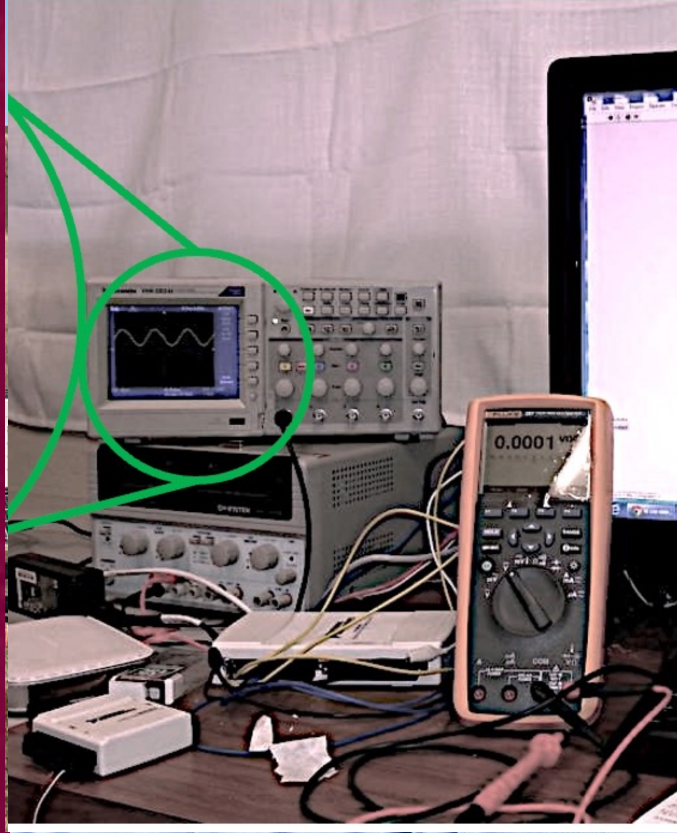
From Poor Man’s DRTS to 5G Power Grid RTDS Testbed:
A Walk Down Memory Lane



ALI MEHRIZI-SANI
ASSOCIATE PROFESSOR

Contributing students: Ardavan Mohammadhassani (PhD: 2023),
Younes Sangsefidi (PhD: 2018), Saleh Ziaieinejad (PhD: 2018), Baza Somda (MSc: 2023)

NORTH AMERICAN RTDS A&T CONFERENCE
Raleigh, NC
May 16-18, 2023

VIRGINIA TECH

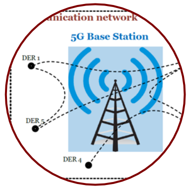
RESILIENT RENEWABLE
ENERGY GRID ADAPTATION
LABORATORY (REGAL)

POWER AND ENERGY CENTER

his work is supported in part by the DOE UNIFI Consortium, in part by Virginia’s Commonwealth Cyber Initiative (CCI), in part by PSERC/SCE, and in part by
SF award CPS-1837700 .

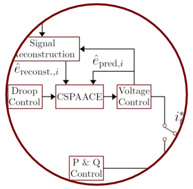
Outline

- Poor man’s DRTS
- A tale of two testbeds
  - Power grid testbed
  - 5G communication testbed
- Example capabilities
  - Control
  - Digital twinning
  - (Black box control)

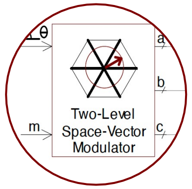


🇺🇸 Virginia Tech

🇺🇸 Washington State Univ.



🇨🇦 Univ. Toronto



🇨🇦 Univ. Manitoba

🇮🇷 Sharif Univ. Tech.

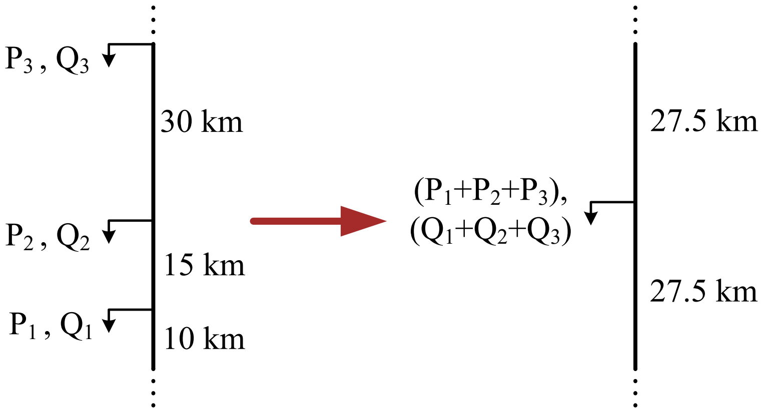
POOR MAN’S DRTS

Poor Man’s DRTS

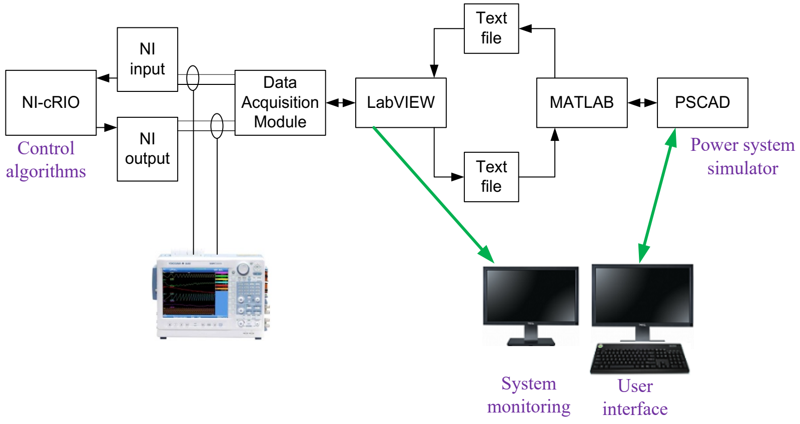
- A software-based solution for HIL evaluation of the controllers in a distribution system (CHIL):
  - The power system is represented via a “traditional” simulator.
  - The controllers are implemented in physical devices.
  - Certain simplifications are made to enable real-time solution.

Feature	Simulink	PowerFactory	PSCAD
Availability of power system components	Limited	Good	Good
Control blocks/functions	Extensive	Limited	Good
Parallel implementation	Yes	No	No
Developing new components	Yes	Yes	Yes
Steady state simulation	Yes	Yes	Yes
Dynamic simulation	Yes	Yes	Yes
Model transfer to RTDS	Difficult	Difficult	Easy
Compatibility with Opal-RT	Yes	No	No
User friendliness	Yes	No	Yes
Limitation in simulating large systems (Educational version)	No	Yes	Yes
Learning curve	Easy	Difficult	Medium
Capability to interface with other software	Good	Limited	Limited
Support team response	Normal	Normal	Fast
Simulation speed	Slow	Slow	Fast

Tool Selection



Aggregation

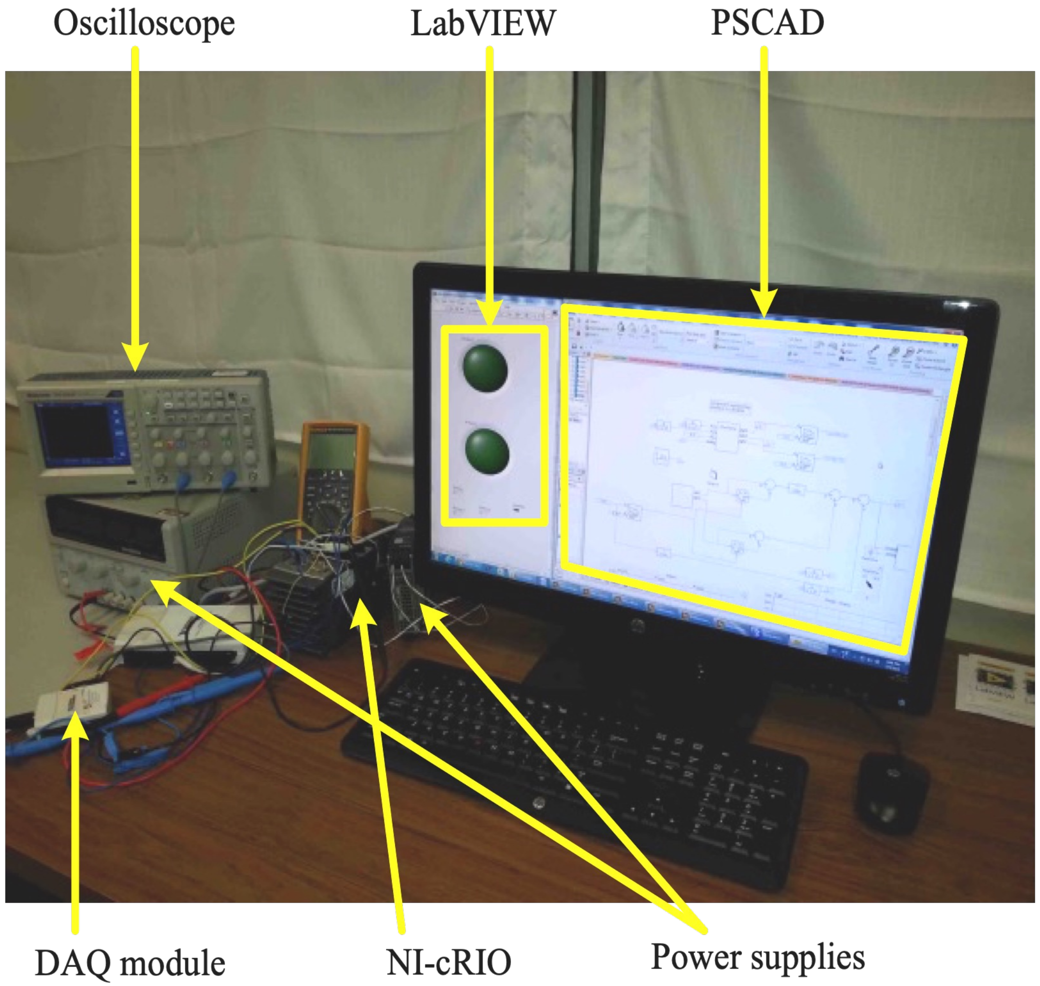


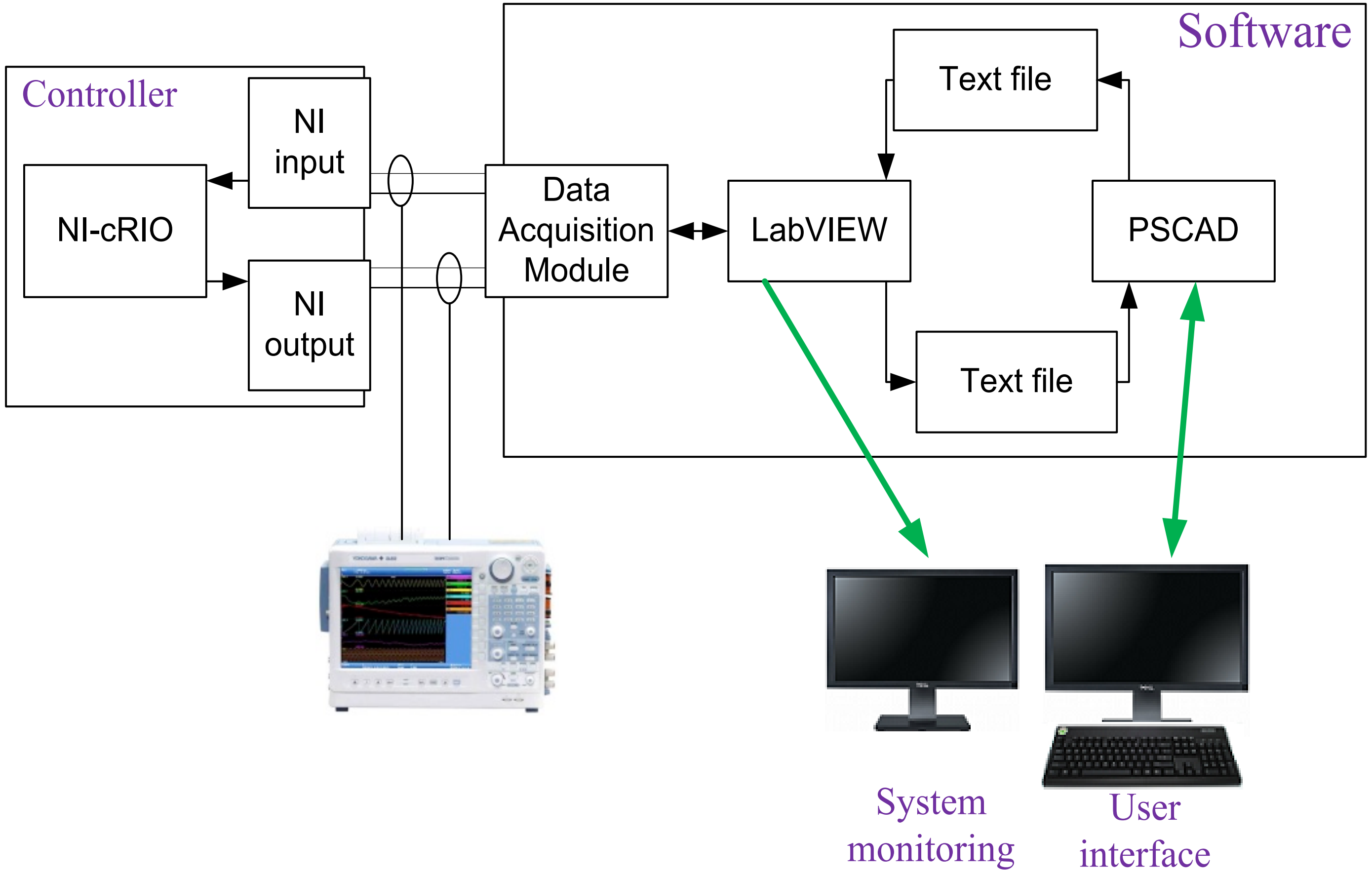
PSCAD-LabVIEW-Controller

A. Mehrizi-Sani, “Establishing a Software-Based Real-Time Simulation Platform for a Controls Laboratory for Training, Research and Development, and Experimentation,” PSERC Publication 15-01, Aug. 2015. [Online] https://pserc.wisc.edu/wp-content/uploads/sites/755/2018/08/T-54G_Final-Report_Aug-2015.pdf

PSCAD-LabVIEW Interface

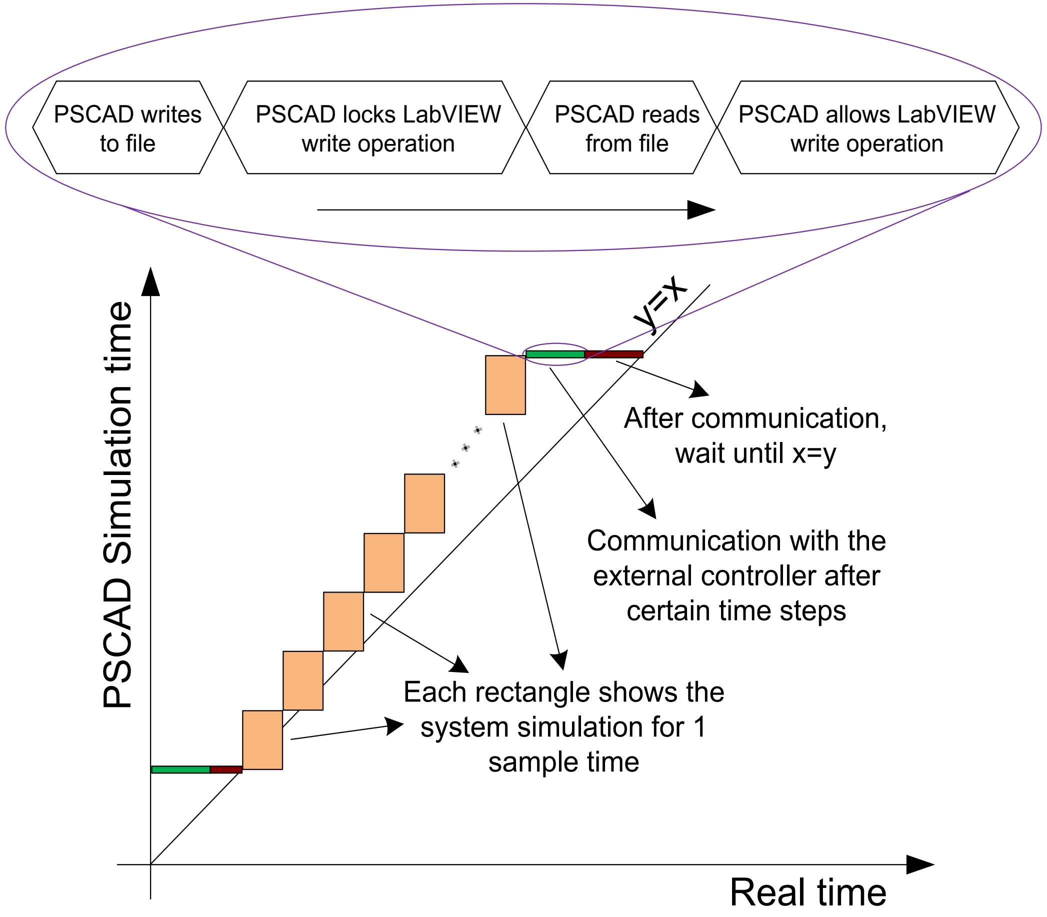
- Direct (i.e., without MATLAB) PSCAD-LabVIEW interface using a custom component (i.e., Fortran code) in PSCAD.
  - (This is years before PSCAD had the co-simulation block.)





Synchronization (1/2)

- The (physical) controller naturally runs in real time, but not PSCAD.
- We enforced real-time simulation by
  - Making simulation fast: Appropriate selection of the power system details, simulation time step, plot time step, and the rate of data exchange with the controllers.
  - Making simulation slow: Slowing down the simulation if it runs faster than real time.
- A custom block was developed to compare the system time (wall-clock time) with the simulation time. It compares the times any time data is exchanged and if needed, equalizes the simulation time with wall clock time.



PSCAD writes to file

PSCAD locks LabVIEW write operation

PSCAD reads from file

PSCAD allows LabVIEW write operation

After communication, wait until x=y

Communication with the external controller after certain time steps

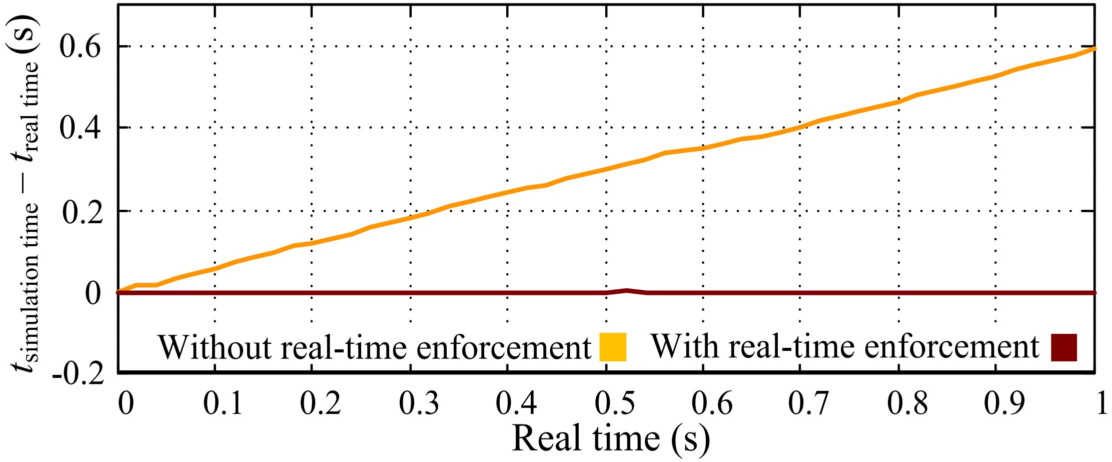
Each rectangle shows the system simulation for 1 sample time

NI-cRIO continually implements the control algorithms and sends and receives data in every time step

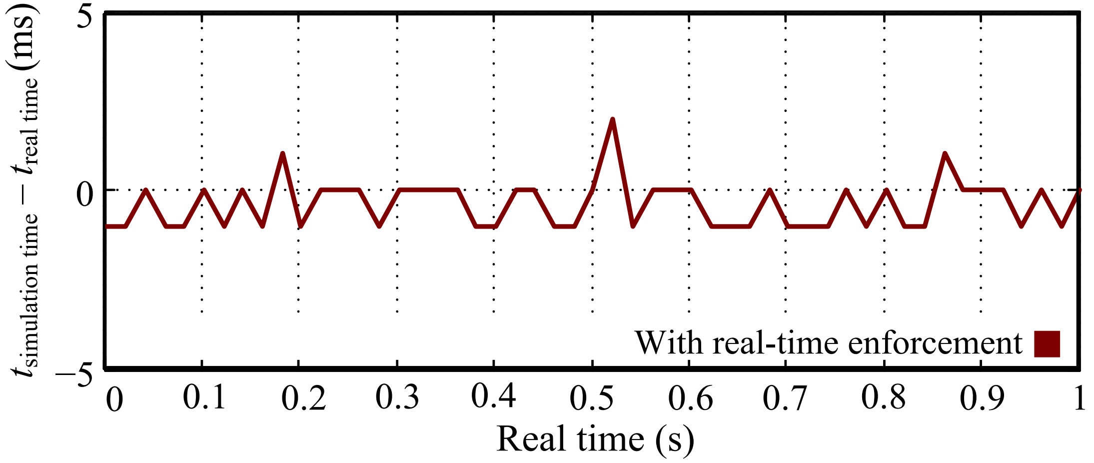
LabVIEW continually reads the last updated (by PSCAD) file and writes the last updated (by NI-cRIO) data to file (unless locked by PSCAD

Synchronization (2/2)

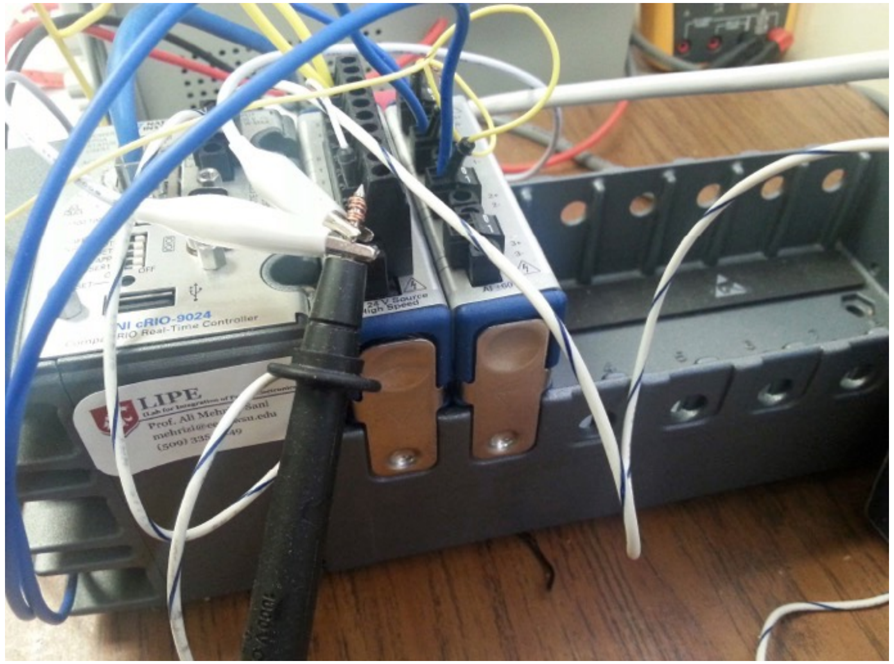
- This is an *ad hoc* solution but it was sufficient for our application.



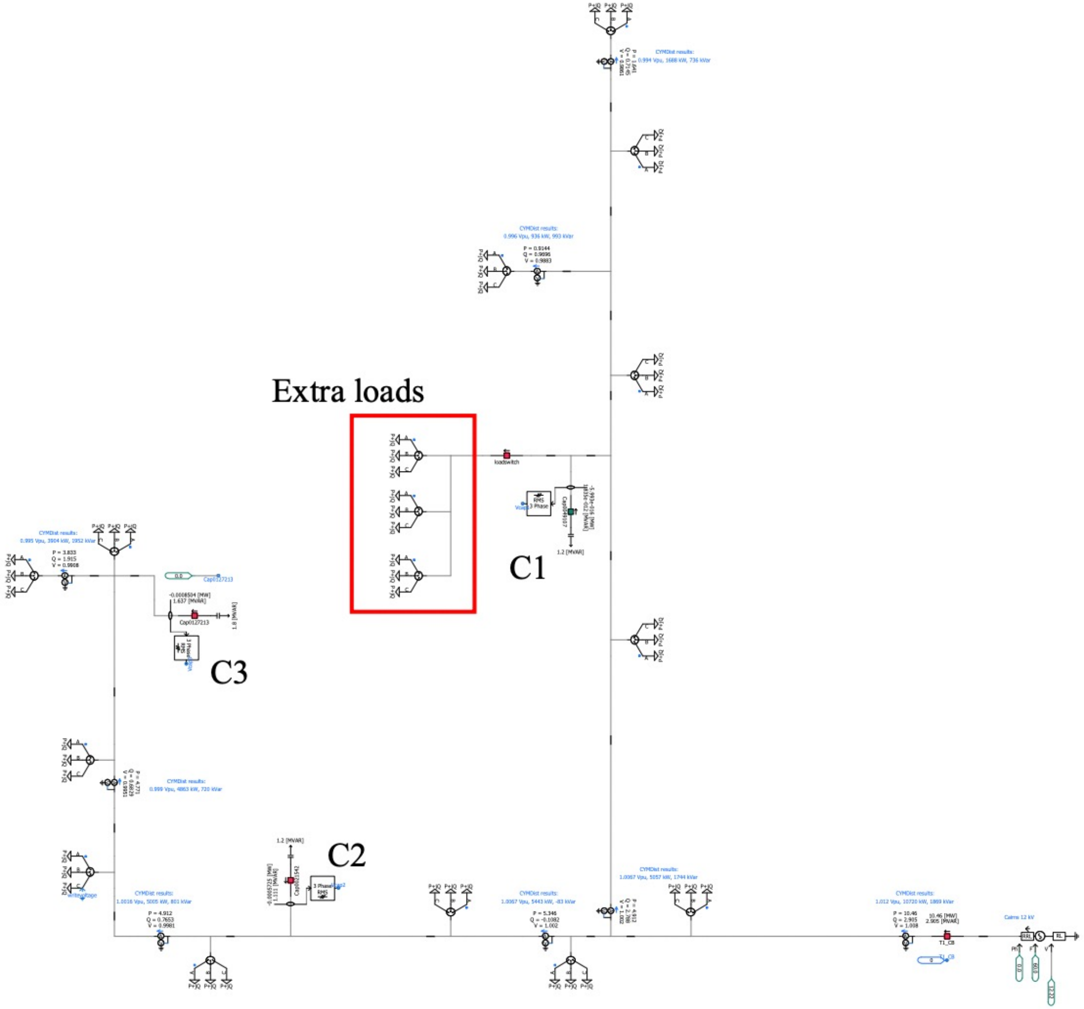
(zoomed)



Setup



An NI-cRIO 9024 is used as the external controller. It reads two analog signals from the simulation file (VC1 and VC2) and sends two digital commands to switch capacitors on/off back. Therefore, one analog input module and one digital output module are needed.

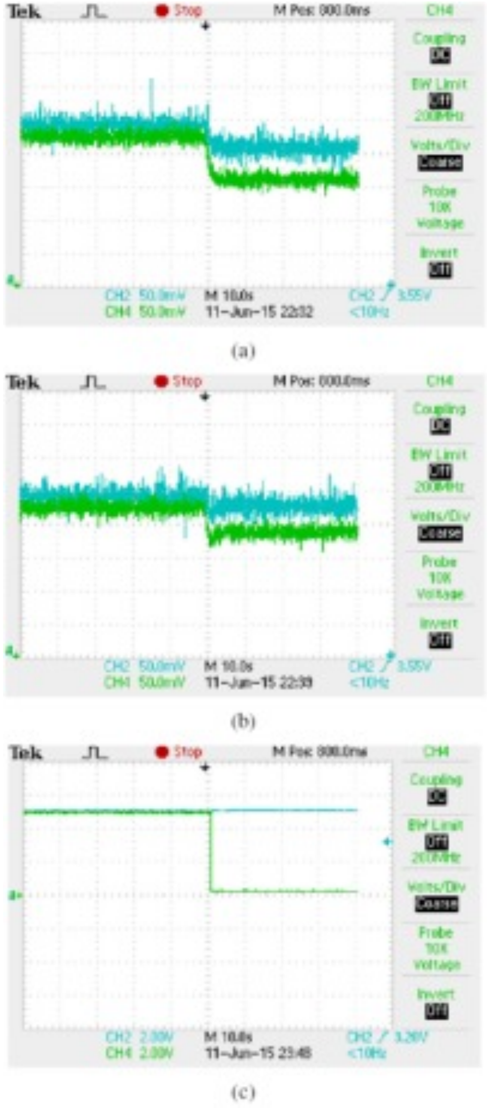


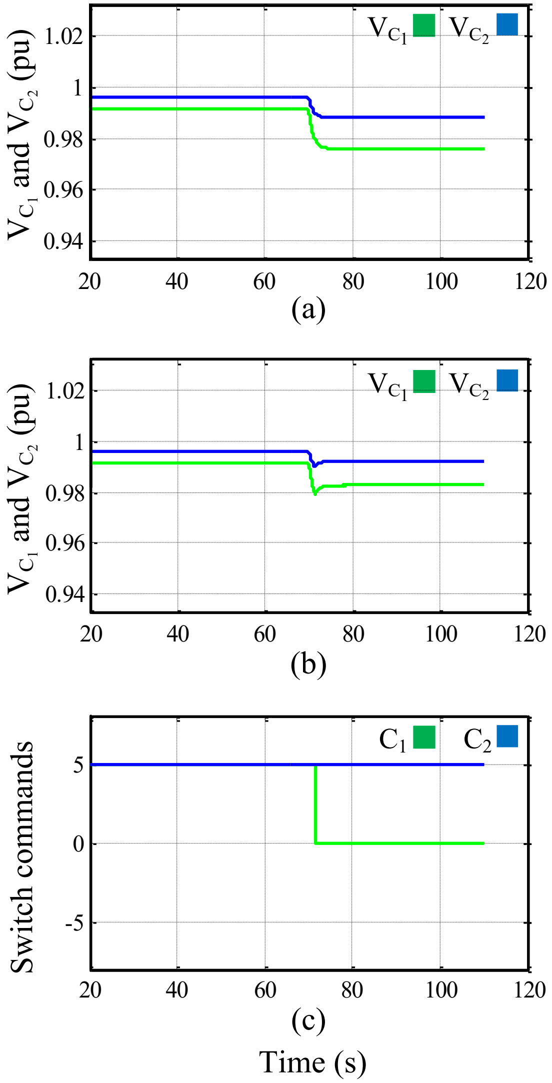
Simplified feeder. P and Q are tested against the original feeder.

- M. Kezunovic, A. Esmaeilian, M. Govindarasu, and A. Mehrizi-Sani, “The use of system in the loop hardware in the loop and co-modeling of cyberphysical systems in developing and evaluating smart grid solutions,” in *Hawaii Int. Conf. Syst. Sciences (HICSS),* Waikoloa, HI, Jan. 2017.
- S. Ziaeinejad and A. Mehrizi-Sani, “Software-based hardware-in-the-loop real-time simulation of distribution systems,” in *IEEE Power and Energy Soc. General Meeting (PESGM),* Boston, MA, Jul. 2016.

Performance Evaluation

- **Loads switched on at $t = 70$ s.**
  - (a) Voltages of the capacitor buses when the external controller does not run and both capacitors are off (0.0125 pu/div)
  - (b) voltages of the capacitor buses when the external controller is interfaced to the simulation (0.0125 pu/div);
  - (c) commands of the capacitor switches in the presence of the external controller (0 V = on; 5 V = off) (2 V/div).



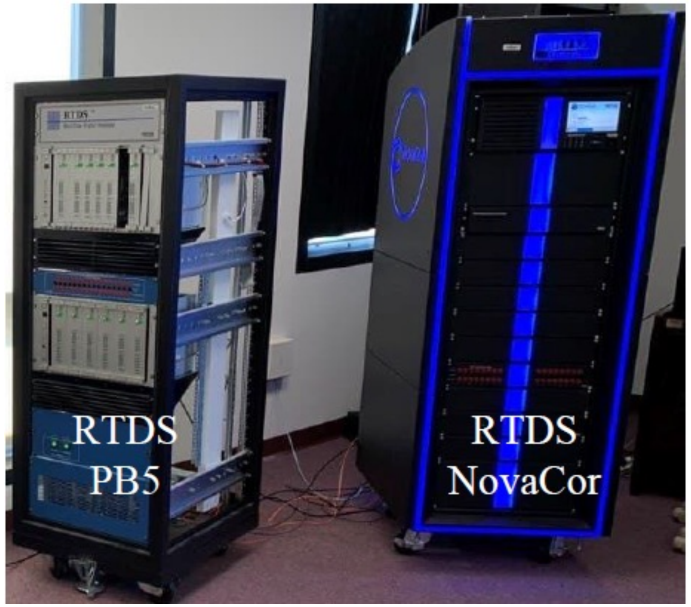


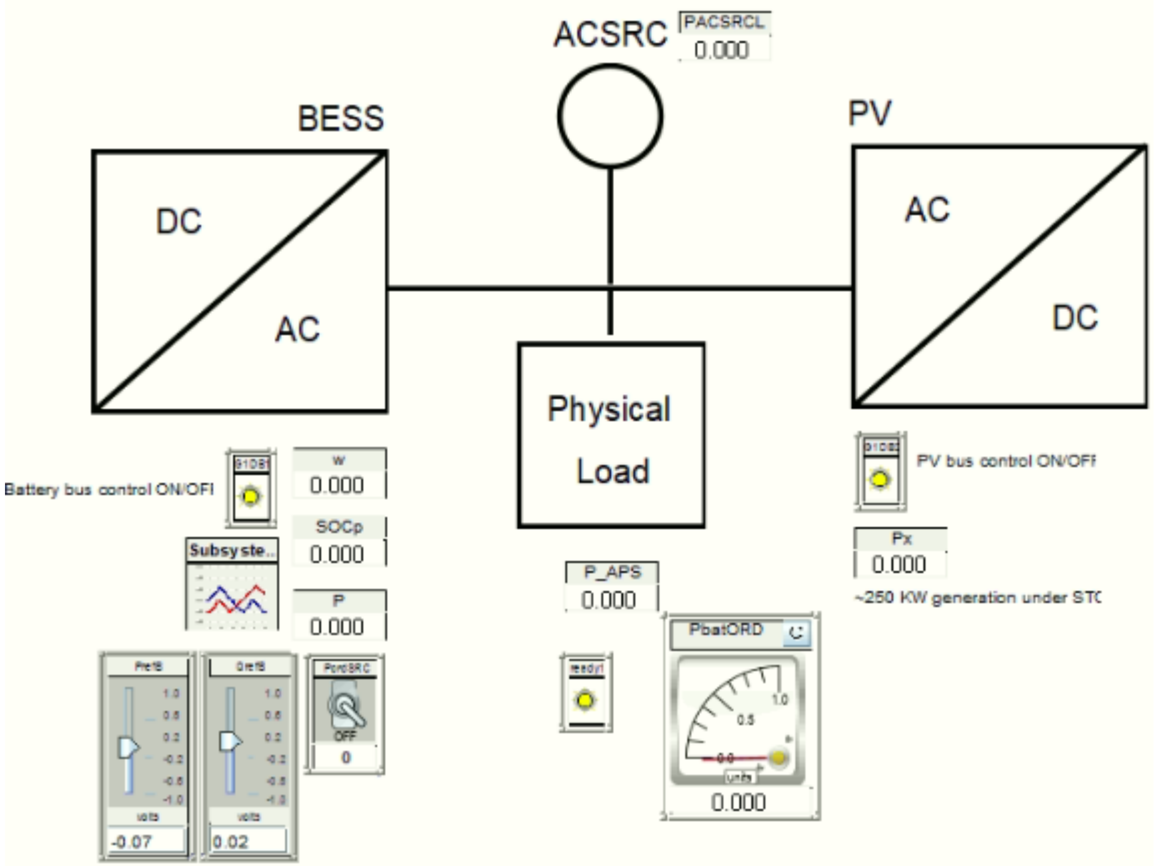
- M. Kezunovic, A. Esmaeilian, M. Govindarasu, and A. Mehrizi-Sani, “The use of system in the loop hardware in the loop and co-modeling of cyberphysical systems in developing and evaluating smart grid solutions,” in Hawaii Int. Conf. Syst. Sciences (HICSS), Waikoloa, HI, Jan. 2017.
- S. Ziaeinejad and A. Mehrizi-Sani, “Software-based hardware-in-the-loop real-time simulation of distribution systems,” in IEEE Power and Energy Soc. General Meeting (PESGM), Boston, MA, Jul. 2016.

A Tale of Two Testbeds

5G POWER GRID (5GPG) TESTBED

The Power Grid Side of the 5GPG Testbed





PACSRCL 0.000

Battery bus control ON/OFI

W 0.000

SOCp 0.000

P 0.000

PrefB volts -0.07

QrefB volts 0.02

PordBRC OFF 0

P_APS 0.000

PbatORD 0.000

PV bus control ON/OFF

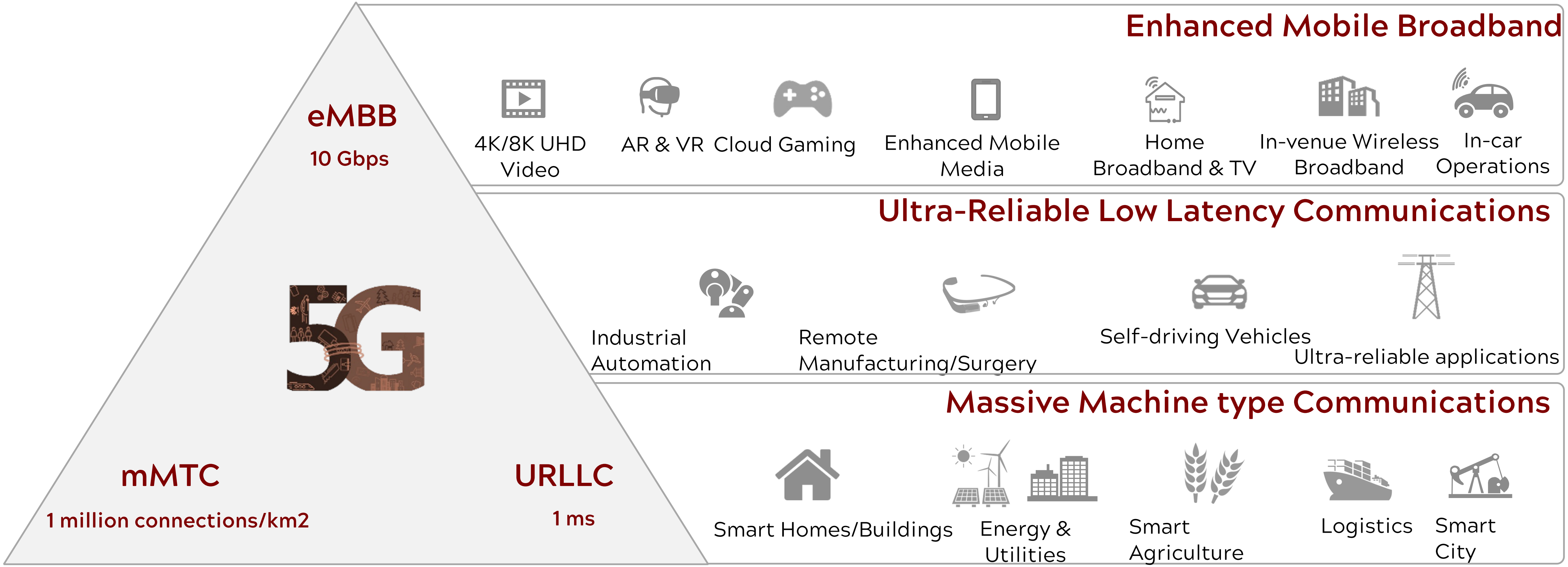
Px 0.000

~250 KW generation under STC

Equipment acquired through a grant from Virginia's Commonwealth Cyber Initiative (CCI). PB5 is donated by Dominion Energy.

5G Key Use Scenarios: Slicing

- Expanding research to communication in the power system:
  - Distributed algorithms; cybersecurity
- Analogy: virtual machines on a desktop computer



eMBB

10 Gbps

mMTC

1 million connections/km2

URLLC

1 ms

Enhanced Mobile Broadband

- 4K/8K UHD Video
- AR & VR
- Cloud Gaming
- Enhanced Mobile Media
- Home Broadband & TV
- In-venue Wireless Broadband
- In-car Operations

Ultra-Reliable Low Latency Communications

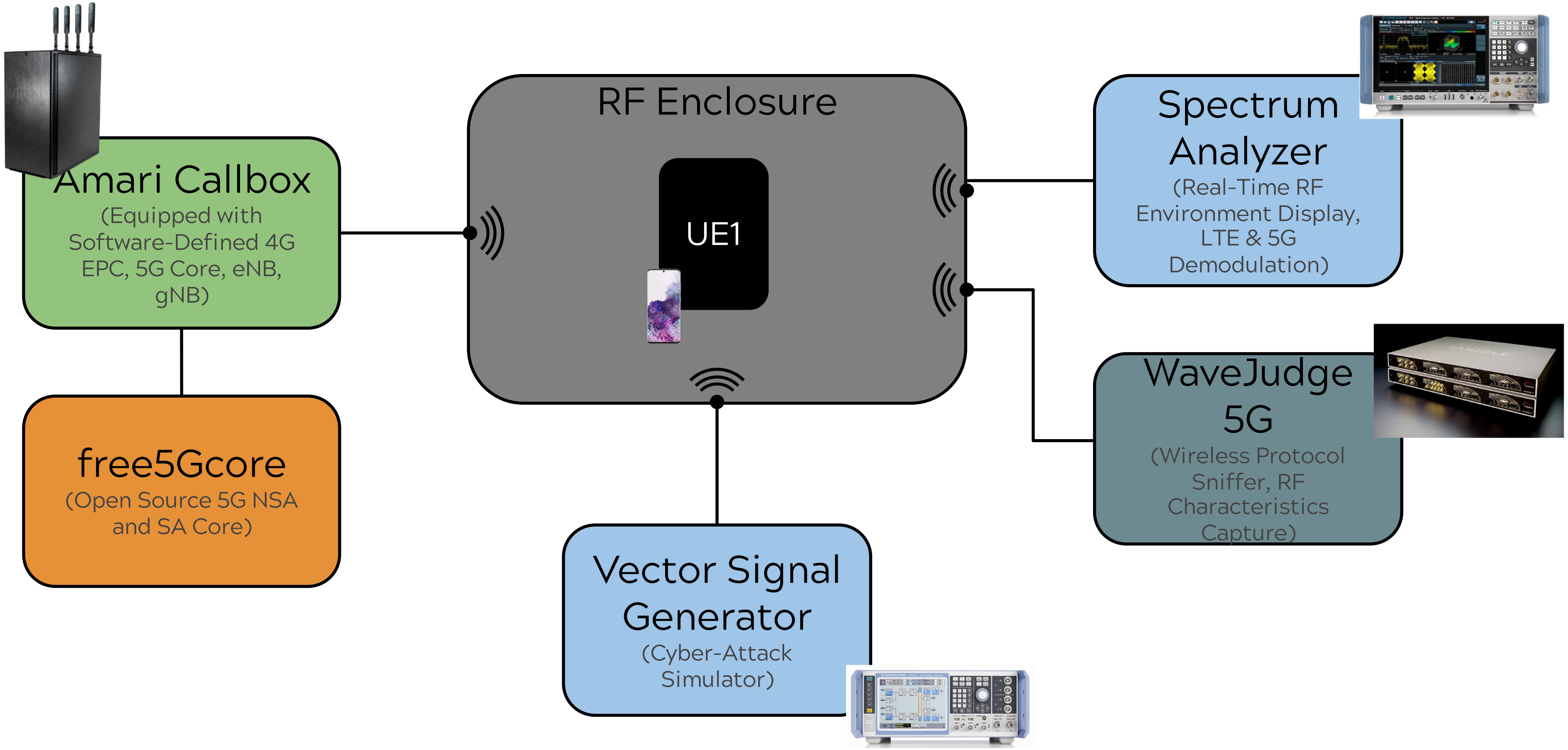
- Industrial Automation
- Remote Manufacturing/Surgery
- Self-driving Vehicles
- Ultra-reliable applications

Massive Machine type Communications

- Smart Homes/Buildings
- Energy & Utilities
- Smart Agriculture
- Logistics
- Smart City

Recommendation ITU-R M.2083

The 5G Side of the 5GPG Testbed



Amari Callbox
(Equipped with Software-Defined 4G EPC, 5G Core, eNB, gNB)

free5Gcore
(Open Source 5G NSA and SA Core)

RF Enclosure

UE1

Spectrum Analyzer
(Real-Time RF Environment Display, LTE & 5G Demodulation)

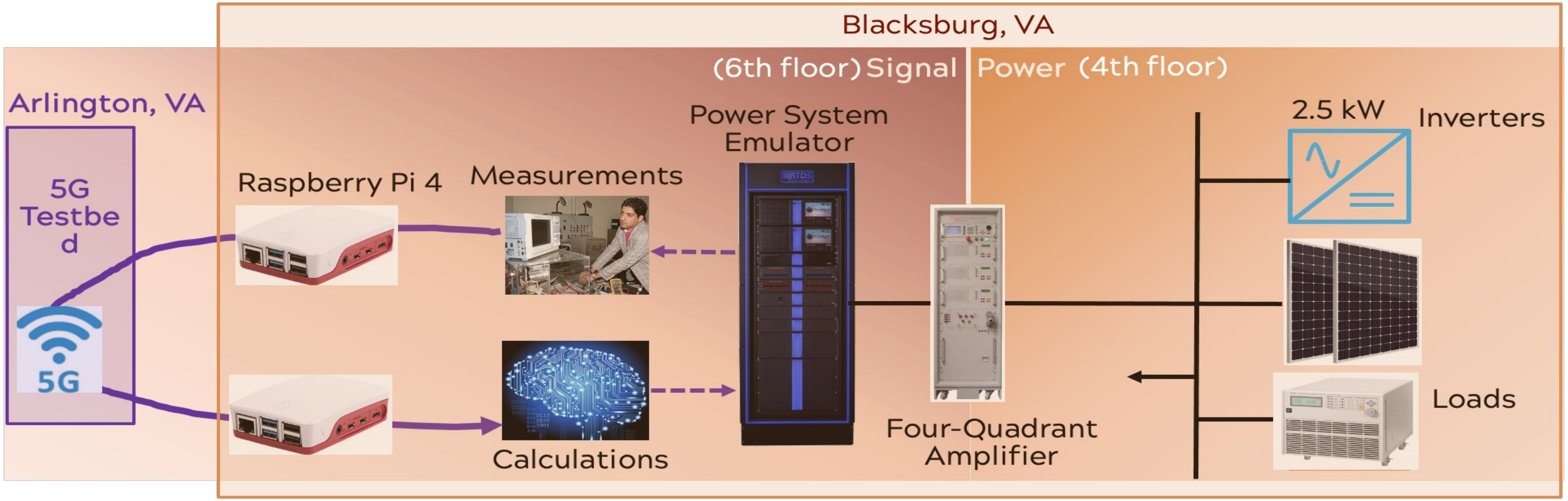
WaveJudge 5G
(Wireless Protocol Sniffer, RF Characteristics Capture)

Vector Signal Generator
(Cyber-Attack Simulator)

Slide Courtesy of Dr. Ying Wang, 2021.

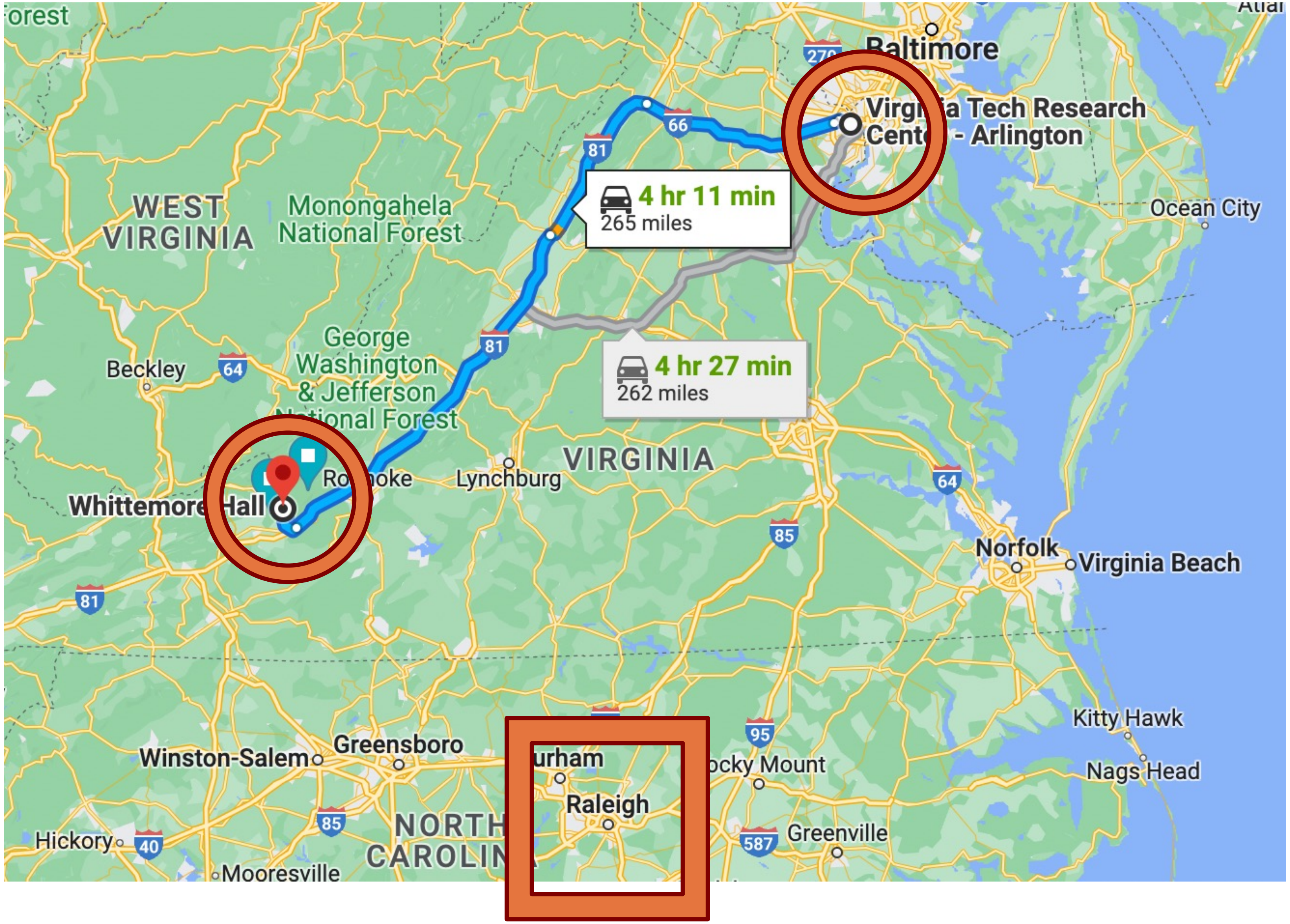
5G Power Grid Testbed

- Power grid applications (control and protection) + communication + cybersecurity assessment and design of cybersecure controllers.
- This testbed is spread over three locations/labs:
  - Blacksburg: Microgrid (inverters, controllers, batteries, controllable loads/sources)
  - Blacksburg: RTDS units + communication (Modbus, DNP3, and IEC 61850)
  - Arlington: 5G testbed

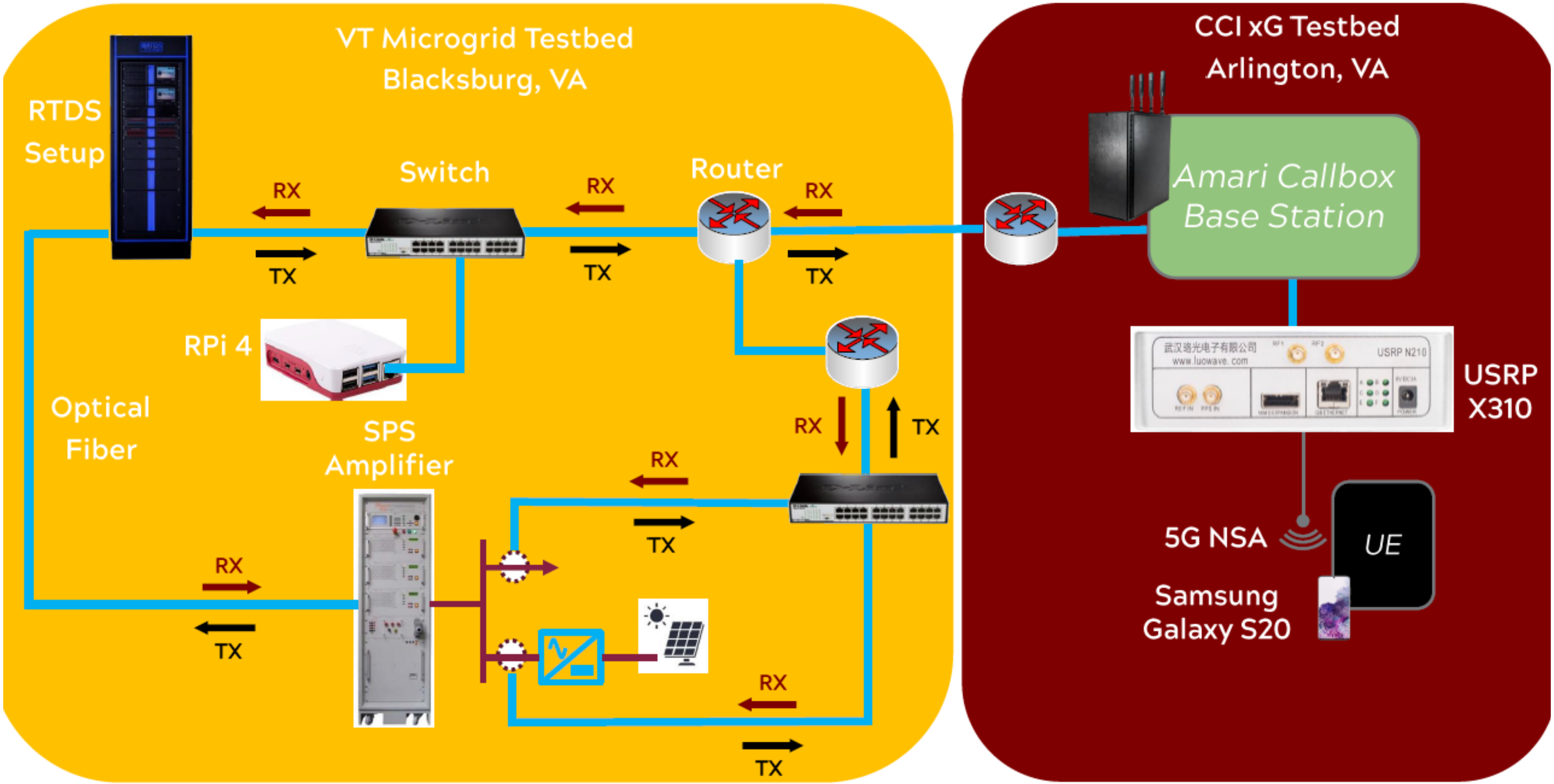


A. Mehrizi-Sani, et al. "Power-Hardware-in-the-Loop Demonstration of Power Systems with 5G Communication," submitted to SmartGridComm Conf., 2023.

Locations and Distances



5G + Power Grid Testbed



Challenges

- Lack of 5G radio peripherals in the microgrid testbed
    - Interfaced through RTDS as proxy devices, in this case an android-based cell phone.

- Different testbed locations
    - Communication over internet and OpenVPN would introduces latencies up to 200 ms!
    - Traffic between the two testbeds is routed through a dedicated optical fiber (8 ms).

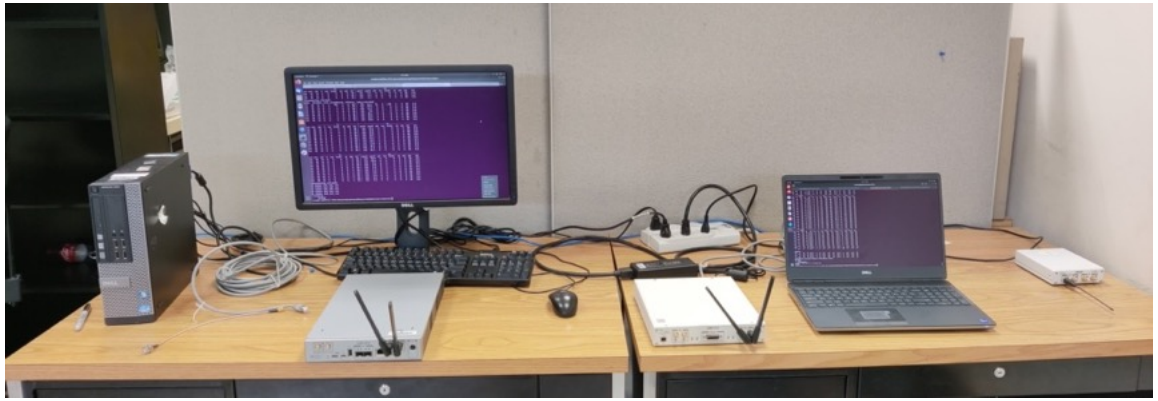
- Different testbed network domains
    - The GTNET cards of the NovaCor rack are assigned private IP addresses by the router in their LAN, while the UE is assigned an IP address by an OpenVPN server. Therefore, communication between the NovaCor and the UE is not possible through OpenVPN.

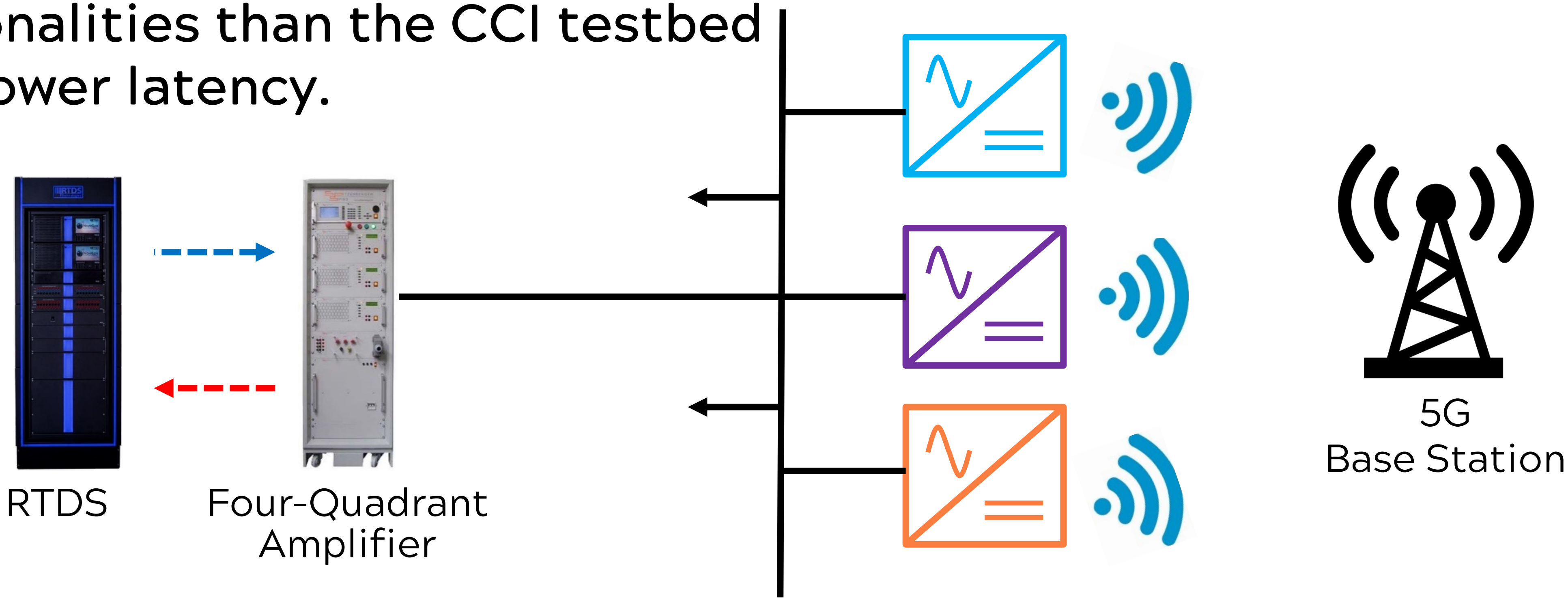
Challenges

- **Lack of application-layer software for NovaCor and the UE**
  - A TCP/IP client-server is written. The GTNET cards of the NovaCor are set to send and receive data as clients using the socket protocol.
  - An Android client program is developed for the UE using the socket library in Java.
  - A multi-connection server program is developed using the socket library in Python to enable communication between RTDS and the UE through the dedicated optical fiber link.
  - This server is hosted on a Raspberry Pi4 (RPi4) to enable monitoring, control, diagnostics, and scalability of the communication link.
- **The total minimum latency for the communication link between the UE and RTDS is 28 ms.**
  - Since RTDS and RPi4 are on the same network and physically close to each other, the latency between the two is approximately 0 ms.
  - The minimum latency between the UE and the CCI xG testbed RAN is 20 ms.
  - Using fiber, the connection latency between Arlington and Blacksburg is 8 ms.
- **This latency defines the types of applications we can study.**

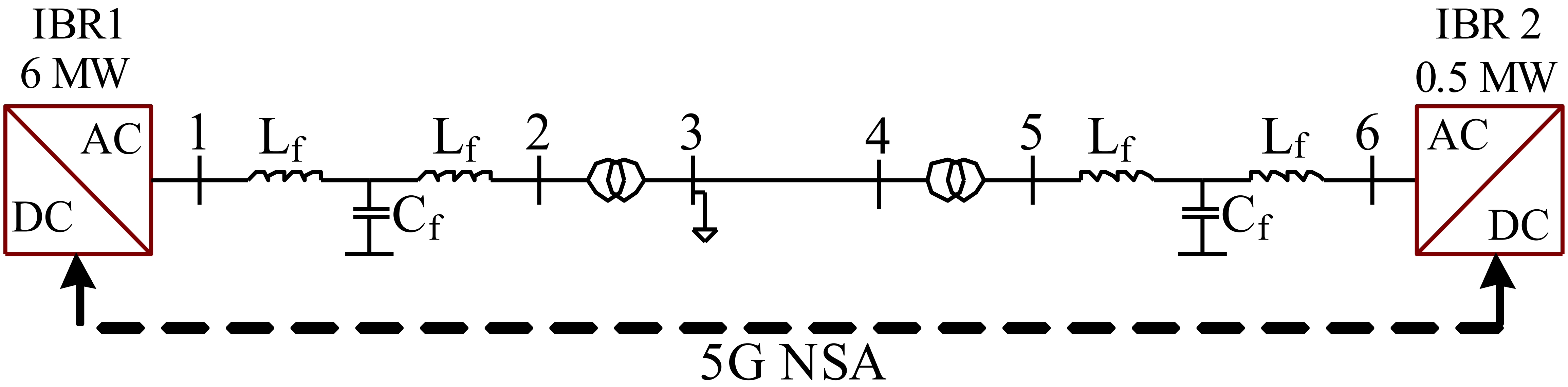
Upgrading the 5G Side of the 5GPG

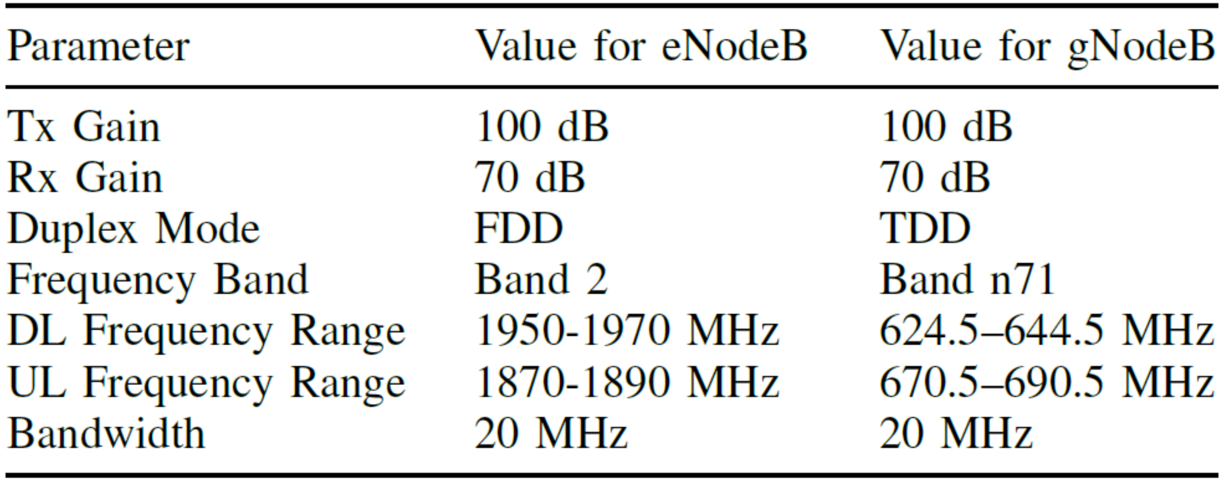
- An in-house 5G testbed is under development by Wireless@VT, which can be used for direct connection between devices in the Power Grid testbed.
- This 5G testbed provides more functionalities than the CCI testbed and a lower latency.





Performance Evaluation





Parameter	Value for eNodeB	Value for gNodeB
Tx Gain	100 dB	100 dB
Rx Gain	70 dB	70 dB
Duplex Mode	FDD	TDD
Frequency Band	Band 2	Band n71
DL Frequency Range	1950-1970 MHz	624.5–644.5 MHz
UL Frequency Range	1870-1890 MHz	670.5–690.5 MHz
Bandwidth	20 MHz	20 MHz

Each IBR uses one GTNET card to establish a duplex connection with the multi-connection server on RPi4.

The packet generation frequency of each GTNET card is set to 1 kHz.

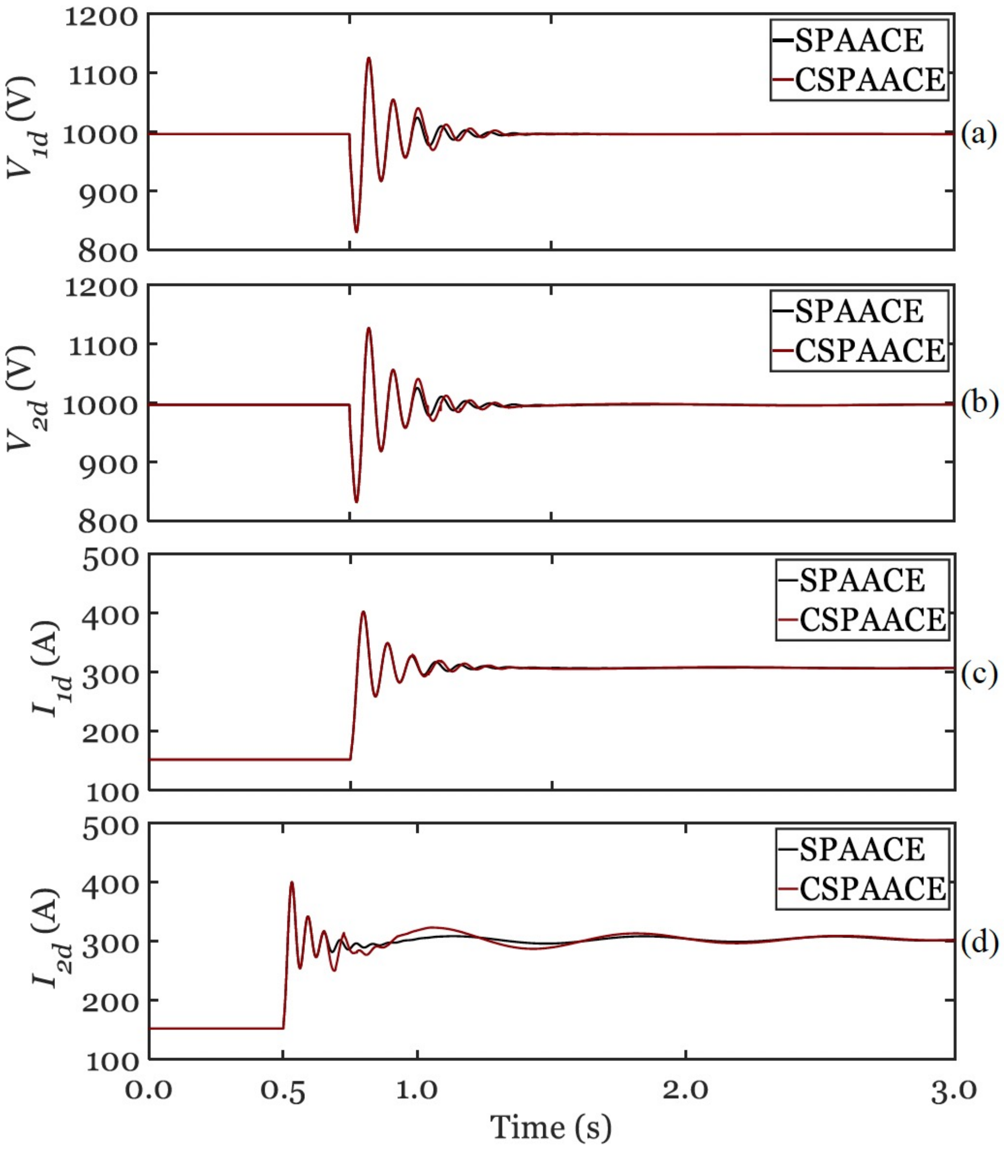


Fig. 6. Real-time simulation results for Case 1: (a) *d*-axis component of voltage for IBR1, (b) *d*-axis component of voltage for IBR2, (c) *d*-axis component of current for IBR1, and (d) *d*-axis component of current for IBR2.

Real power of the load at bus 3 increases in a step from 1 MW to 2 MW.

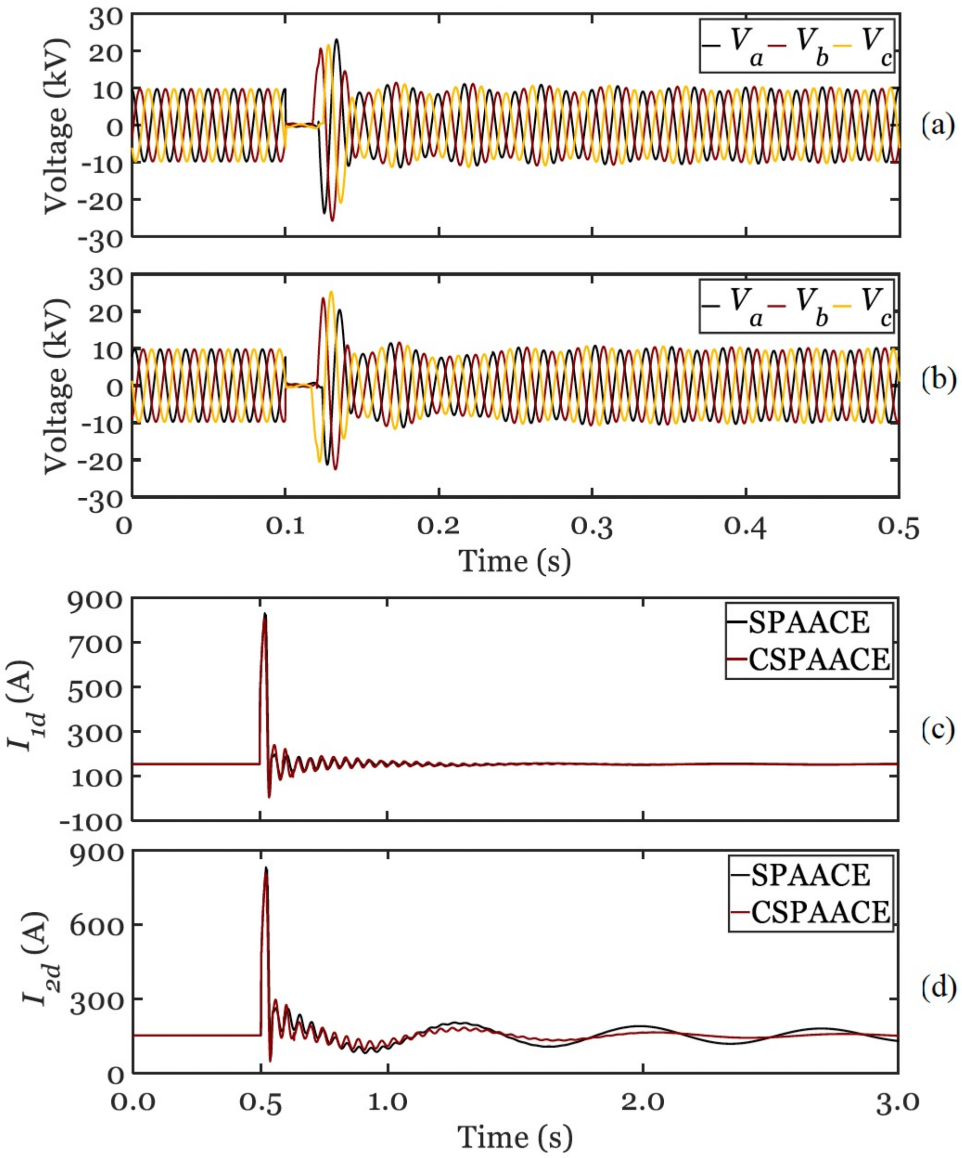


Fig. 7. Real-time simulation results for Case 2: (a) load voltages under SPAACE, (b) load voltages under C-SPAACE, (c) *d*-axis component of current injected by IBR1, and (d) *d*-axis component of current injected by IBR2.

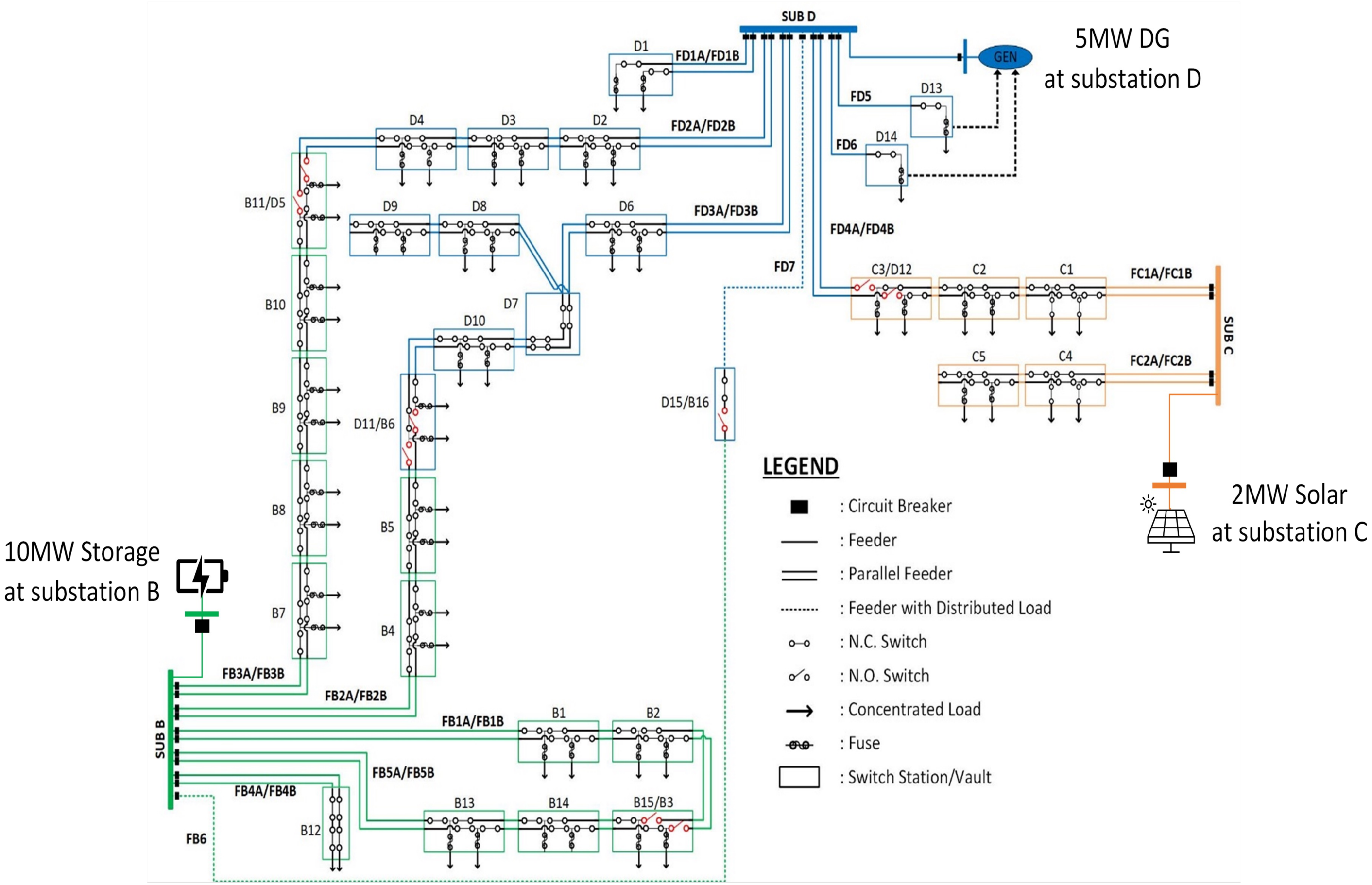
A bolted temporary balanced fault occurs at the midpoint of line 3-4 and stays for one cycle.

DIGITAL TWINNING

Digital Twin of the VT Electric Service

- Peak load: 60 MW
- 3 substations, 26 feeders, 31 nodes.
- Deployment of DERs to reach climate action goal.

- This represents an opportunity to develop a microgrid-based resilience plan for VTES.



5MW DG at substation D

10MW Storage at substation B

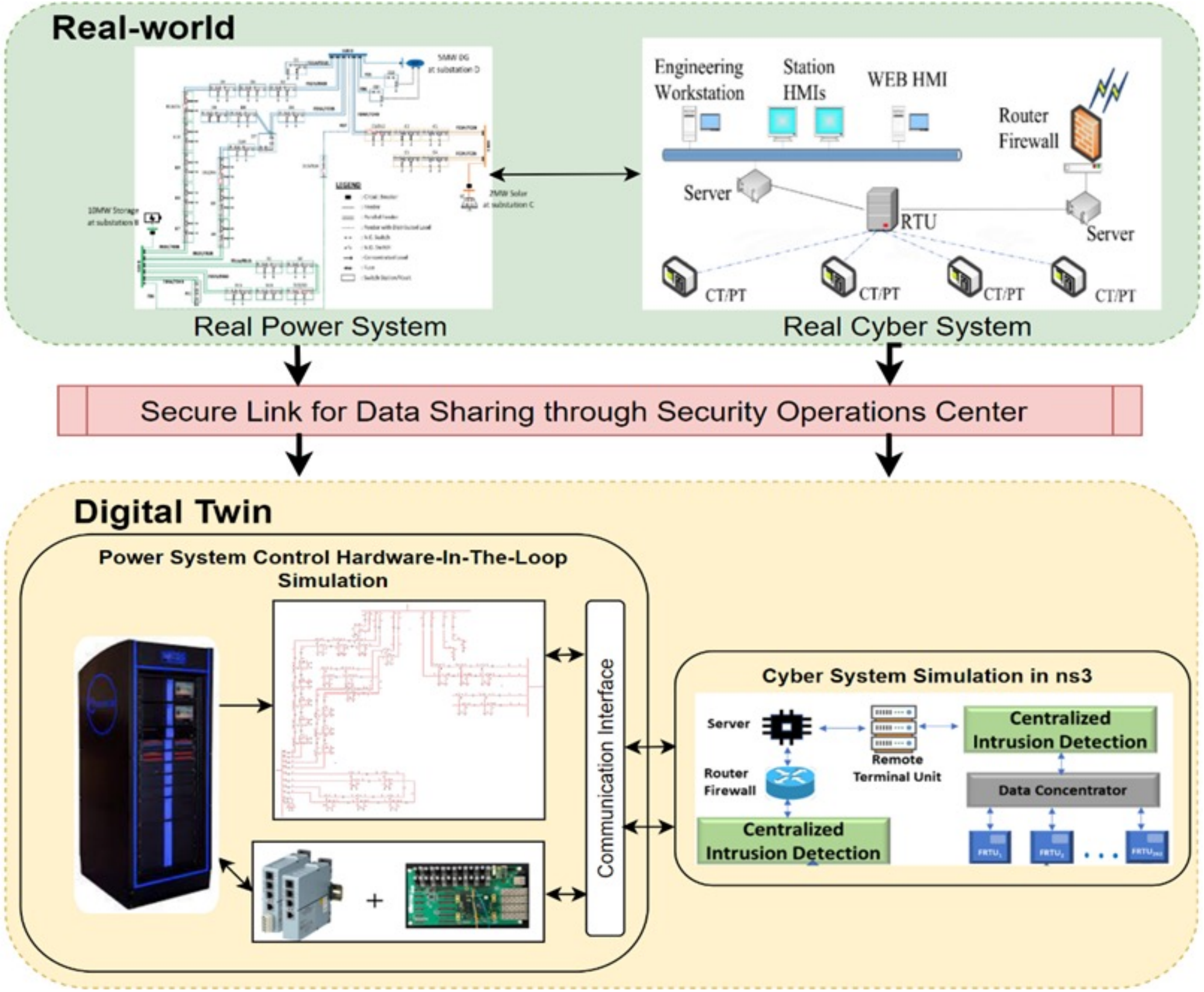
2MW Solar at substation C

Courtesy of Prof. Chen-Ching Liu, Virginia Tech, 2023.

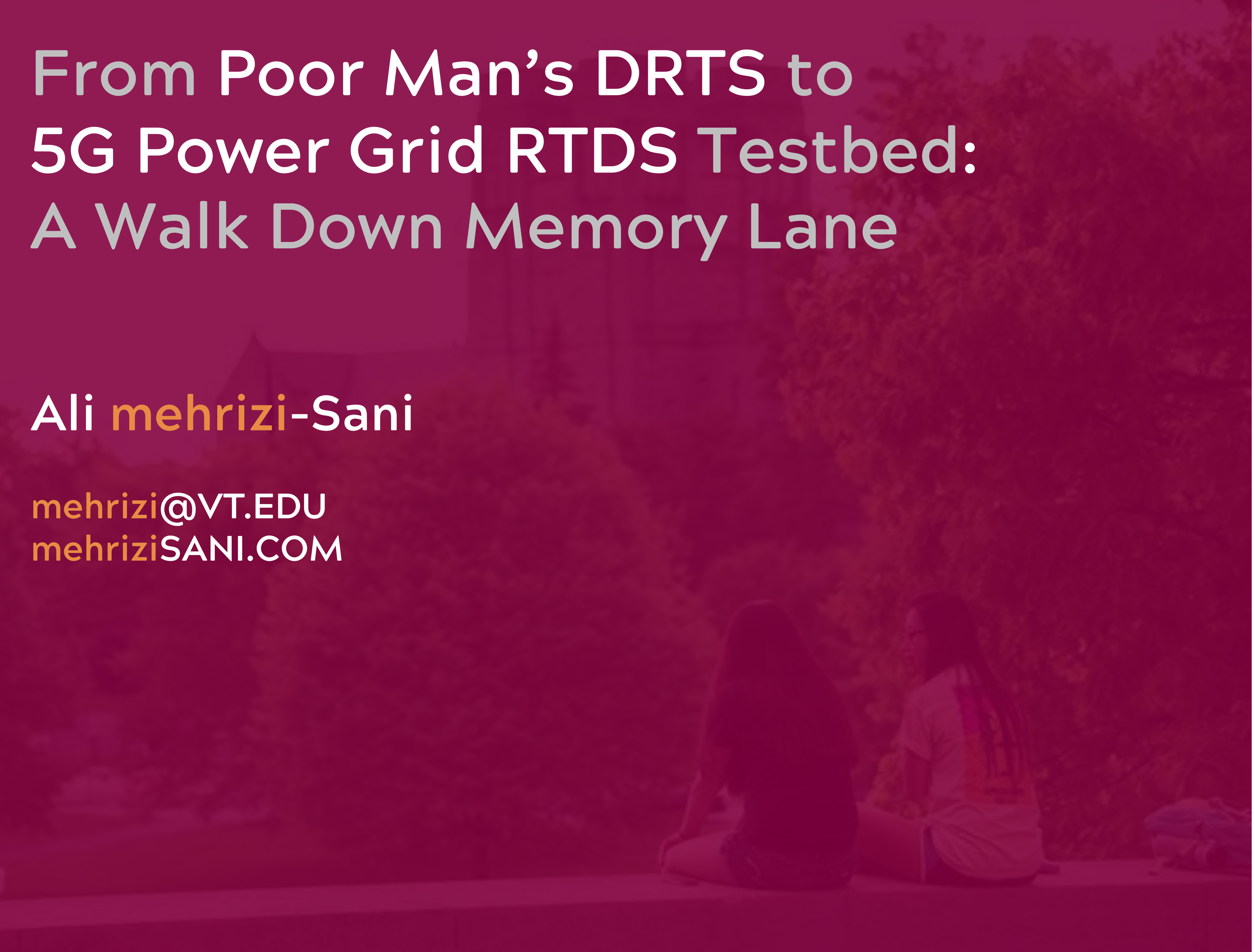
VTES Digital Twin Architecture

- Components
  - Physical system
  - Cyber system
  - Cyber-power simulation testbed
  - Connection
  - Real-time data

- Services
  - Resilience planning
  - Cybersecurity testing
  - Decision support



Courtesy of Prof. Chen-Ching Liu, Virginia Tech, 2023.



From Poor Man’s DRTS to 5G Power Grid RTDS Testbed: A Walk Down Memory Lane

Ali mehrizi-Sani

mehrizi@VT.EDU
mehriziSANI.COM

VIRGINIA TECH

POWER AND ENERGY CENTER