Cyber-Physical Real-time Simulation of Digitalized Power Systems

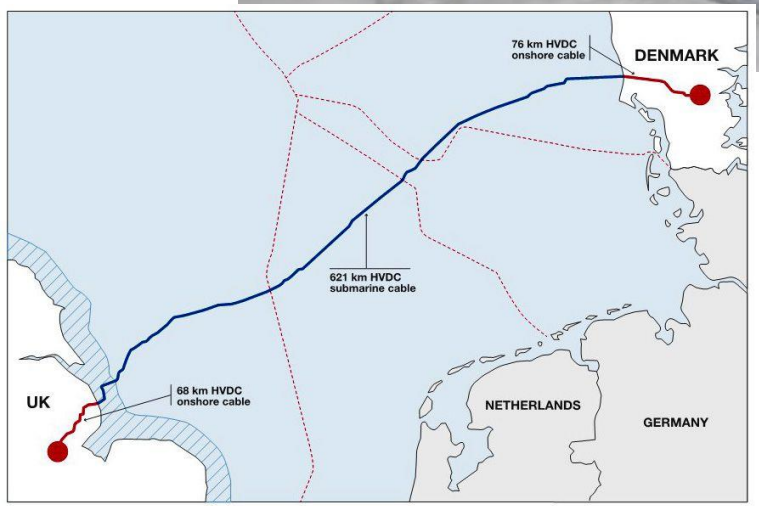
Testbed Design and Application

The Internet Meets the Electricity Grid:
Technical Standards & Societal Challenges
16-17 July, 2026, University Passau

Steffen Vogel, M.Sc.
R&D / Software Engineer
OPAL-RT Germany GmbH
steffen.vogel@opal-rt.com

An Example
VIKING LINK

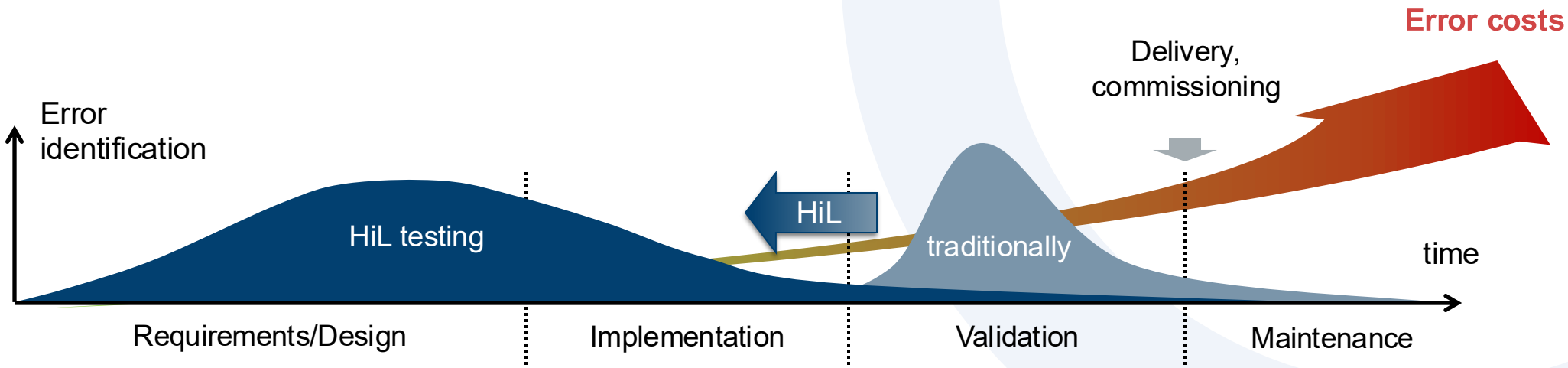
- DK / UK HVDC Interconnector
- 2.2 bn USD
- Planning 2015 => Operation 2023
- 1.4 GW Capacity
- ±525 kV DC
- 760 / 540km Cable Length



https://en.wikipedia.org/wiki/Viking_Link

OPAL-RT TECHNOLOGIES

DE-RISKING



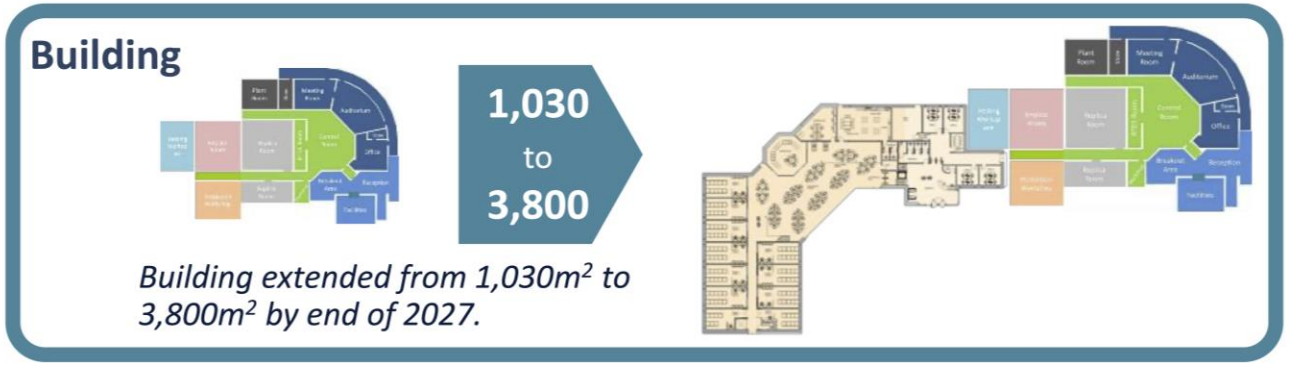
- HIL Testing is crucial for De-Risking of:
  - Planning / Commissioning
  - Maintenance
  - Training

OPAL-RT TECHNOLOGIES

HVDC SYSTEM TESTING

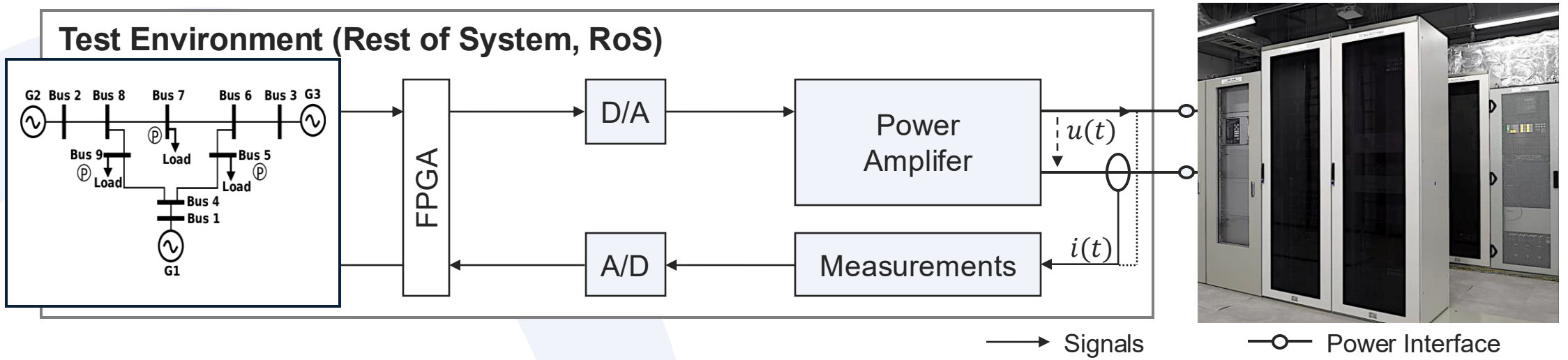
- Complex Control Systems
  - ~ 8-10 Cabinets per Terminal
  - Custom SCADA
  - Measurements
  - Fast PWM Generation
  - Latencies
  - Interconnected & Hierarchical

- **Example UK:** National HVDC Center
  - Aims to host a replica of each HVDC control system in their network
  - Upcoming extension:
    - Planned to host 28 replicas
    - "Datacenter of Replicas"

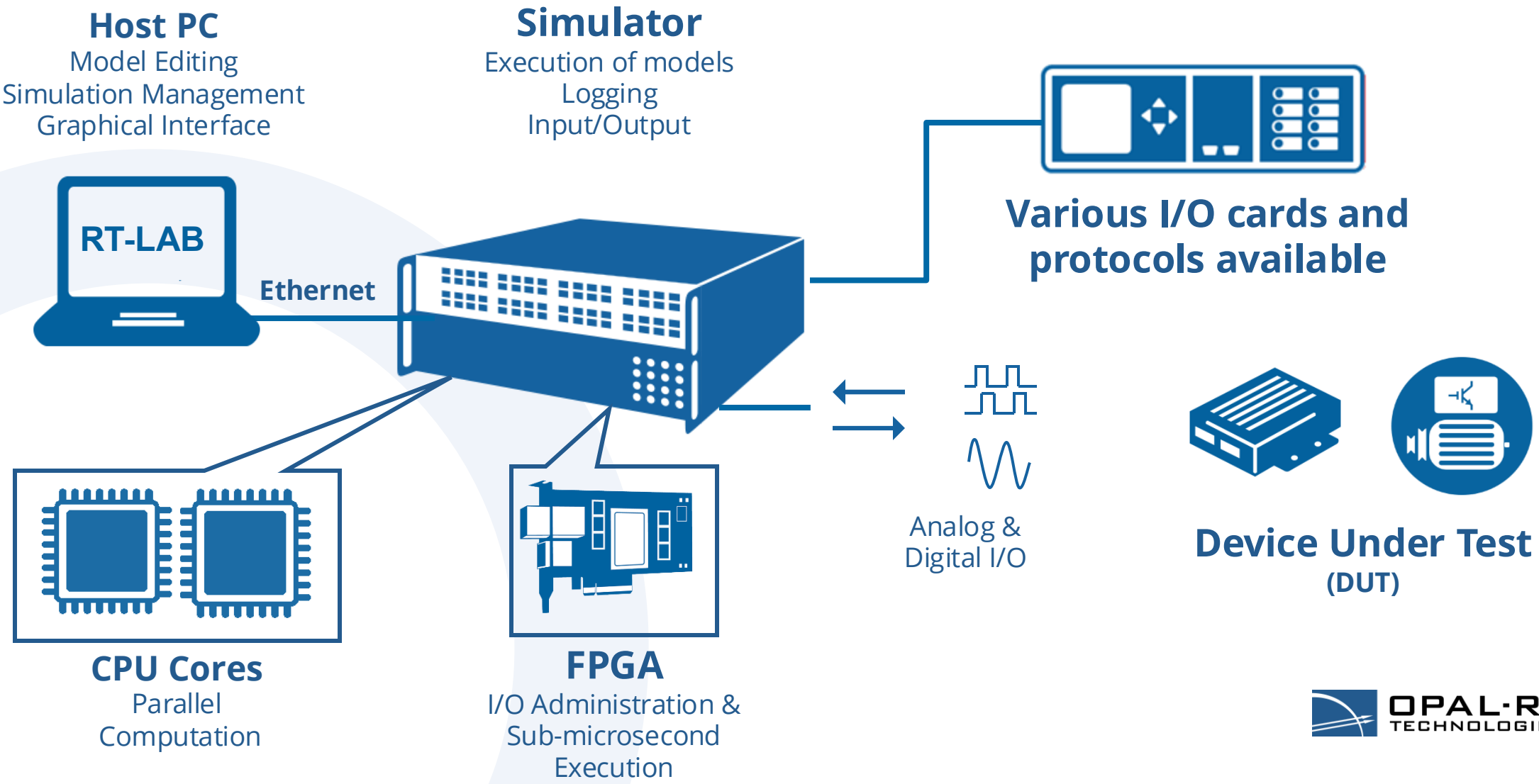


The National HVDC Centre

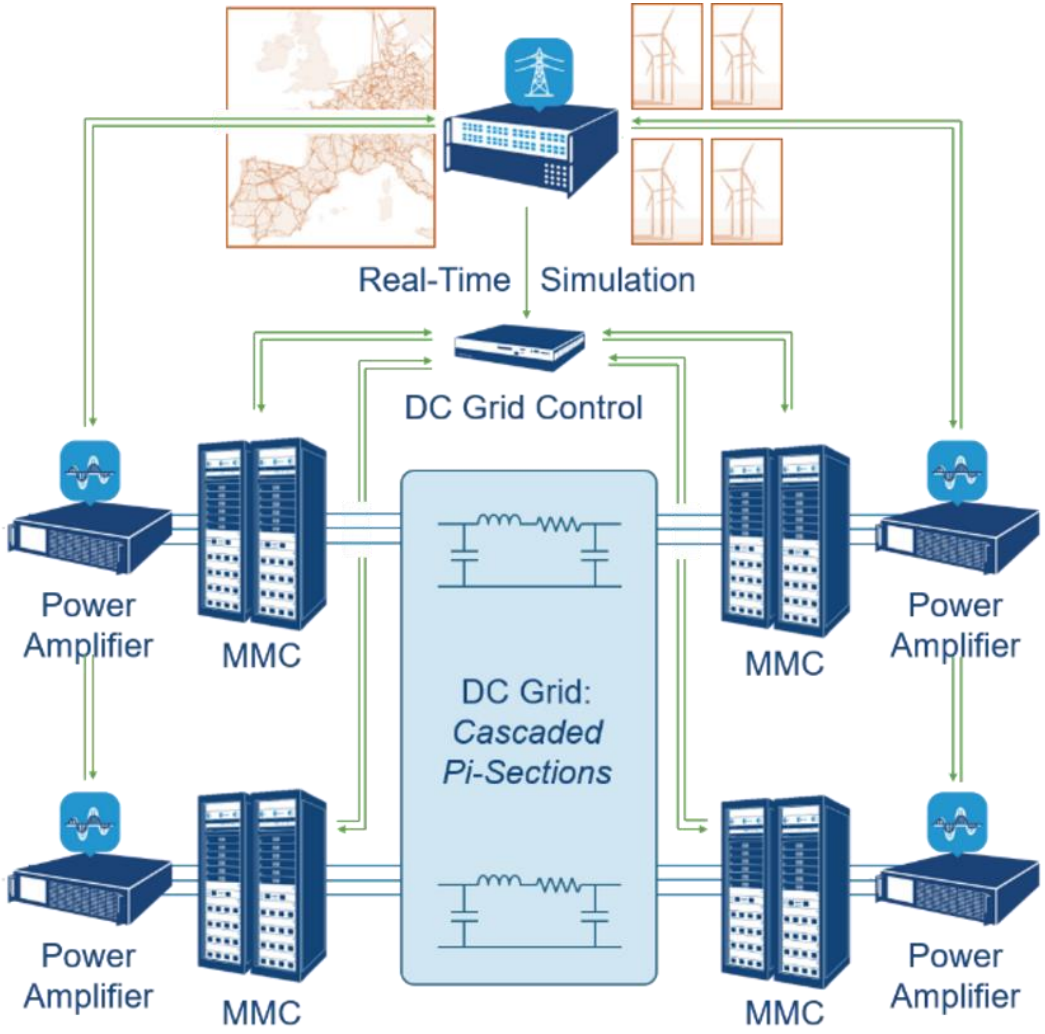
POWER HARDWARE-IN-THE-LOOP
BASIC SETUP



REAL-TIME SIMULATION SYSTEM



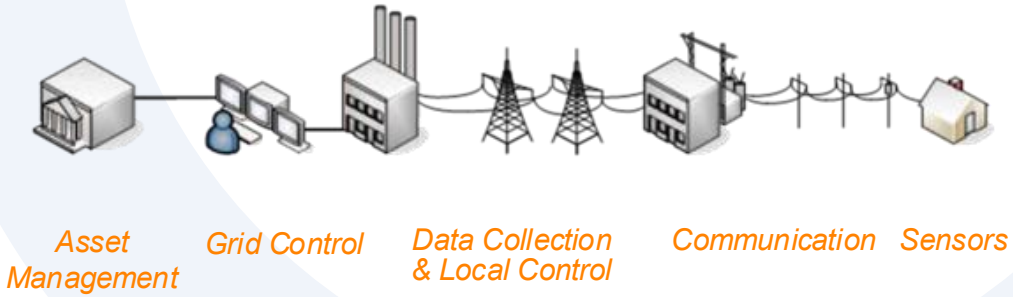
TESTING OF MMC PROTECTION AND CONTROL SYSTEMS
FOR HVDC CONNECTION OF OFFSHORE WIND FARMS



Nominal DC Voltage	$V_{DC,n}$	400 V
Nominal DC Current	$I_{DC,n}$	15 A
Nominal Output Power	$P_{DC,n}$	6 kW
Nominal AC Voltage per phase	$V_{AC,1}/V_{AC,2}$	400/208 V
Number of Cells (Submodules)	n_{SM}	10
Nominal Cell Voltage	$V_{c,n}$	40 V

CYBER PHYSICAL SYSTEMS

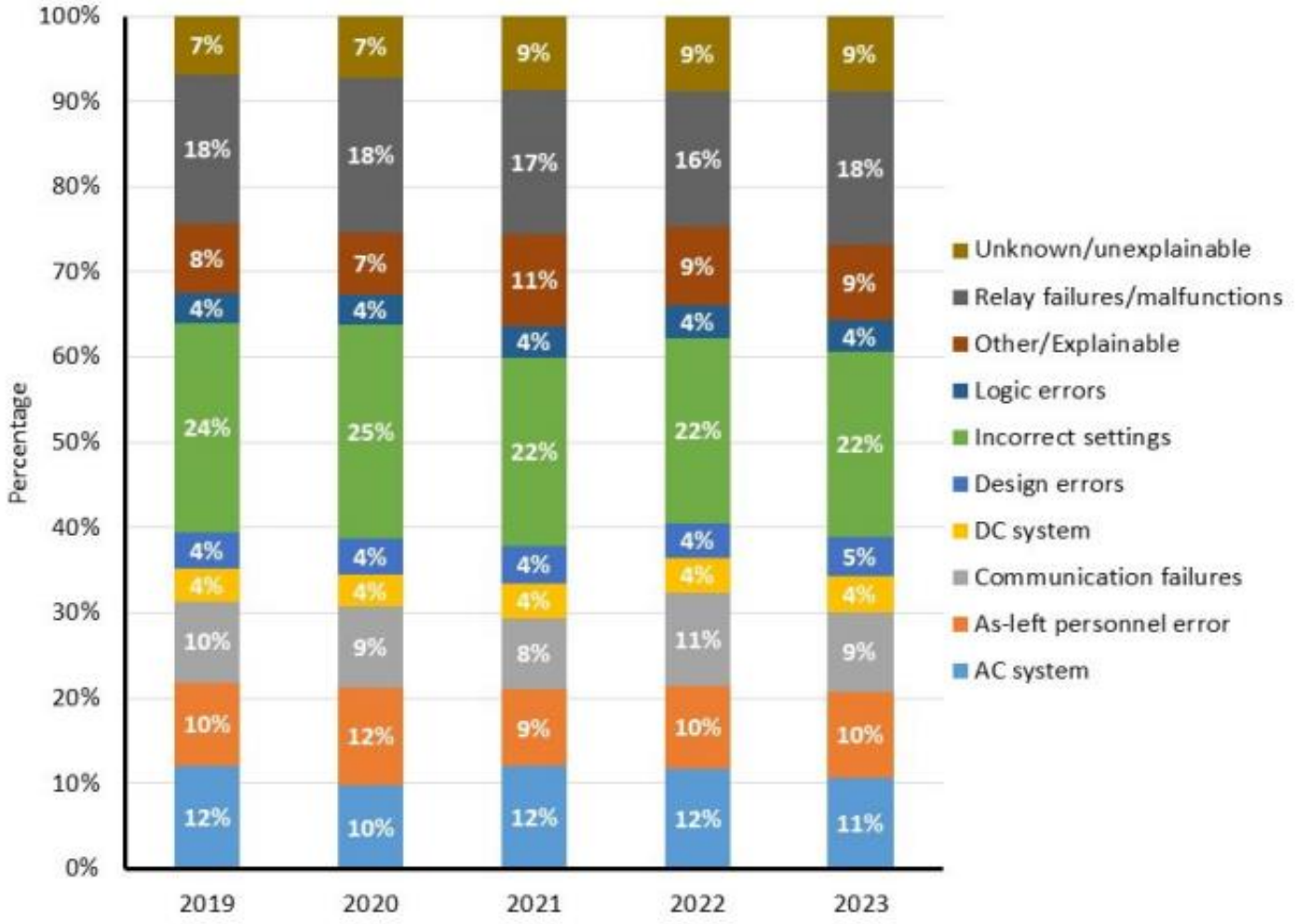
- Modern power grids are Cyber-Physical System (CPS) composed of electrical and ICT infrastructure
- Risk **of Malicious** and **Accidental** disruptions is increasing
- Testing for
  - Fearless reconfiguring / updates
  - Training
  - ICT / PS Interactions
  - Combined ICT / PS contingency analysis
  - New Protocols
  - New Communication Channels (NTN, 5G, ...)



OPAL-RT TECHNOLOGIES

NERC REPORTING ON PROTECTION SYSTEM MISOPERATIONS

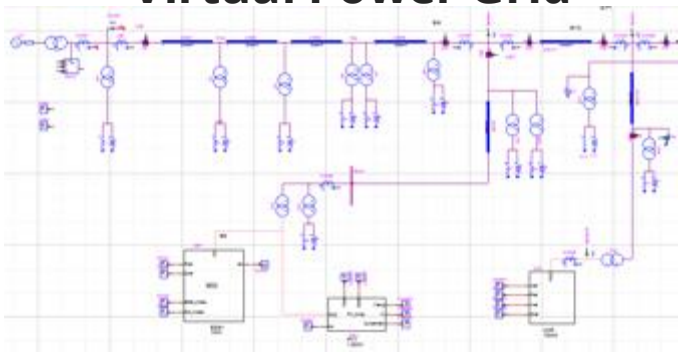
- Protection System Misoperation is Critical
  - Source of Cascading Failures
  - Large-scale Blackouts
- On average 5-8% Misoperation
- Most dominant
  - Incorrect Settings
  - HW Malfunctions
  - Communications Failures



https://www.nerc.com/globalassets/programs/rapa/pa/nerc_sor_2024_technical_assessment.pdf

CYBER-PHYSICAL POWER SYSTEMS (CPS) TESTBED

Virtual Power Grid



+

Virtual Communication Network

Physical Devices & Systems
(SCADA, Relays, PMUs, IEDs, Controllers, etc)

Digital I/Os

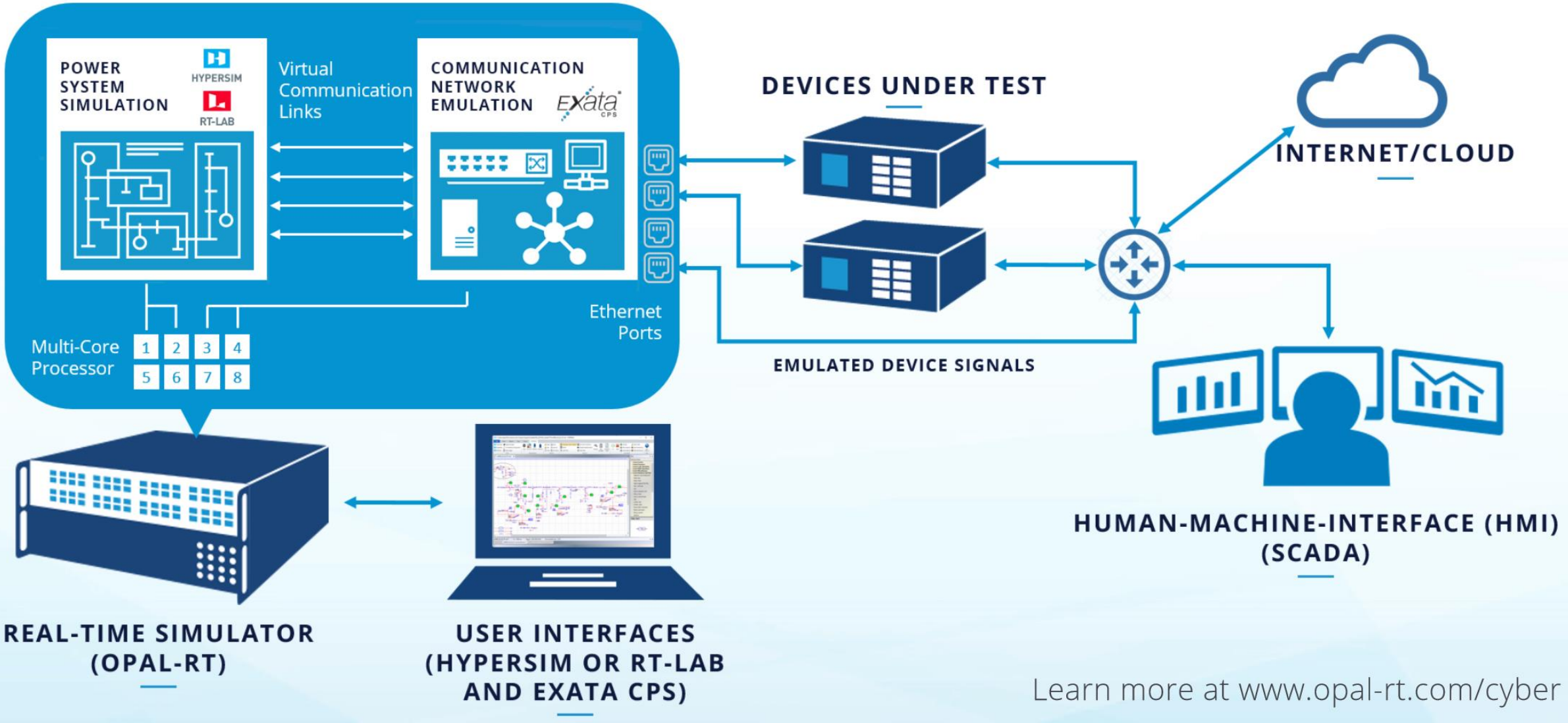
Analog I/Os

Time Synchronization (IRIG-B, 1PPS, IEEE 1588 PTP)

Communication Protocols (DNP3, IEC 61850, Modbus, C37.118, OPC-UA, IEC-104, etc.)

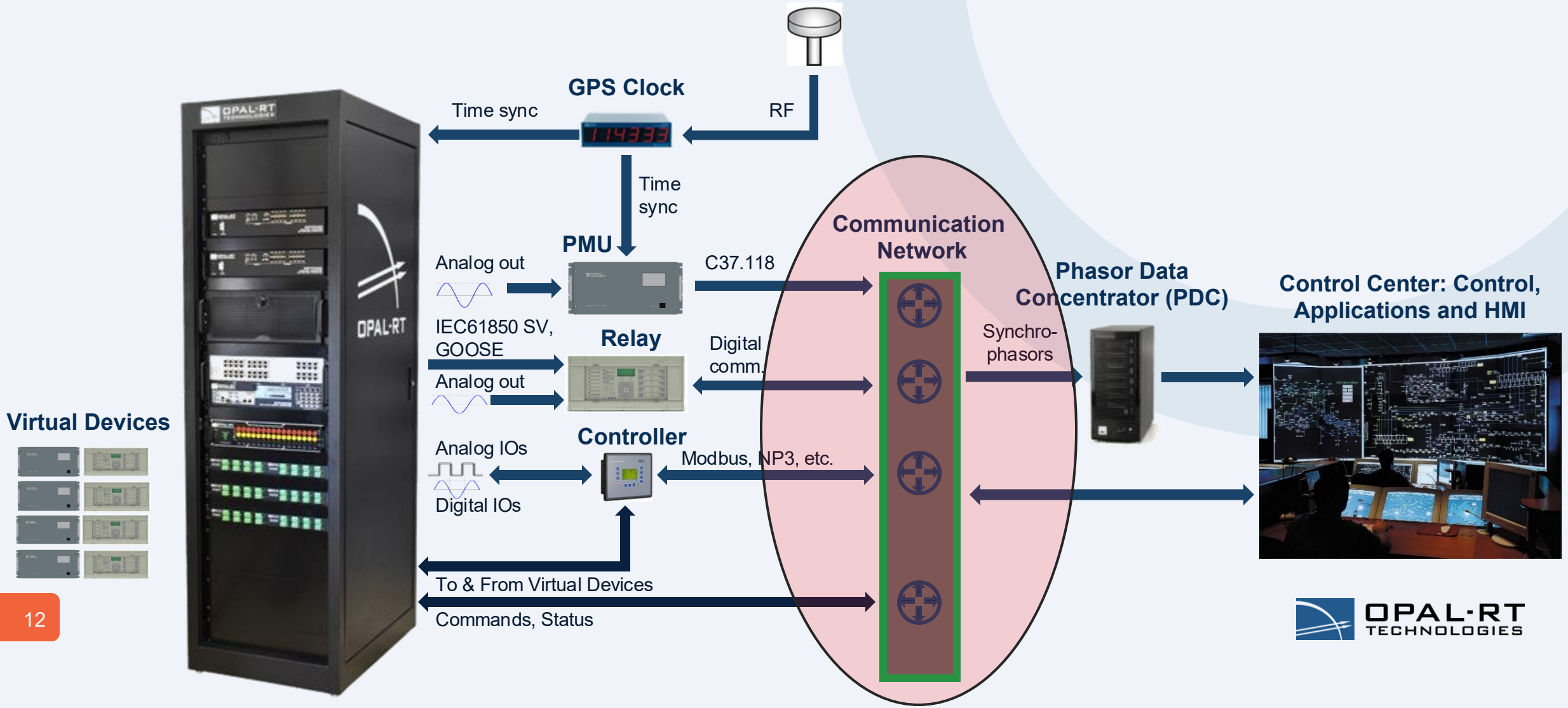
OPAL-RT TECHNOLOGIES

CPS Simulation Setup



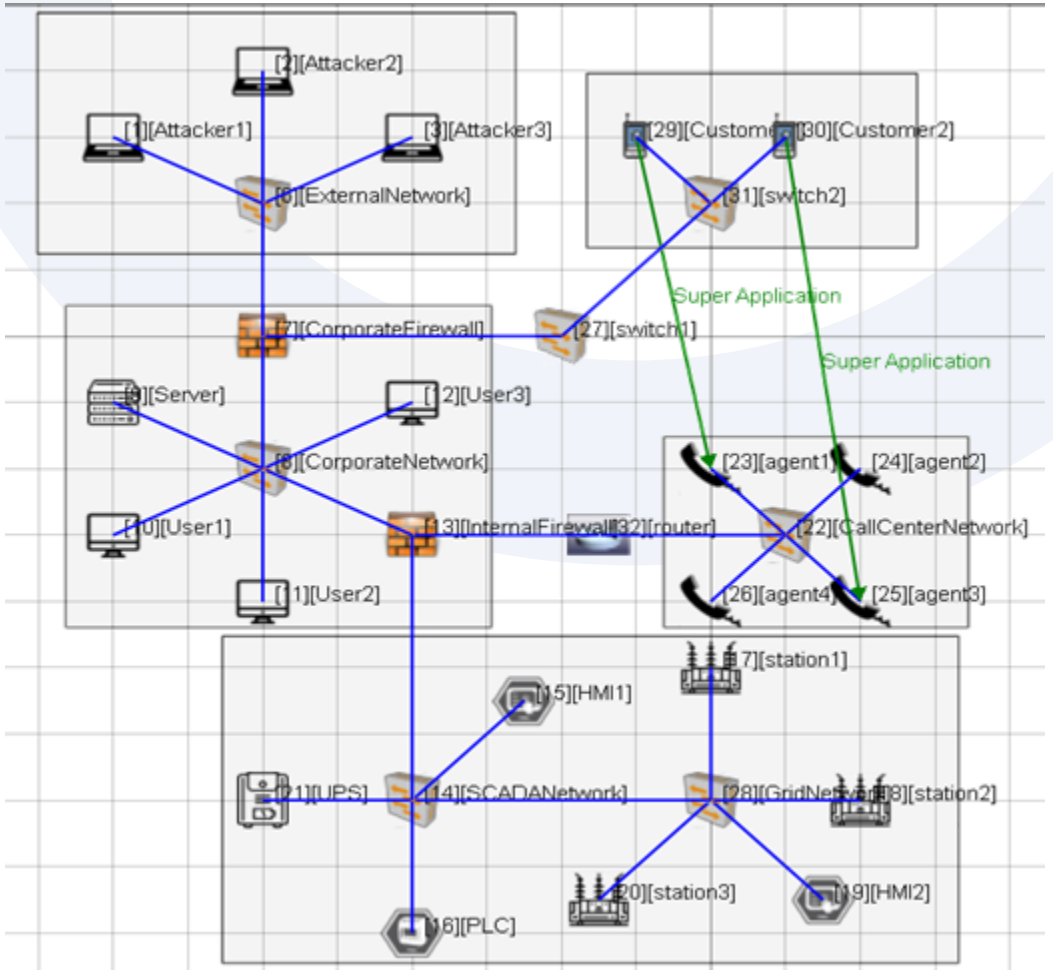
Learn more at www.opal-rt.com/cyber

ELECTRICAL AND COMMUNICATION NETWORK CO-SIMULATION

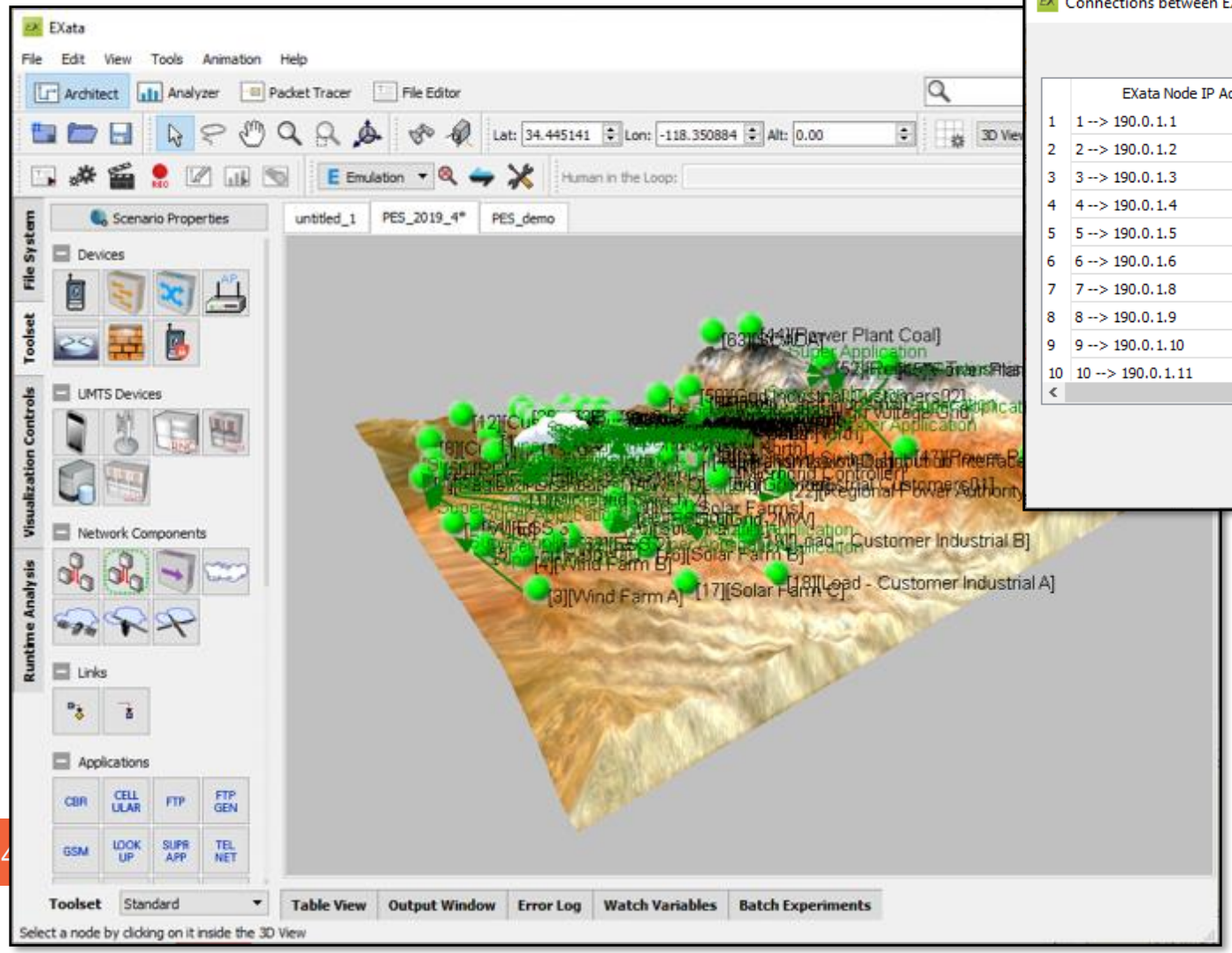


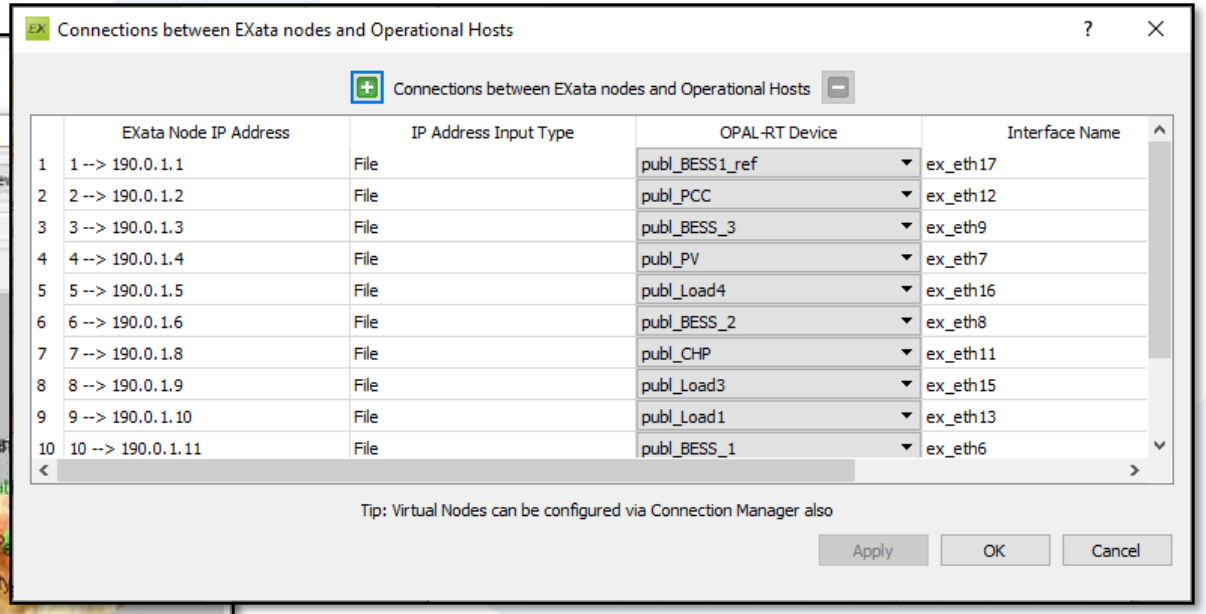
EXATA CPS – FEATURES & LIBRARIES

- GUI Modeling of
  - Topology
  - Geographical
    - Radio Links & Weather
  - Cyber
    - Attack Modeling
    - Defense Modeling
- Wireless / 5G / LTE / NTN
- Packet Sniffer Interface
- Multimedia and Enterprise
- Scenario Player



EXATA CPS – MODELING & MAPPING





CPS Toolset (ICT)

- Network Emulation
- Attack Simulation
- Honeypots
- Virtual Machines (VM)
- Network Analyzer / Scanners
- Vulnerability Scanners
- Intrusion / Anomaly Detection Systems (IDS)
- Security Information and Event Management Systems (SIEM)

Conclusion

- Hardware-in-the-Loop Testing is crucial for De-risking
- We need Integrated Cyber & Physical Testbeds
  - Resiliency & Security
  - Long-term Maintenance
- Establish Continuous Integration pipelines a common practice
  - Of Energy & Smart Grid Infrastructure
  - For testing / validation by Vendors
  - For maintenance / operation by Operators

Thank you
for your attention!

RESOURCES

- OPAL-RT:
  - Product Page: Securing cyber-physical systems with *EXata CPS*
  - Whitepaper: The cyber-physical simulation testbed for power systems
- Keysight*:* EXata Network Modeling – Critical Infrastructure

OPAL-RT TECHNOLOGIES