXata+CPS+%7C+Installation+and+License+Request>