Towards a Secure and Resilient Industrial Control System Using Software-Defined Networking

Dong (Kevin) Jin

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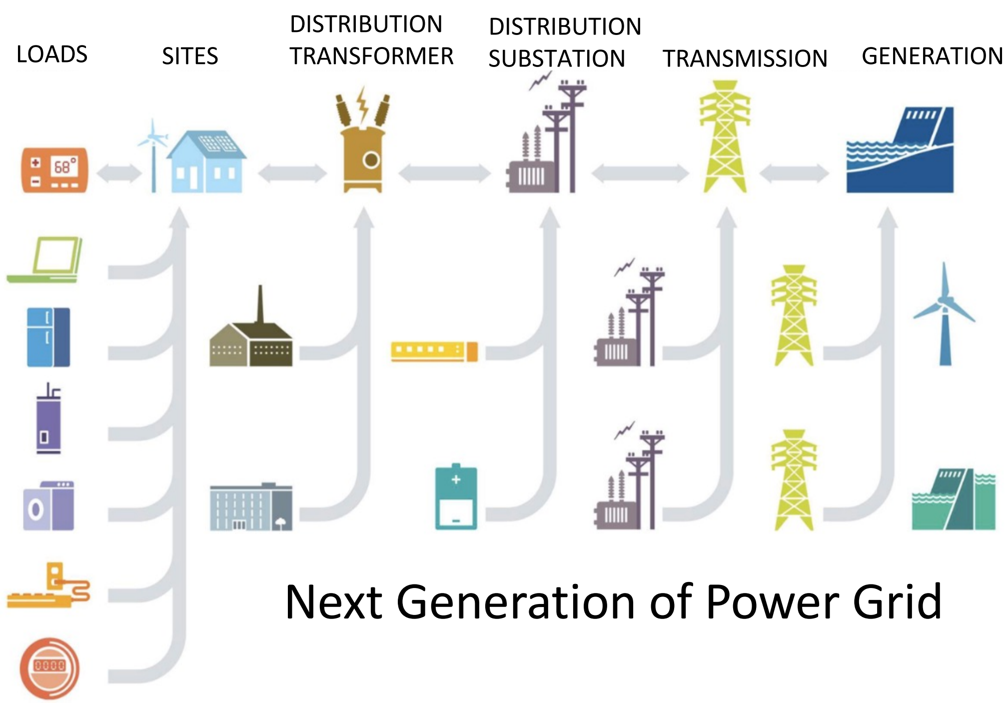
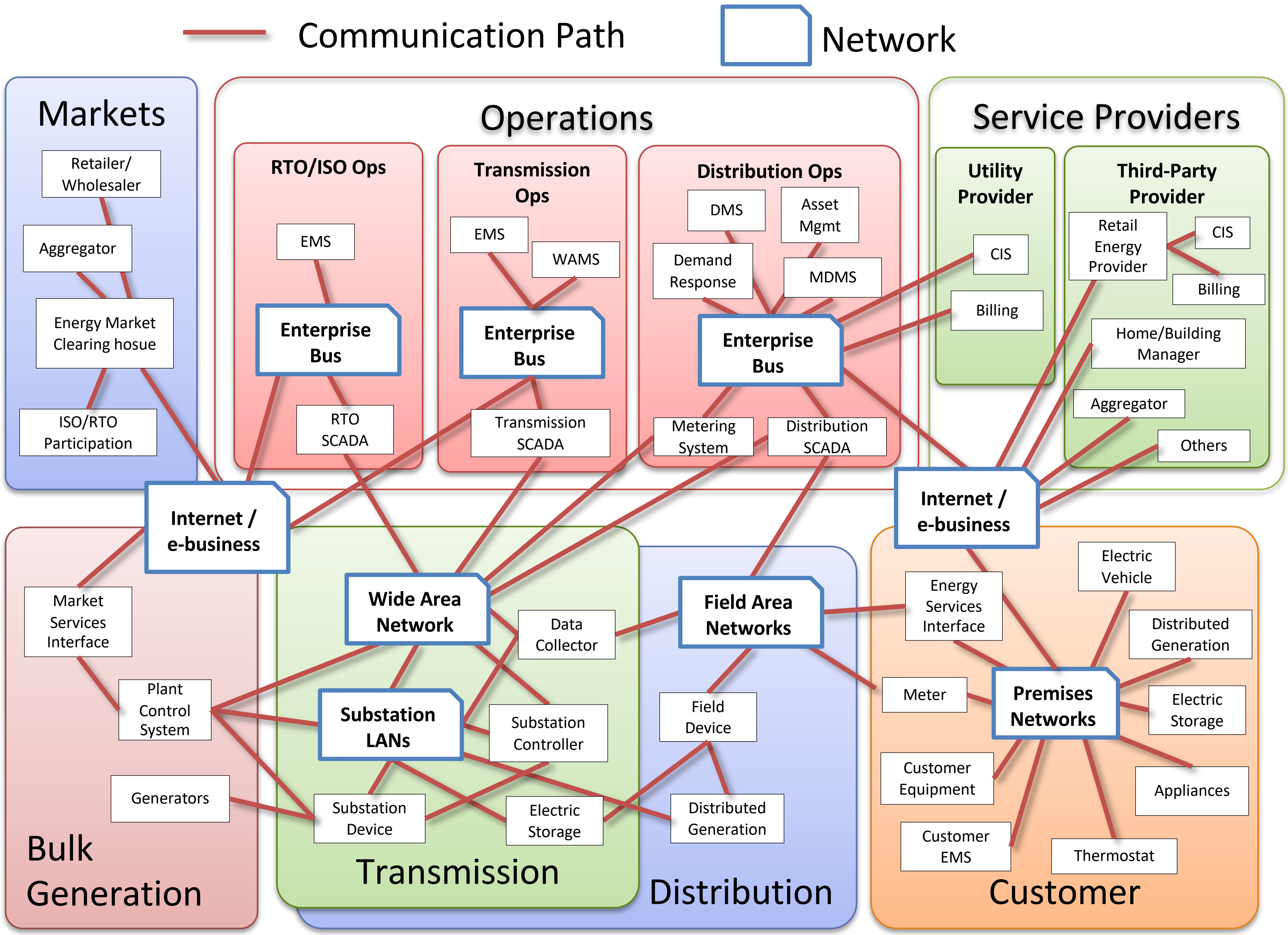
Industrial Control Systems (ICS)

- Control many critical infrastructures
- Modern ICSes increasingly adopt Internet technology to boost control efficiency



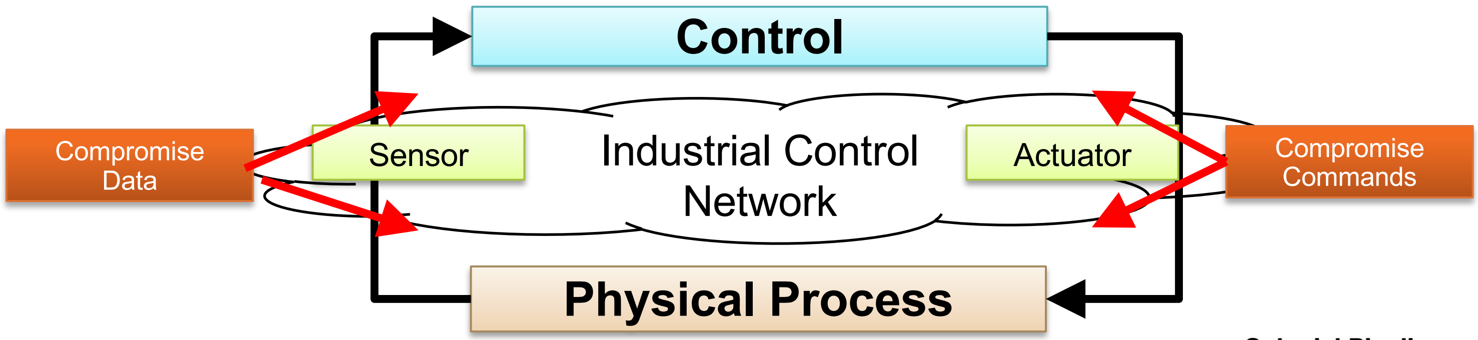
Next Generation of Power Grid

More Efficient or More Vulnerable?



Picture source: NIST Framework and Roadmap for Smart Grid Interoperability Standards

Cyber Threats in Power Grids



POLITICS THE WALL STREET JOURNAL.

Russian Hackers Reach U.S. Utility Control Rooms, Homeland Security Officials Say July 23, 2018 7:21 p.m. ET

Blackouts could have been caused after the networks of trusted vendors were easily penetrated

Colonial Pipeline ransomware attack

Date	• May 6, 2021 (data stolen)[1] • May 7, 2021 (malware attack) • May 12, 2021 (pipeline restarted)
Location	United States
Type	Cyberattack, data breach, ransomware
Target	Colonial Pipeline
Suspects	DarkSide[2][3]

WSJ.com - U.S. regulator says knoc nine key substations could cause na blackout

THE DAILY SIGNAL

Ukraine Goes Dark: Russia-Attributed Hackers Take Down Power Grid

NATIONAL SECURITY 1 comments

Stuxnet Raises 'Blowback' Risk In Cyberwar

Researchers uncover holes that open power stations to hacking

Hacks could cause power outages and don't need physical access to substations.

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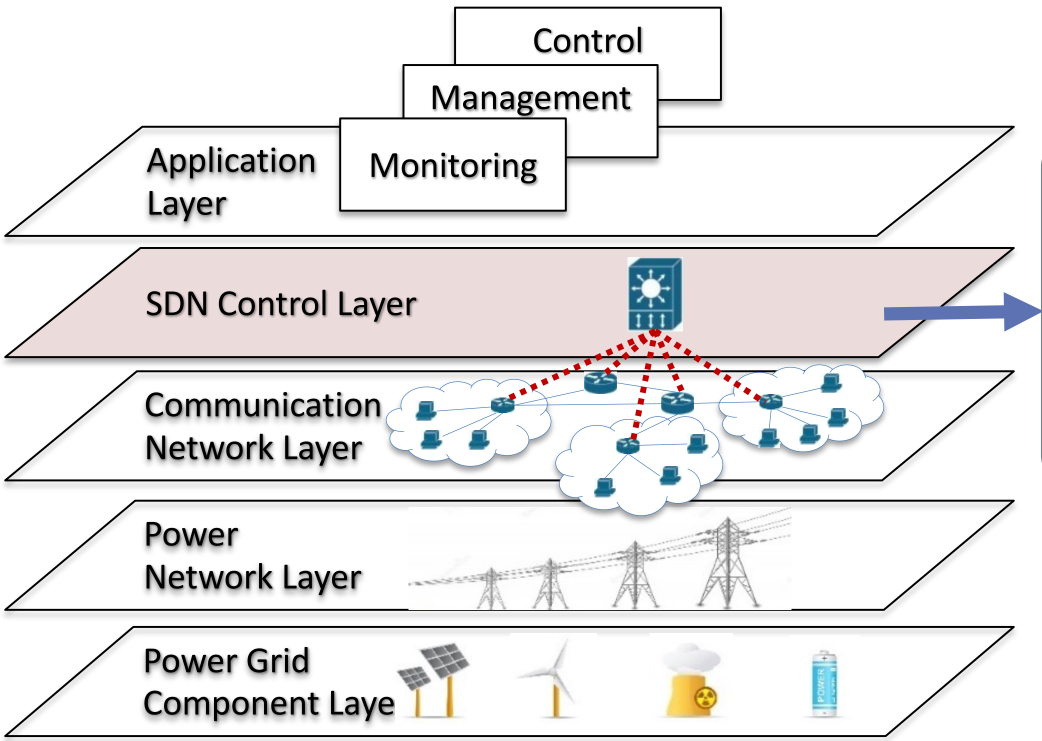
Protection of Industrial Control Systems

- Commercial off-the-shelf products
  - e.g., firewalls, anti-virus software
  - fine-grained protection at single device only
- How to check system-wide requirements?
  - Security (e.g., access control)
  - Performance (e.g., end-to-end delay)
- How to safely incorporate existing networking technologies into control systems?
  - Real time operations
  - Large-scale networks
  - Lack of real testbed (unlike Internet)

Our Work: Enable a Secure and Resilient ICS in Microgrid with SDN



Contribution I
A novel SDN architecture in microgrid

ICS – industrial control system
SDN – software-defined networking

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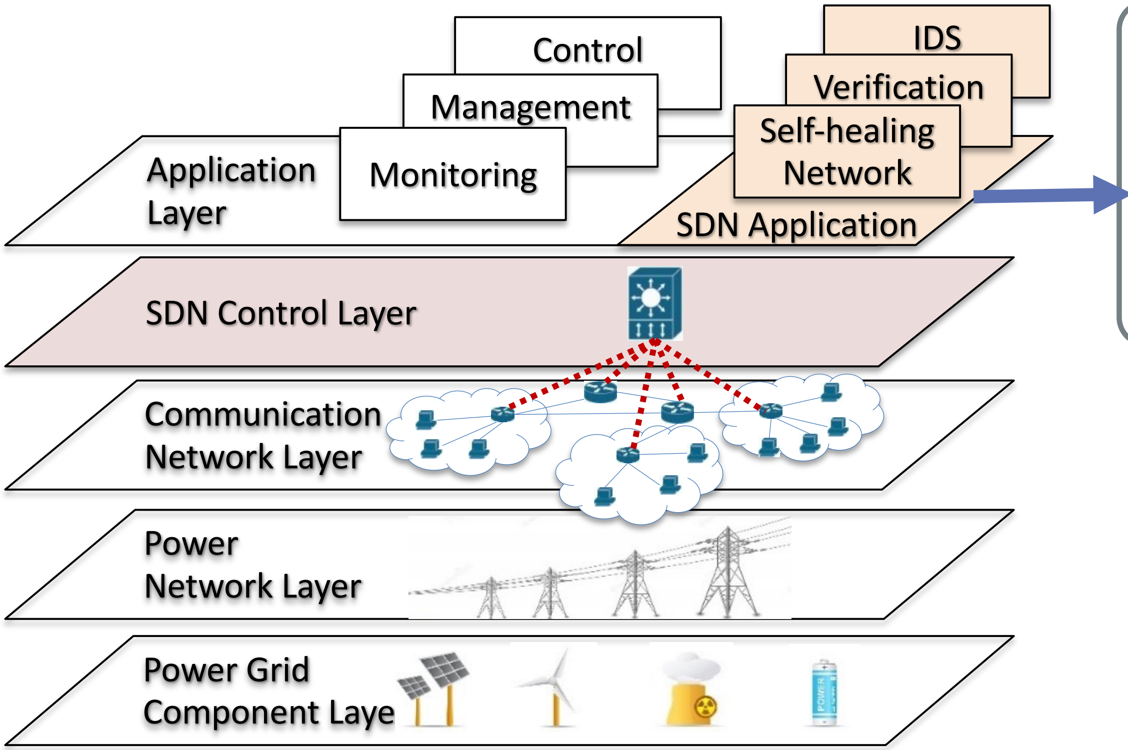
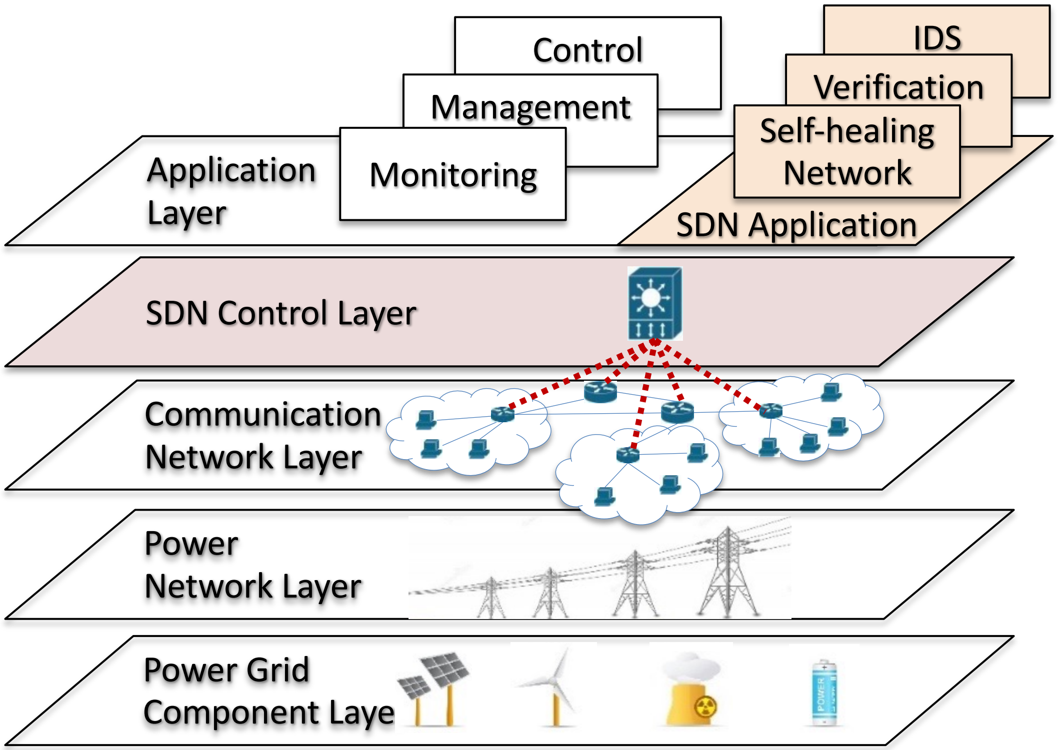
Our Work: Enable a Secure and Resilient ICS in Microgrid with SDN



Contribution II
Innovative SDN-based security applications

ICS – industrial control system
SDN – software-defined networking

Our Work: Enable a Secure and Resilient ICS in Microgrid with SDN



Contribution III
SDN-enabled microgrid testbed

- Parallel Simulation (scalability)
- Virtual-Machine-based Emulation (fidelity)

ICS – industrial control system
SDN – software-defined networking

Outline

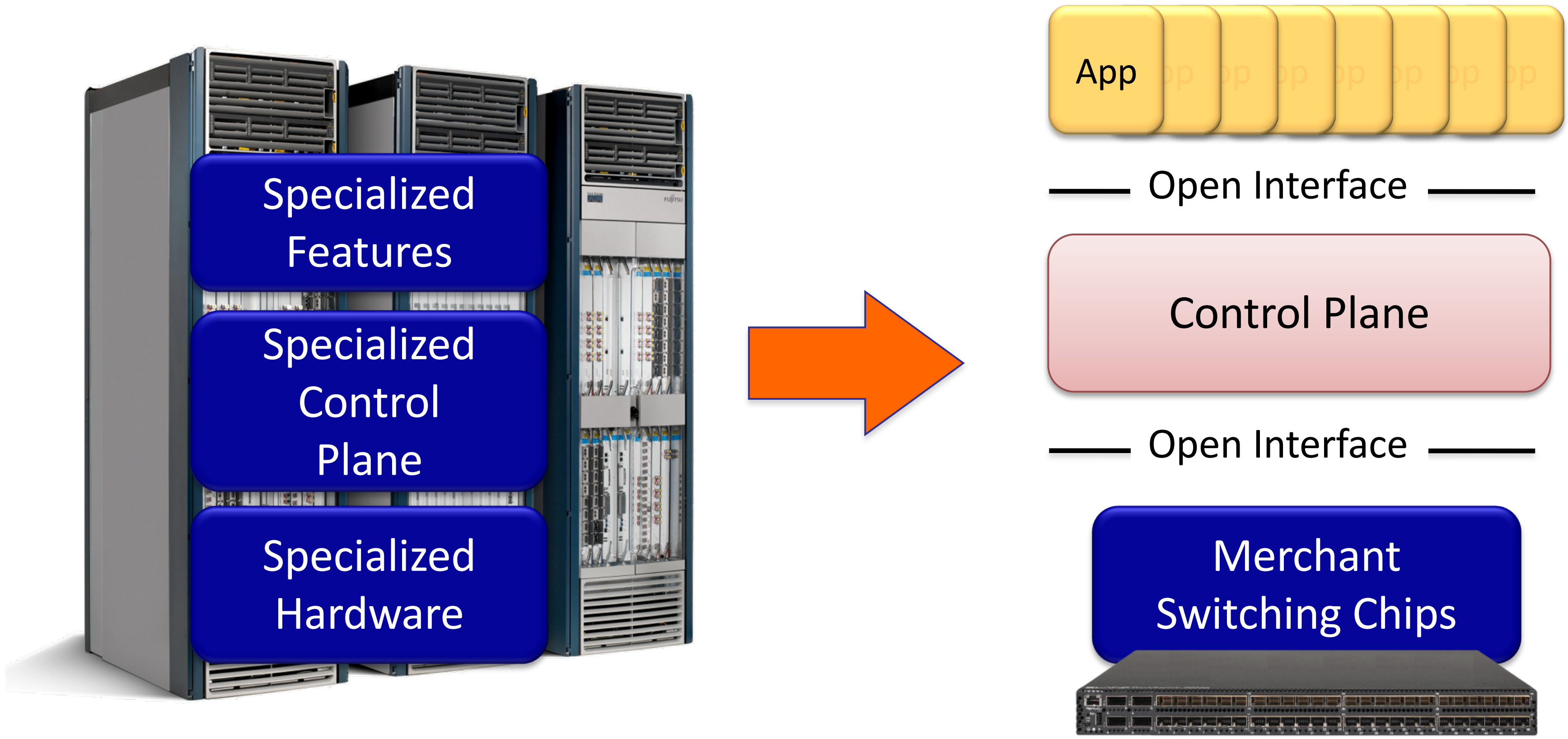
- SDN Background
- Applications
  - Network Verification[1]
  - Self-healing PMU system [2]
- Testing and Evaluation Platform[3]

[1] Wenxuan Zhou, Dong Jin, Jason Croft, Matthew Caesar, and Brighten Godfrey. *"Enforcing Customizable Consistency Properties in Software-Defined Networks."* **USENIX NSDI**

[2] Yanfeng Qu, Gong Chen, Xin Liu, Jiaqi Yan, Bo Chen, and Dong Jin. Cyber-Resilience Enhancement of PMU Networks Using Software-Defined Networking. **IEEE SmartGridComm, (Best Paper Award)**

[3] Christopher Hannon, Jiaqi Yan and Dong Jin. *"DSSnet: A Smart Grid Modeling Platform Combining Electrical Power Distribution System Simulation and Software Defined Networking Emulation."* **ACM SIGSIM-PADS (Best Paper Finalist)**

SDN Background

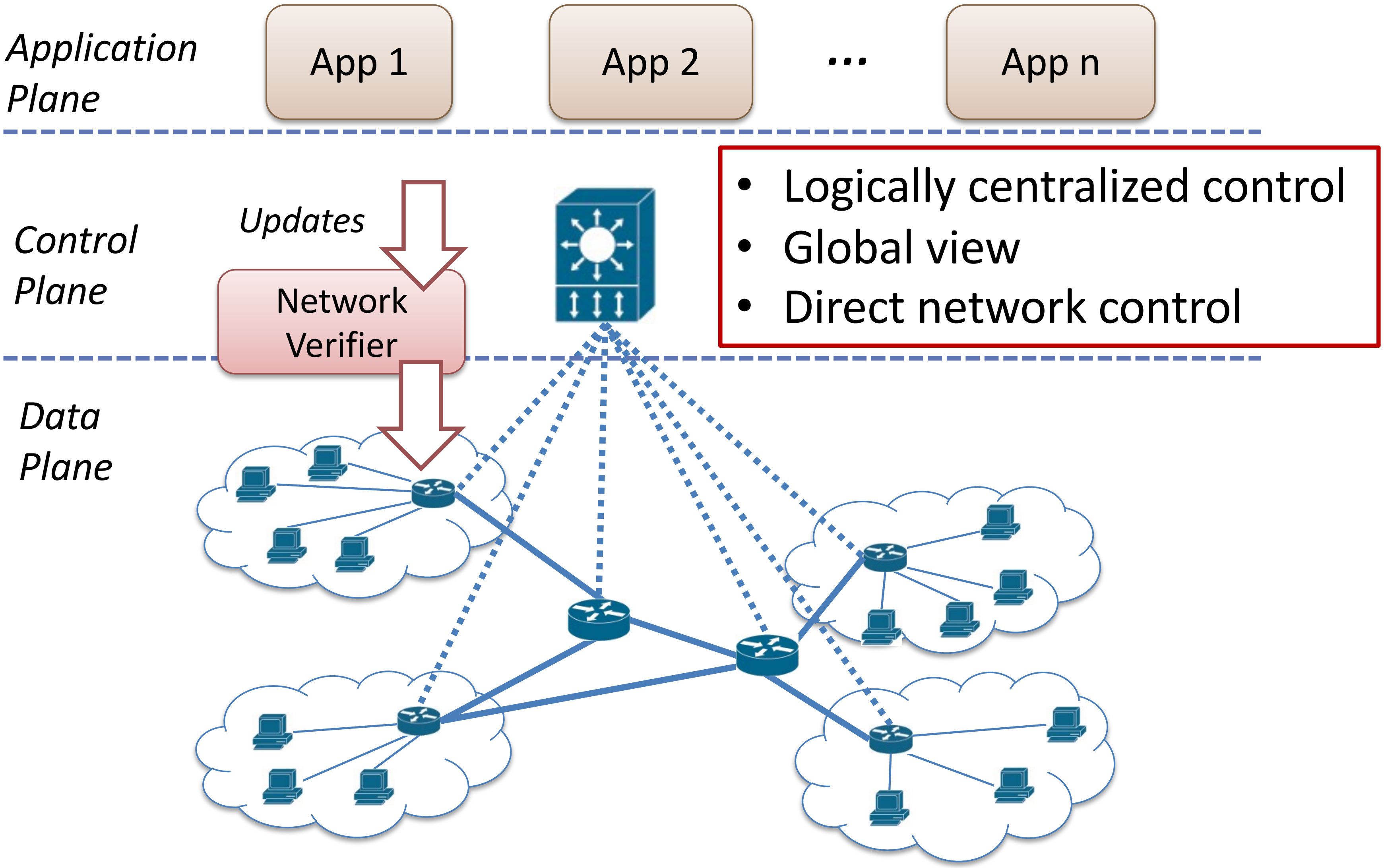


Closed, proprietary
Slow innovation

Open interfaces
Rapid innovation

Picture Source: Nick McKeown, Open Networking Summit 2012

SDN Architecture



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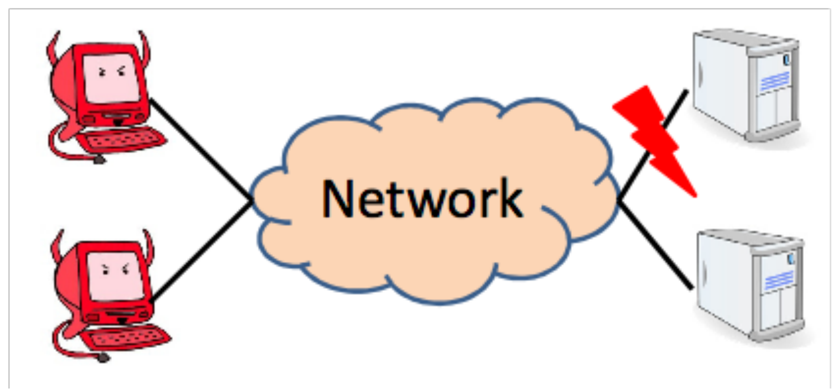
Network Verification - Motivation

89% of operators never sure that config changes are bug-free

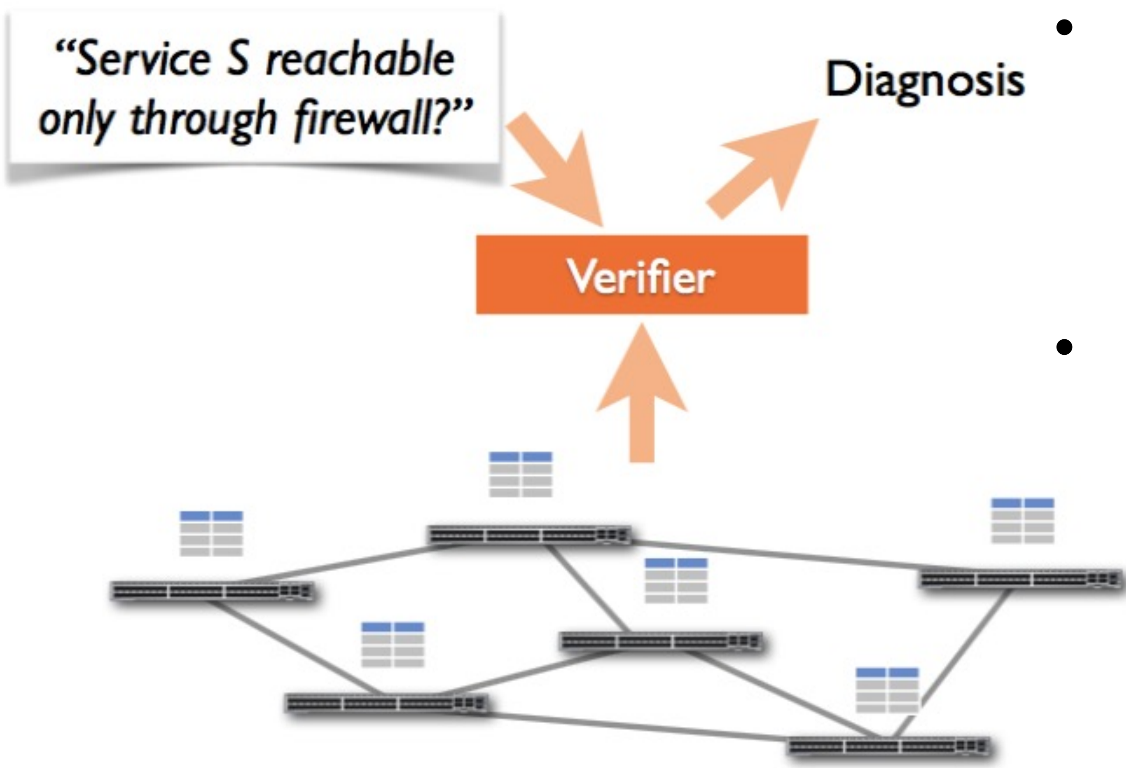
82% concerned that changes would cause problems with existing functionality

- Unauthorized access
- Unavailable critical services
- Performance drop
  - Instability
  - Loss of load
  - Synchronization Failure



Survey of network operators: [Kim, Reich, Gupta, Shahbaz, Feamster, Clark, USENIX NSDI 2015]

Network Verification



Prior Work

- Static network snapshot analysis
  - Klee
  - Anteater
- Dynamic verification
  - FlowChecker
  - VeriFlow
  - HSA
  - Sphinx

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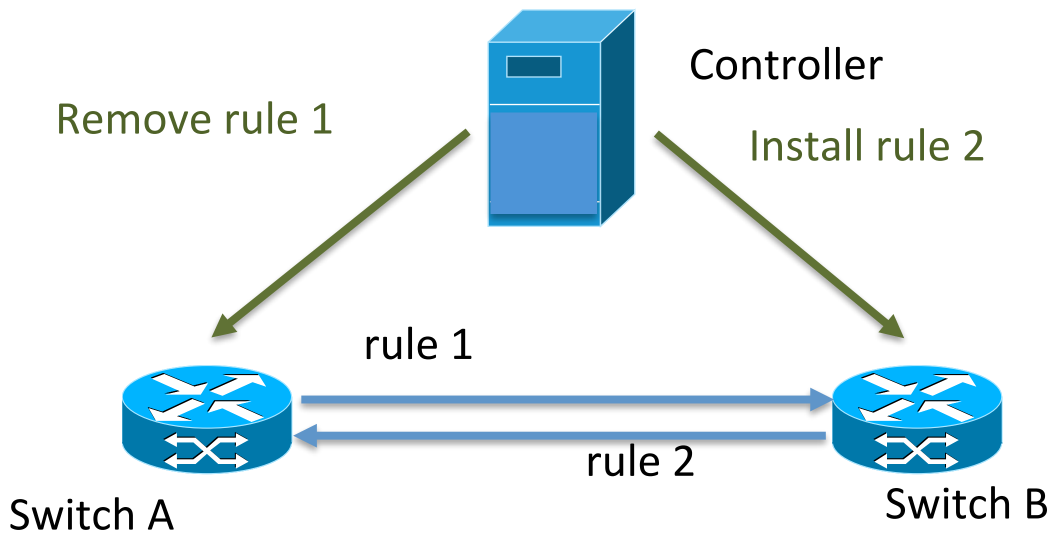
Challenge: Timing Uncertainty

Old config: A => B (rule 1)

New config: B => A (rule 2)



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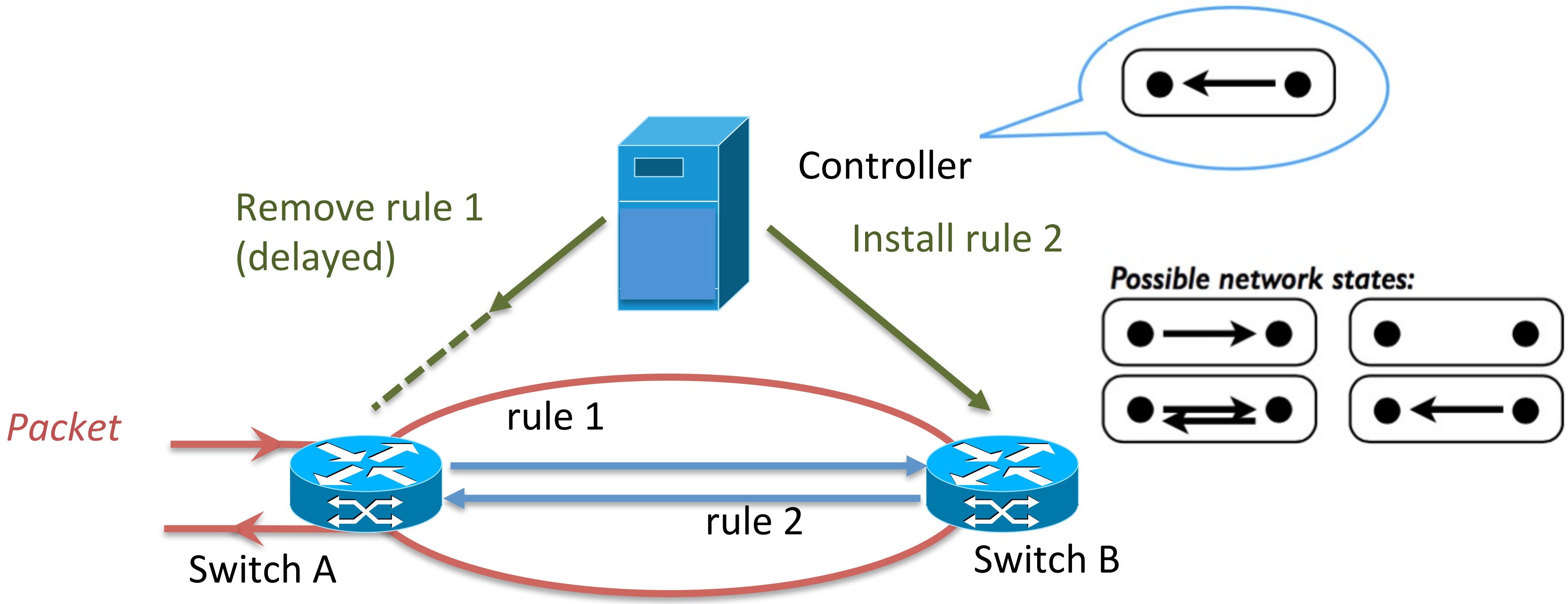
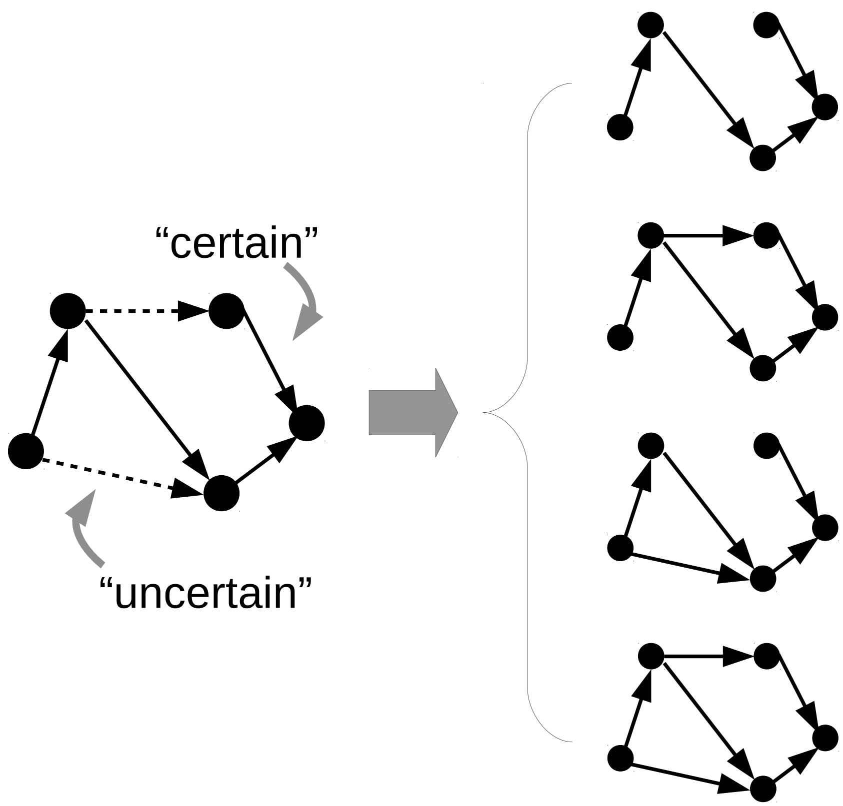


Loop-freedom Violation

Uncertainty-aware Modeling

- Naively, represent every possible network state $O(2^n)$
- Uncertainty-aware graph: represent all possible combinations



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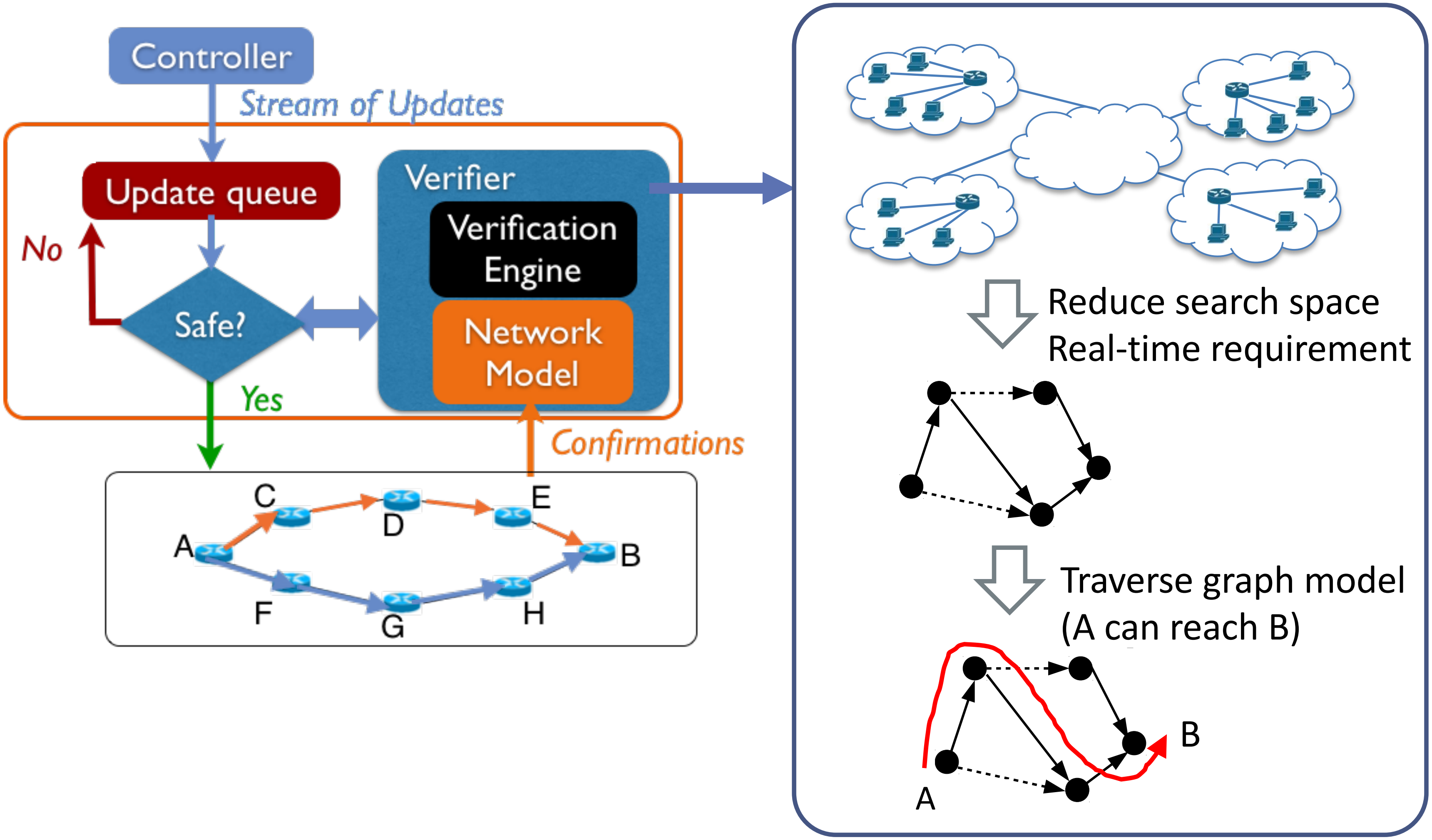
SDN-based Verification System



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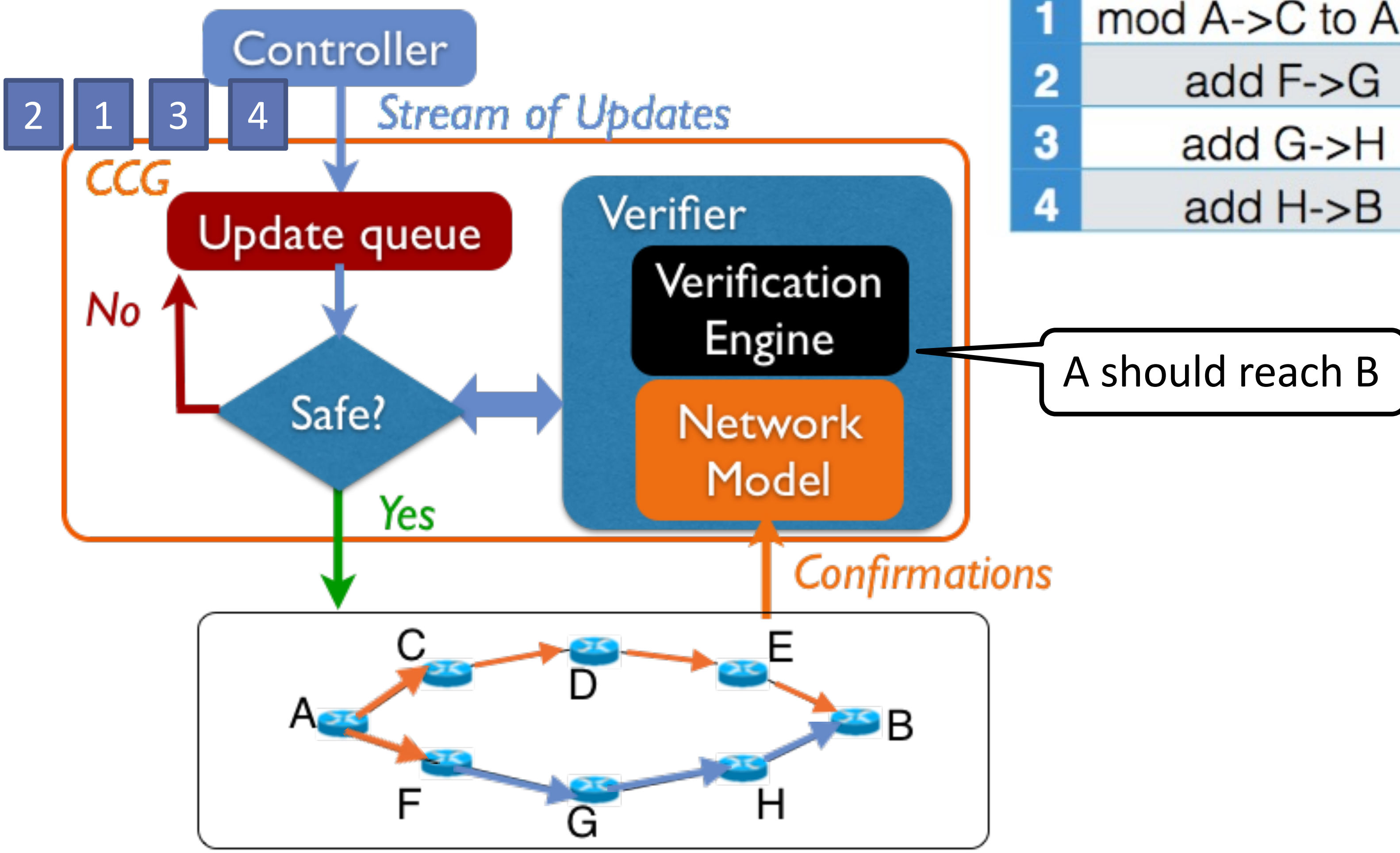


1	mod A->C to A->F
2	add F->G
3	add G->H
4	add H->B

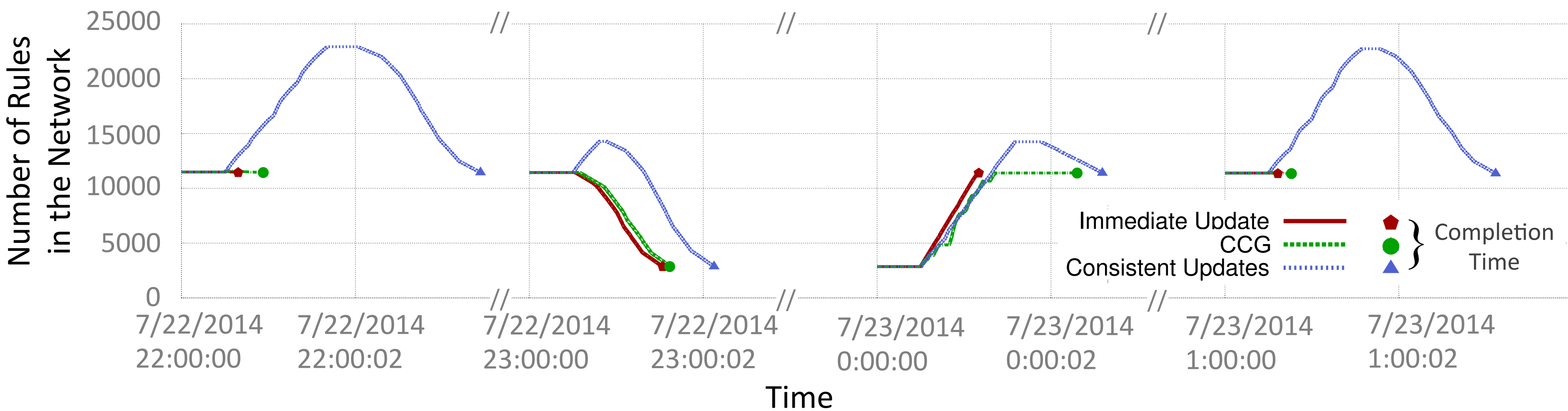
Enforcing dynamic correctness with heuristically maximized parallelism

OK, but…

Can the system "deadlock"?

- Proved classes of networks that never deadlock
- Experimentally rare in practice!
- Last resort: heavyweight "fallback" like consistent updates [Reitblatt et al, SIGCOMM 2012]

Is it fast?



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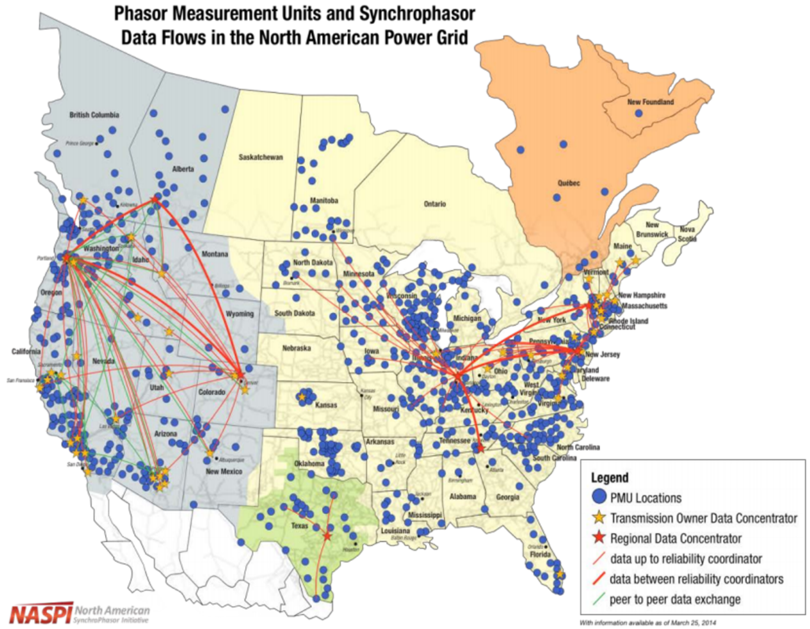
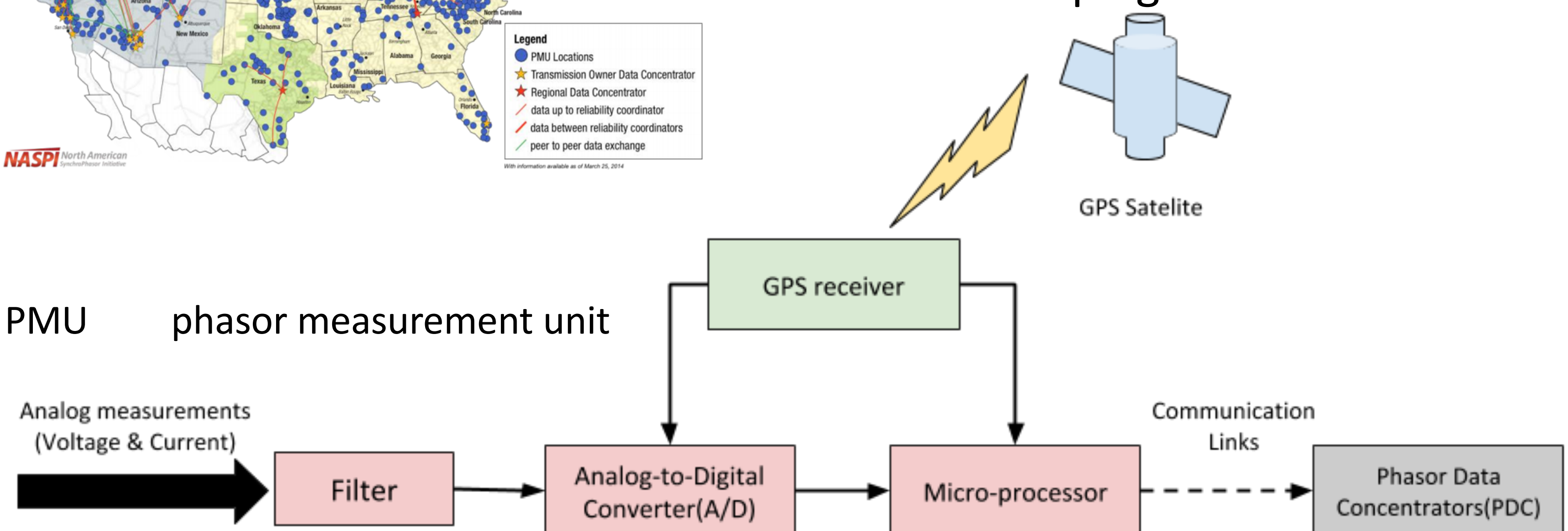
PMU Network



- Wide Area Measurement Systems (WAMS)
- Synchrophasor/PMU
  - microprocessor-based device
  - collect analog data like voltage, current and phasor angle
- GPS time stamping

PMU phasor measurement unit



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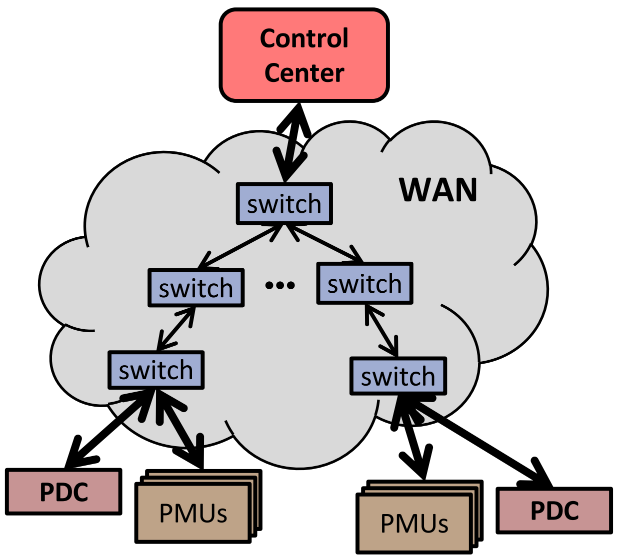
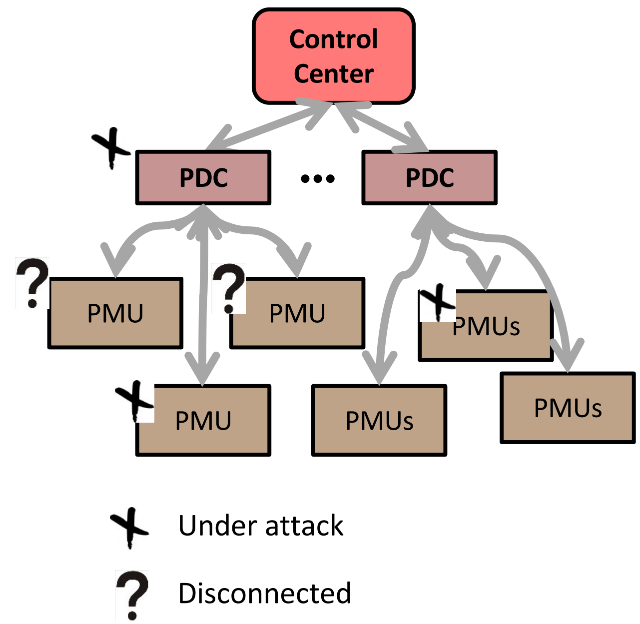
Source: https://www.naspi.org/sites

Challenges

- High volume of measurement data
- Network architecture – no standard yet
- Cyber-attacks and human errors
  - e.g., denial-of-service, man-in-the-middle attacks [1][2]





PMU phasor measurement unit
PDC phasor data concentrator

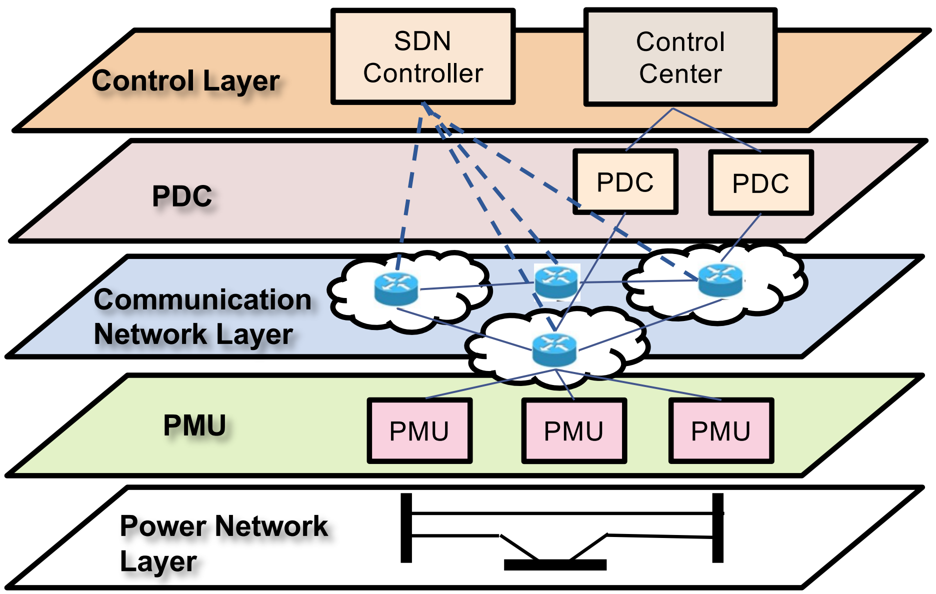
- Lose system observability
- Affect state estimation

[1] C. Beasley, G. K. Venayagamoorthy, and R. Brooks. Cyber security evaluation of synchrophasors in a power system.
[2] T. Morris, S. Pan, J. Lewis, J. Moorhead, N. Younan, R. King, M. Freund, and V. Madani. Cybersecurity risk testing of substation phasor measurement units and phasor data concentrators.

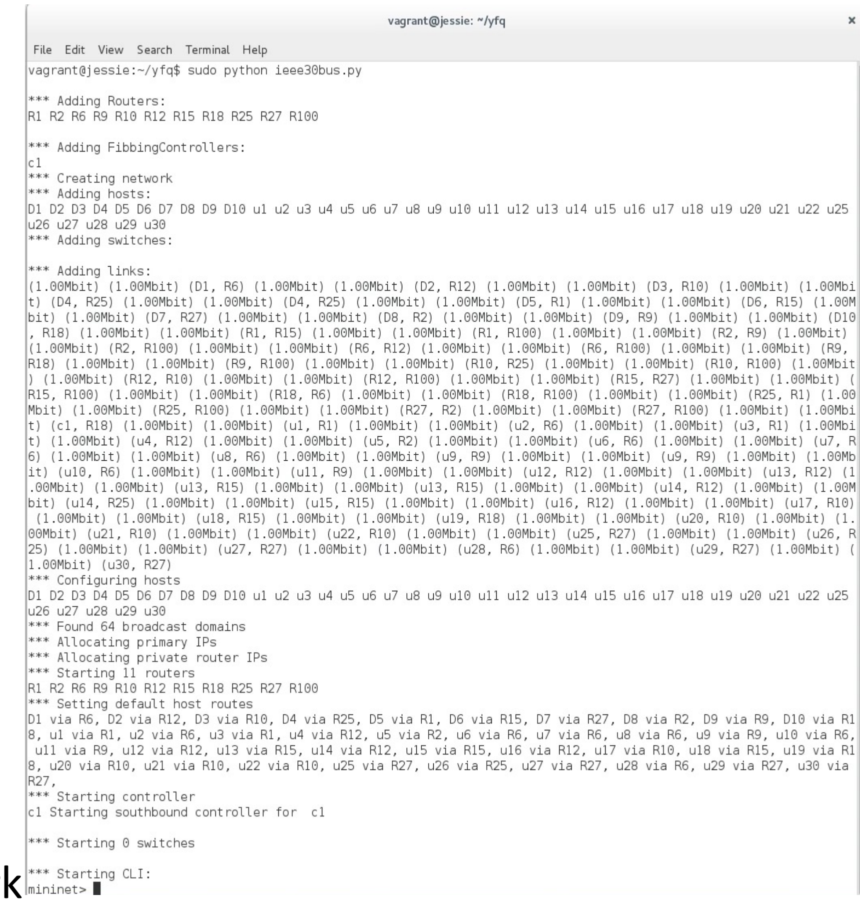
Self-healing PMU network

- Objectives
  - Recover power system observability
  - Isolate compromised devices; re-connect uncompromised devices
  - Fast recovery speed
  - Easy and inexpensive deployment
- Contributions
  - An SDN-based architecture
  - Global-optimized self-healing solution
  - A working prototype system with good system performance

Self-healing PMU network



Self-healing PMU Infrastructure



```
vagrant@jessie: ~/yfq
File Edit View Search Terminal Help
vagrant@jessie:~/yfq$ sudo python ieee30bus.py

*** Adding Routers:
R1 R2 R6 R9 R10 R12 R15 R18 R25 R27 R100

*** Adding FibbingControllers:
c1
*** Creating network
*** Adding hosts:
D1 D2 D3 D4 D5 D6 D7 D8 D9 D10 u1 u2 u3 u4 u5 u6 u7 u8 u9 u10 u11 u12 u13 u14 u15 u16 u17 u18 u19 u20 u21 u22 u25
u26 u27 u28 u29 u30
*** Adding switches:

*** Adding links:
(1.00Mbit) (1.00Mbit) (D1, R6) (1.00Mbit) (1.00Mbit) (D2, R12) (1.00Mbit) (1.00Mbit) (D3, R10) (1.00Mbit) (1.00Mbi
t) (D4, R25) (1.00Mbit) (1.00Mbit) (D4, R25) (1.00Mbit) (1.00Mbit) (D5, R1) (1.00Mbit) (1.00Mbit) (D6, R15) (1.00M
bit) (1.00Mbit) (D7, R27) (1.00Mbit) (1.00Mbit) (D8, R2) (1.00Mbit) (1.00Mbit) (D9, R9) (1.00Mbit) (1.00Mbit) (D10
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6) (1.00Mbit) (1.00Mbit) (u8, R6) (1.00Mbit) (1.00Mbit) (u9, R9) (1.00Mbit) (1.00Mbit) (u9, R9) (1.00Mbit) (1.00Mb
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25) (1.00Mbit) (1.00Mbit) (u27, R27) (1.00Mbit) (1.00Mbit) (u28, R6) (1.00Mbit) (1.00Mbit) (u29, R27) (1.00Mbit) (
1.00Mbit) (u30, R27)
*** Configuring hosts
D1 D2 D3 D4 D5 D6 D7 D8 D9 D10 u1 u2 u3 u4 u5 u6 u7 u8 u9 u10 u11 u12 u13 u14 u15 u16 u17 u18 u19 u20 u21 u22 u25
u26 u27 u28 u29 u30
*** Found 64 broadcast domains
*** Allocating primary IPs
*** Allocating private router IPs
*** Starting 11 routers
R1 R2 R6 R9 R10 R12 R15 R18 R25 R27 R100
*** Setting default host routes
D1 via R6, D2 via R12, D3 via R10, D4 via R25, D5 via R1, D6 via R15, D7 via R27, D8 via R2, D9 via R9, D10 via R1
8, u1 via R1, u2 via R6, u3 via R1, u4 via R12, u5 via R2, u6 via R6, u7 via R6, u8 via R6, u9 via R9, u10 via R6,
 u11 via R9, u12 via R12, u13 via R15, u14 via R12, u15 via R15, u16 via R12, u17 via R10, u18 via R15, u19 via R1
8, u20 via R10, u21 via R10, u22 via R10, u25 via R27, u26 via R25, u27 via R27, u28 via R6, u29 via R27, u30 via
R27,
*** Starting controller
c1 Starting southbound controller for  c1

*** Starting 0 switches

*** Starting CLI:
mininet>
```

PMU network layer creation

System models

Graph $G_p(B, L_p)$ power transmission network

$G_c(U \cup D \cup R, L_c)$ IP-based PMU network

B - set of buses; L_p - set of transmission lines ; *U* - set of PMUs
D - set of PDC; *R* - set of router; L_c - set of links

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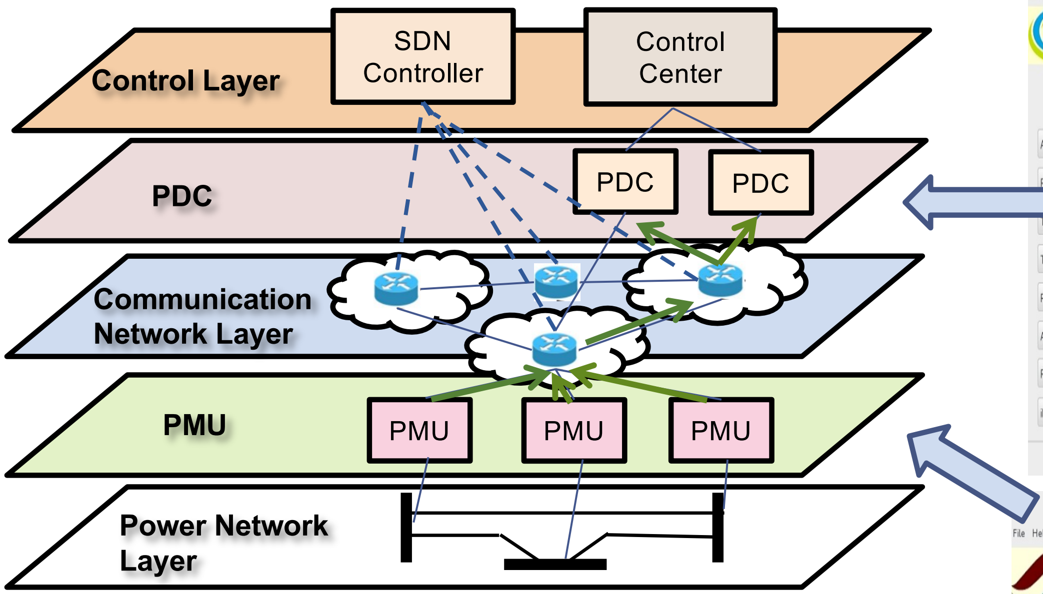
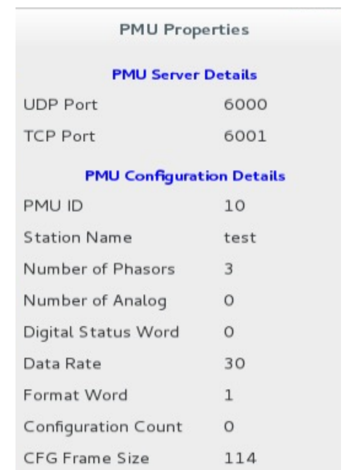
Self-healing PMU network





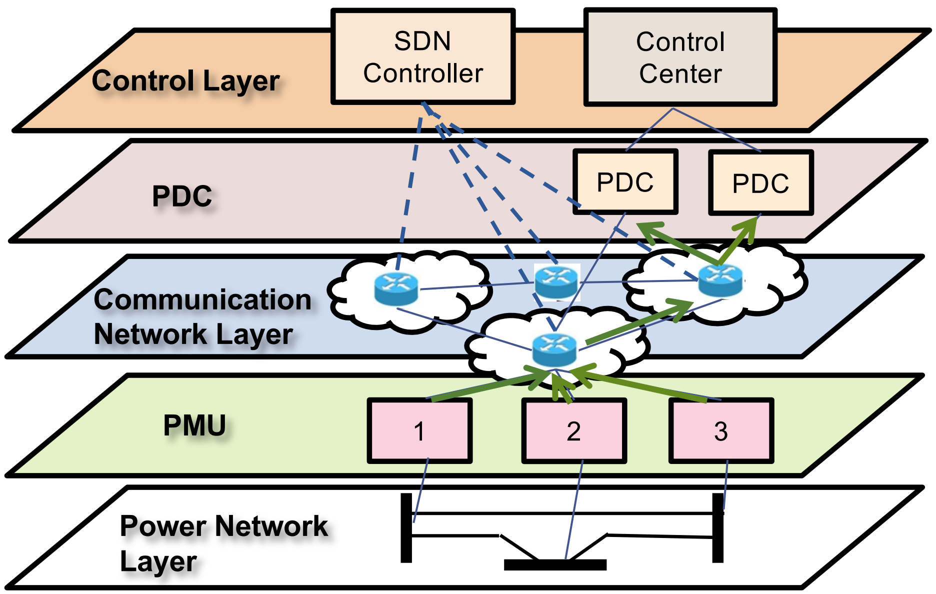
PMU/PDC application layer creation

Observability function of bus *i* $O_i = \sum a_{i,j} p_j$

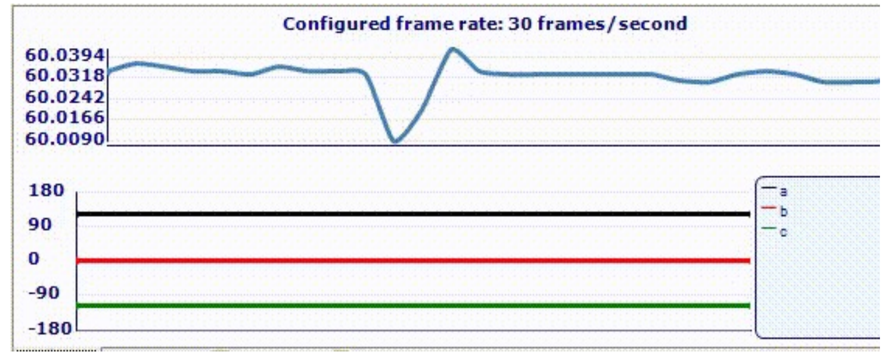
where $a_{i,j}$ defines the bus connectivity

$$a_{i,j} = \begin{cases} 1 & \text{if } i = j \\ 1 & \text{if } i \neq j \text{ and bus } i \text{ and bus } j \text{ are connected} \\ 0 & \text{otherwise} \end{cases}$$

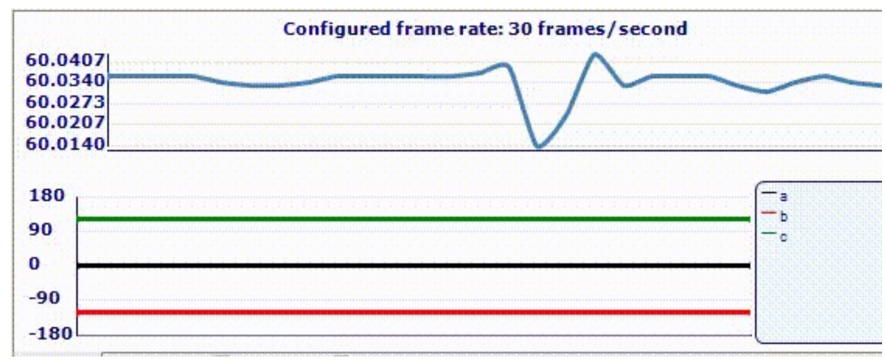
Self-healing PMU network



Control Center Monitoring System

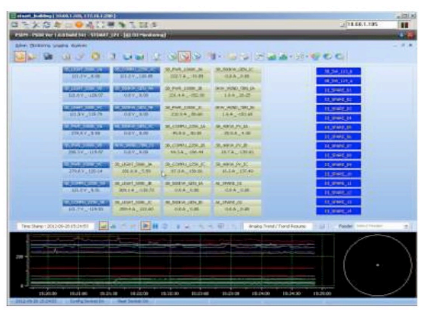


PMU3



PMU1

Real Data Collected from Campus Distribution System PMU network



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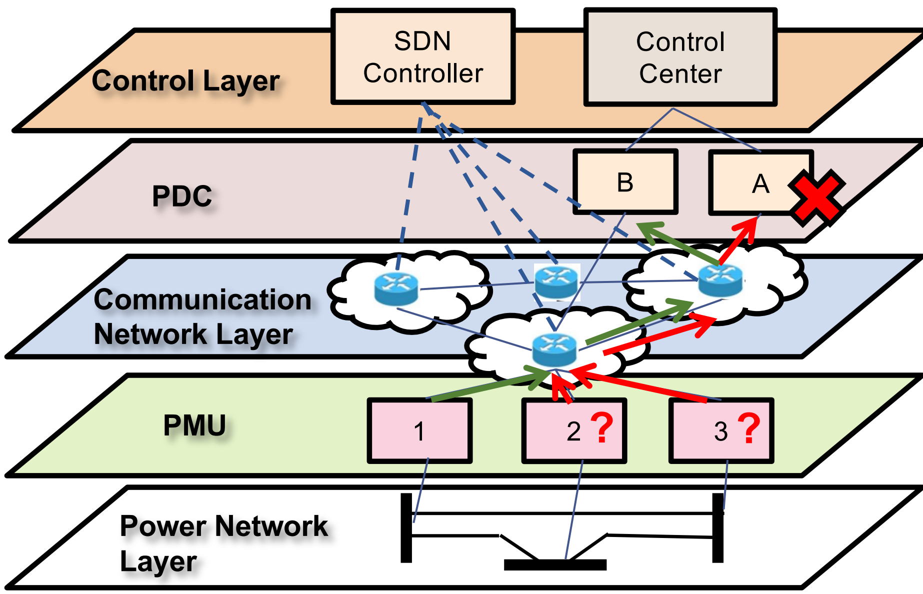
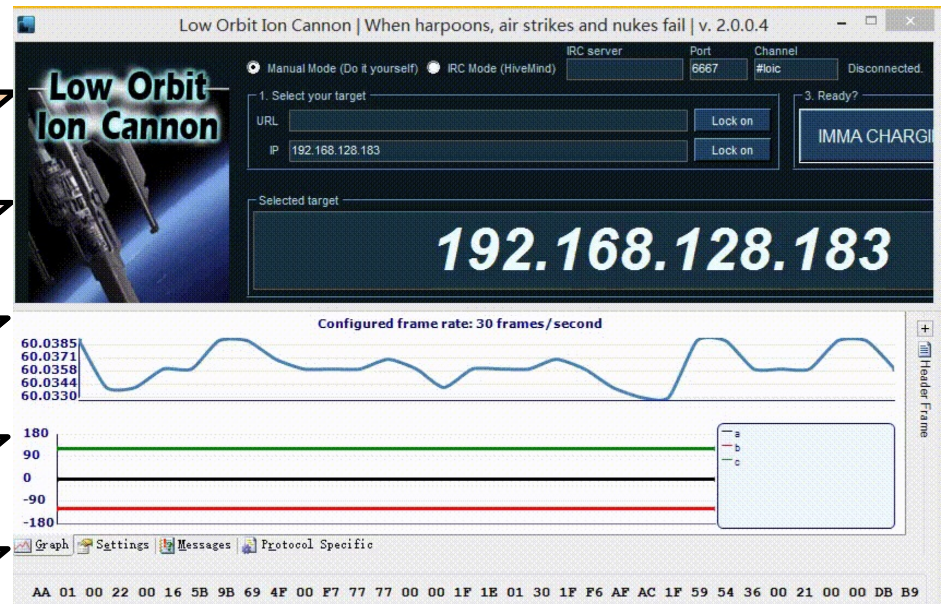
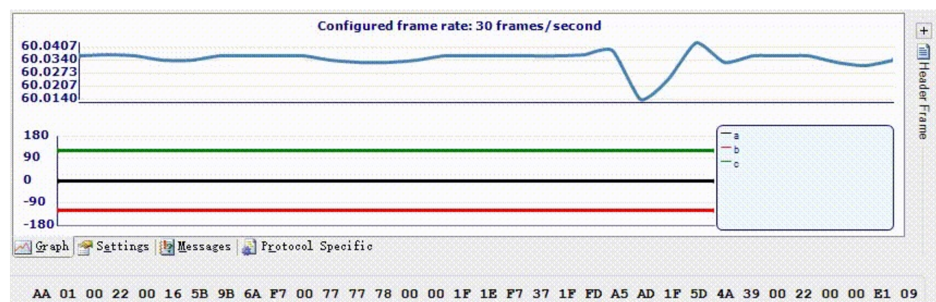
Self-healing PMU network





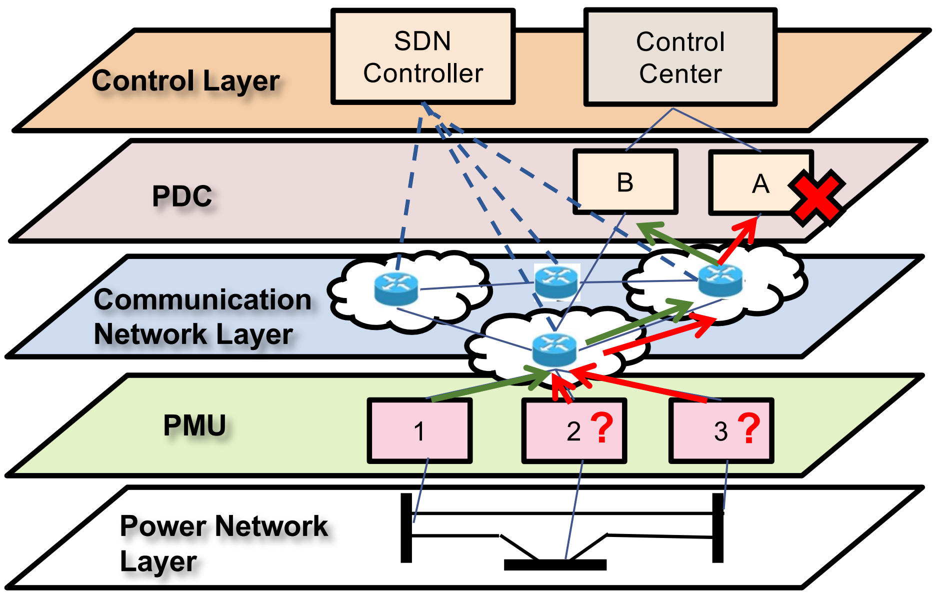
PMU3

PDC A stop functioning under a cyber-attack



PMU1

Self-healing PMU network



Constraints

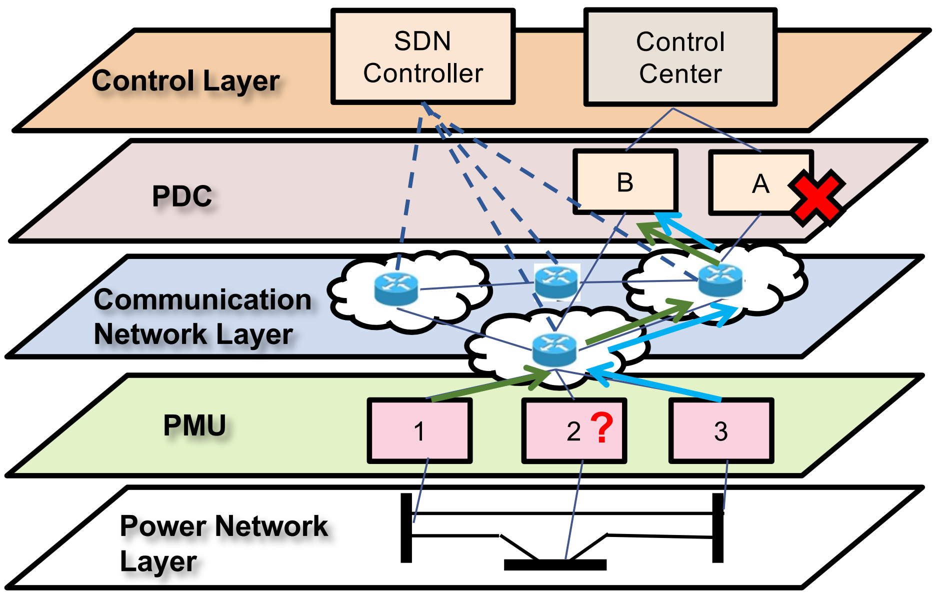
- PDC connection space constraints
- Congestion freedom constraints
- Rule capacity constraints

Objective: quickly restore system power observability

Stage I   minimize # of reconnected PMUs

Stage II   minimize # of new rules on SDN switches

Self-healing PMU network



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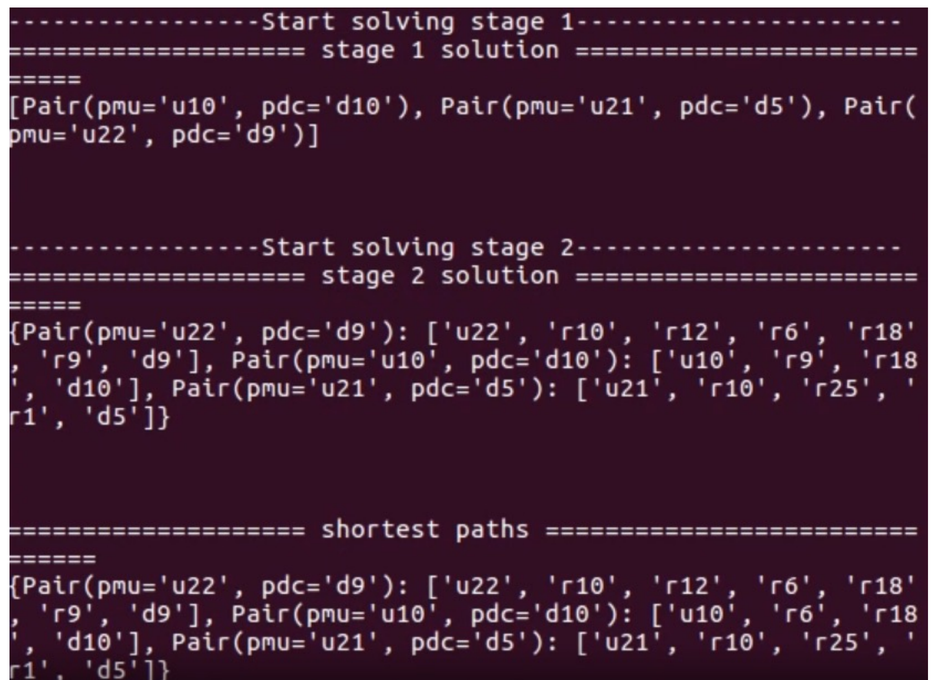
- Congestion freedom constraints
- Rule capacity constraints

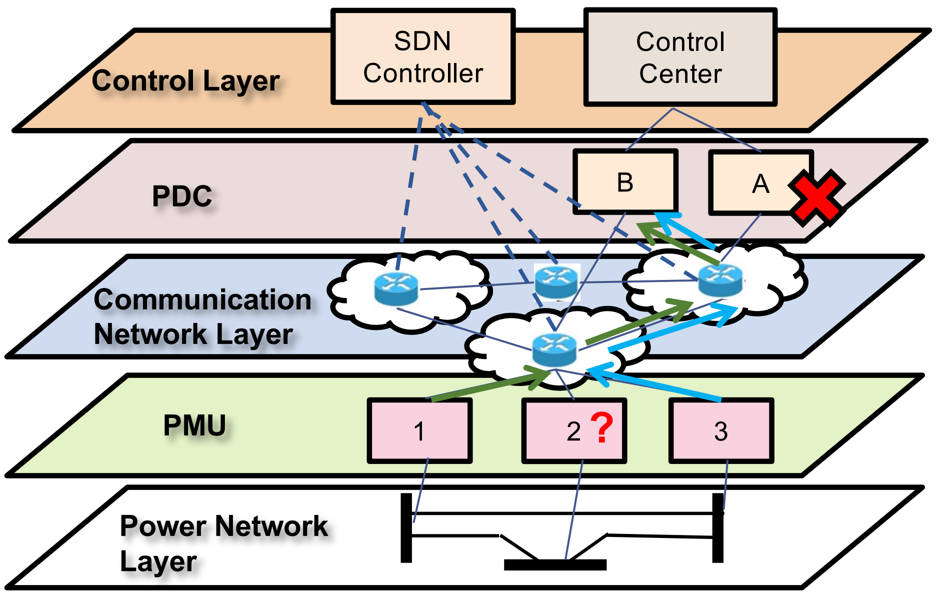


Objective: quickly restore system power observability

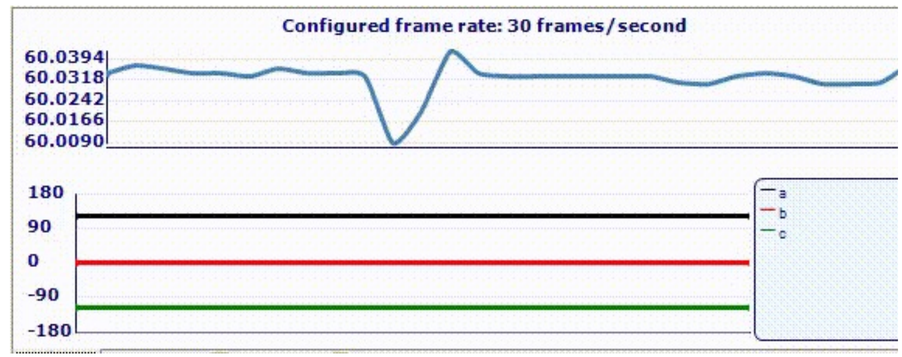
Stage I minimize # of reconnected PMUs

Stage II minimize # of new rules on SDN switches

Self-healing PMU network



Constraints
- PDC connection space constraints
- Congestion freedom constraints
- Rule capacity constraints

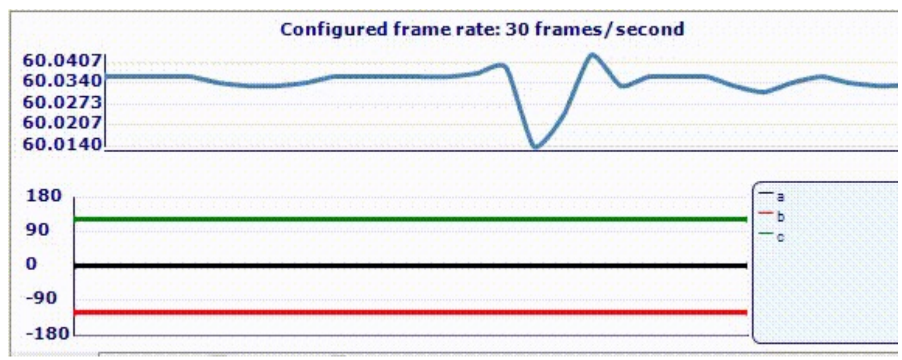


PMU3 - reconnected

Objective: quickly restore system power observability

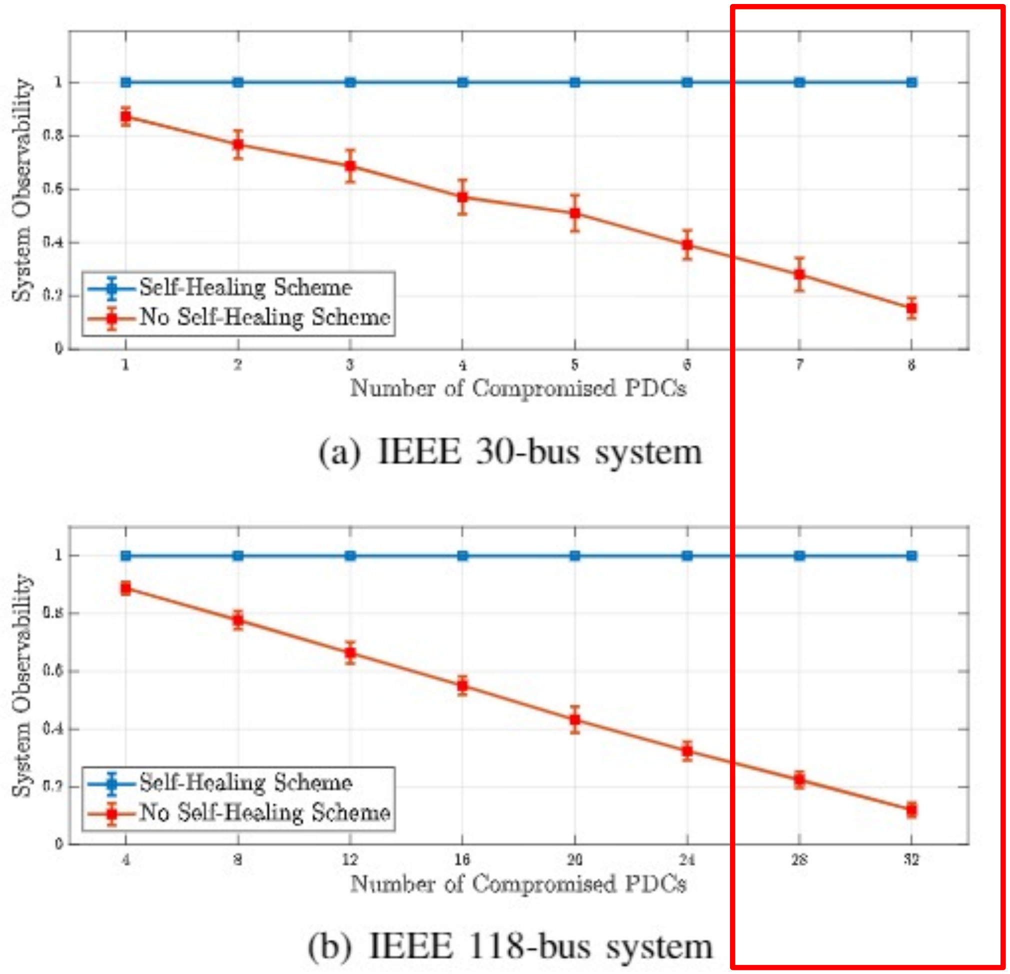
Stage I minimize # of reconnected PMUs

Stage II minimize # of new rules on SDN switches



PMU1

Evaluation- Power System Observability



(a) IEEE 30-bus system

(b) IEEE 118-bus system

Drop to 15.3%

Drop to 12.3%

Outline

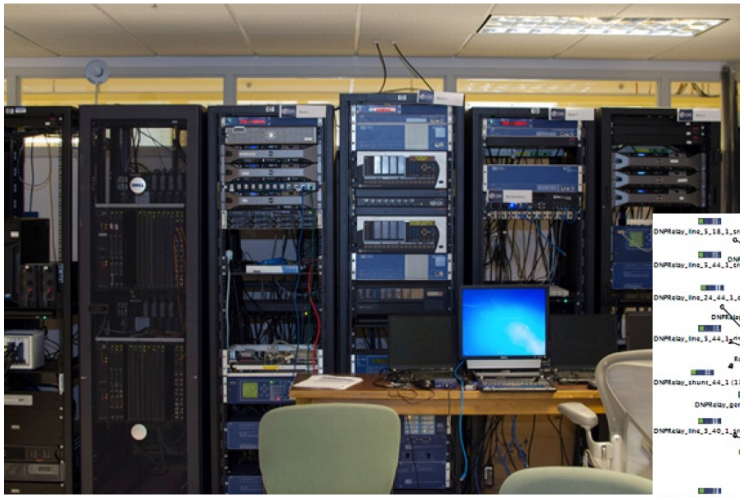
- SDN Background
- Applications
  - Network Verification[1]
  - Self-healing PMU system [2]
- Testing and Evaluation Platform[3]

[1] Wenxuan Zhou, Dong Jin, Jason Croft, Matthew Caesar, and Brighten Godfrey. *"Enforcing Customizable Consistency Properties in Software-Defined Networks."* **USENIX NSDI**

[2] Yanfeng Qu, Gong Chen, Xin Liu, Jiaqi Yan, Bo Chen, and Dong Jin. Cyber-Resilience Enhancement of PMU Networks Using Software-Defined Networking. IEEE SmartGridComm, (Best Paper Award)

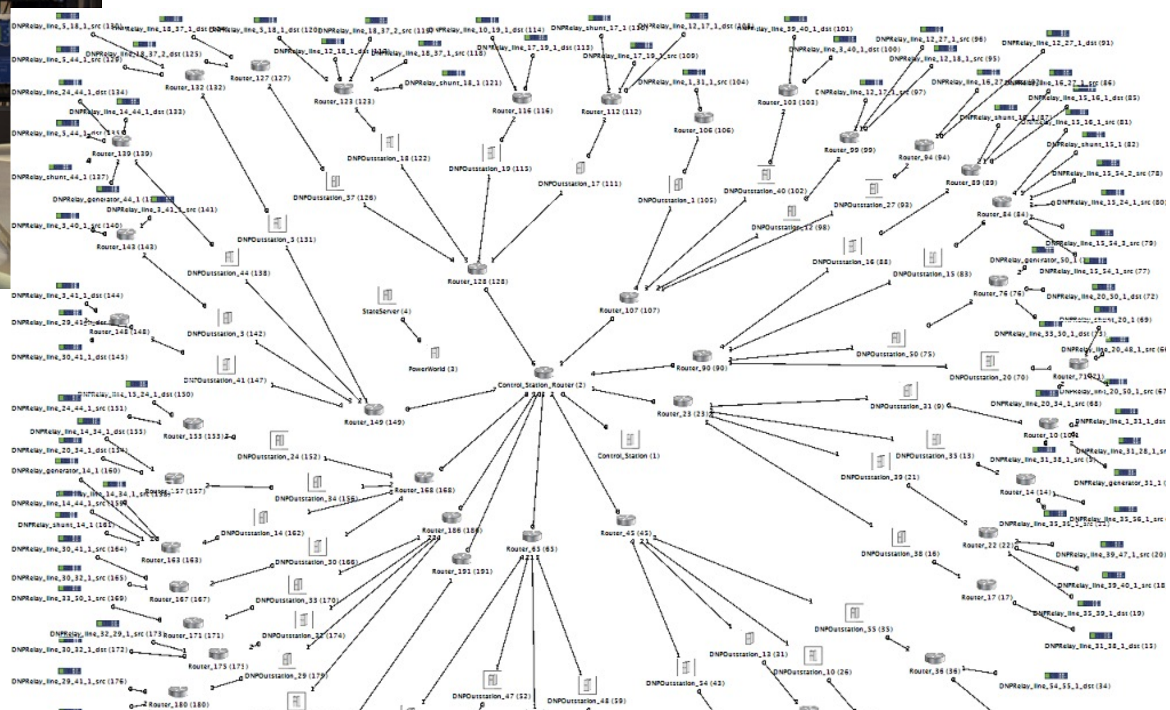
[3] Christopher Hannon, Jiaqi Yan and Dong Jin. *"DSSnet: A Smart Grid Modeling Platform Combining Electrical Power Distribution System Simulation and Software Defined Networking Emulation."* **ACM SIGSIM-PADS (Best Paper Finalist)**

Testbed for Smart Grid Security



Test Systems in Lab

- No interference with real systems
- Realistic settings

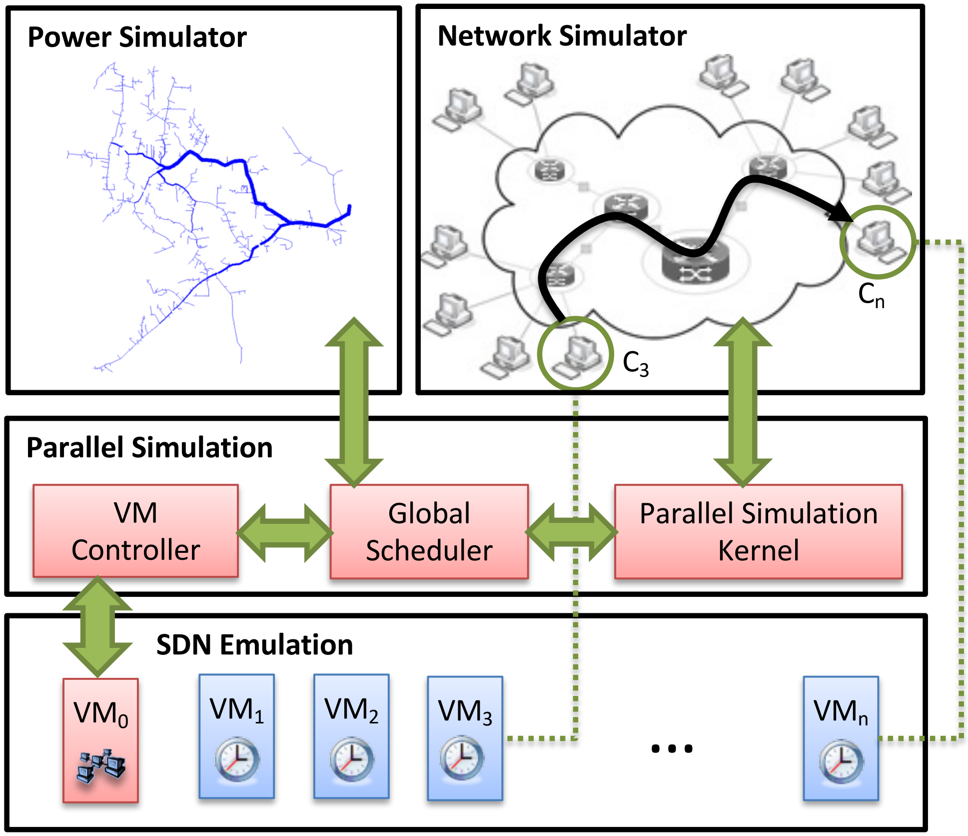


Security Exercise/Evaluation

- Scalable
- Flexible
- Controllable
- Reproducible

A Large-scale, High-fidelity Simulation/Emulation Testbed

Testbed Design



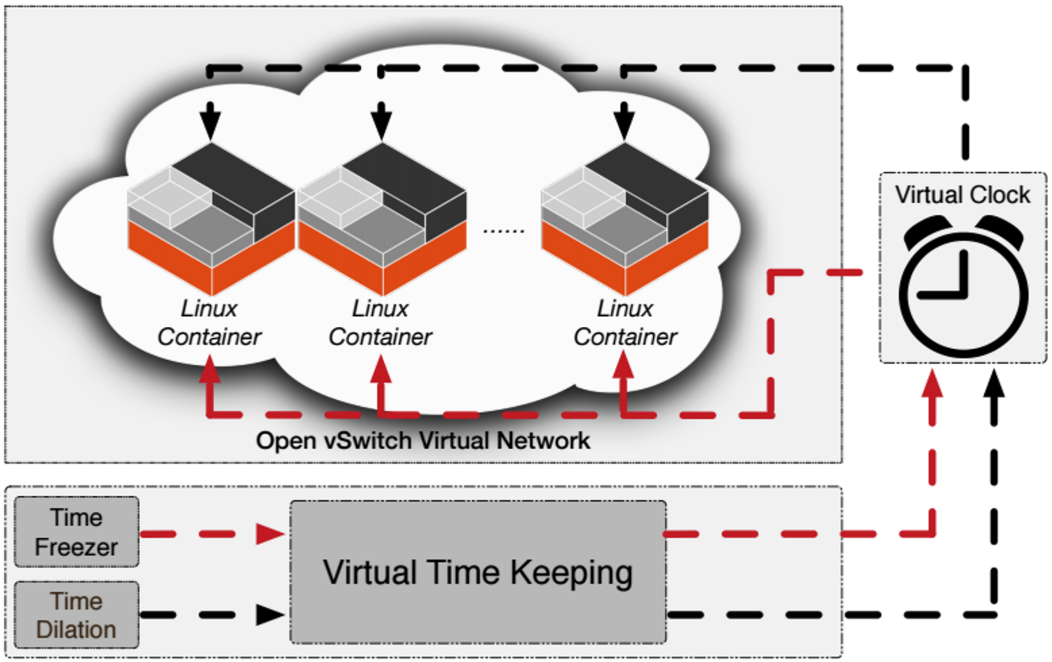
Parallel Simulation/Emulation Testbed

[Best paper award, PADS'19], [Best paper finalist, PADS'16]

- SDN Emulation
  - lightweight virtual machine
  - unmodified code execution
  - virtual time system
- Parallel Simulation Engine
  - 1 million nodes
- Simulation
  - S3FNet: communication network
  - OpenDSS: power distribution system
- Using by
  - IBM Research
  - Boeing
  - Argonne National Lab

Virtual Time System Design and Implementation

- Each process has a virtual clock managed by the Virtual Time Manager
- Virtual time module allows for
  - *Clock Pause/Resume*
  - *Clock Dilation*
- To retrieve virtual time
  - *Modify system calls*
  - *e.g.,* **gettimeofday()**



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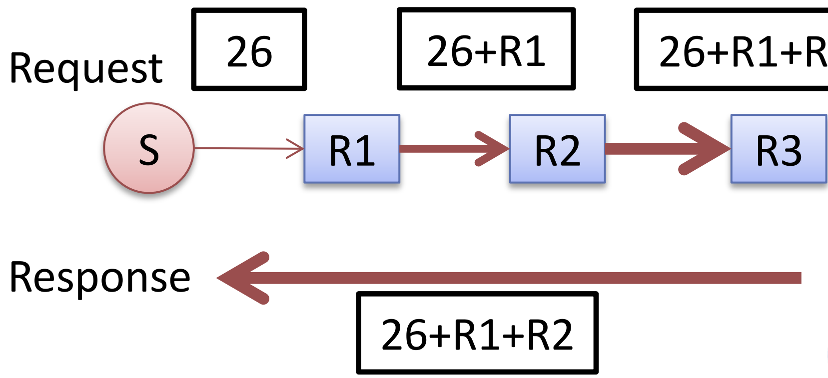
Cyber-security Evaluation

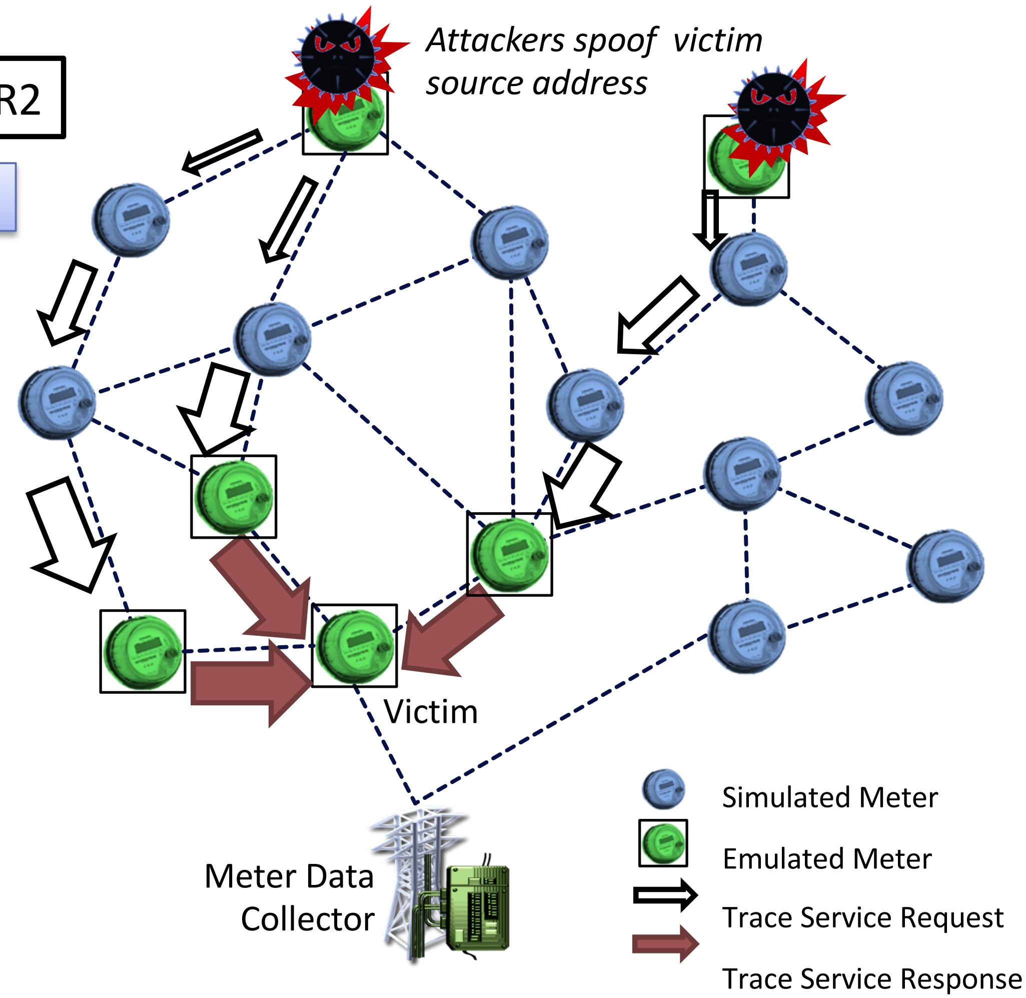
Extensively utilize the testbed to evaluate cyber-attacks

- Power grid control network
  - supervisory control and data acquisition (SCADA)
- Wide area monitoring
  - Phasor measurement unit (PMU)
- Advanced metering infrastructure (AMI)
  - Demand response
  - Load disaggregation
- Transactive control networks

Use Case: DDoS Attack in Smart Meter Networks

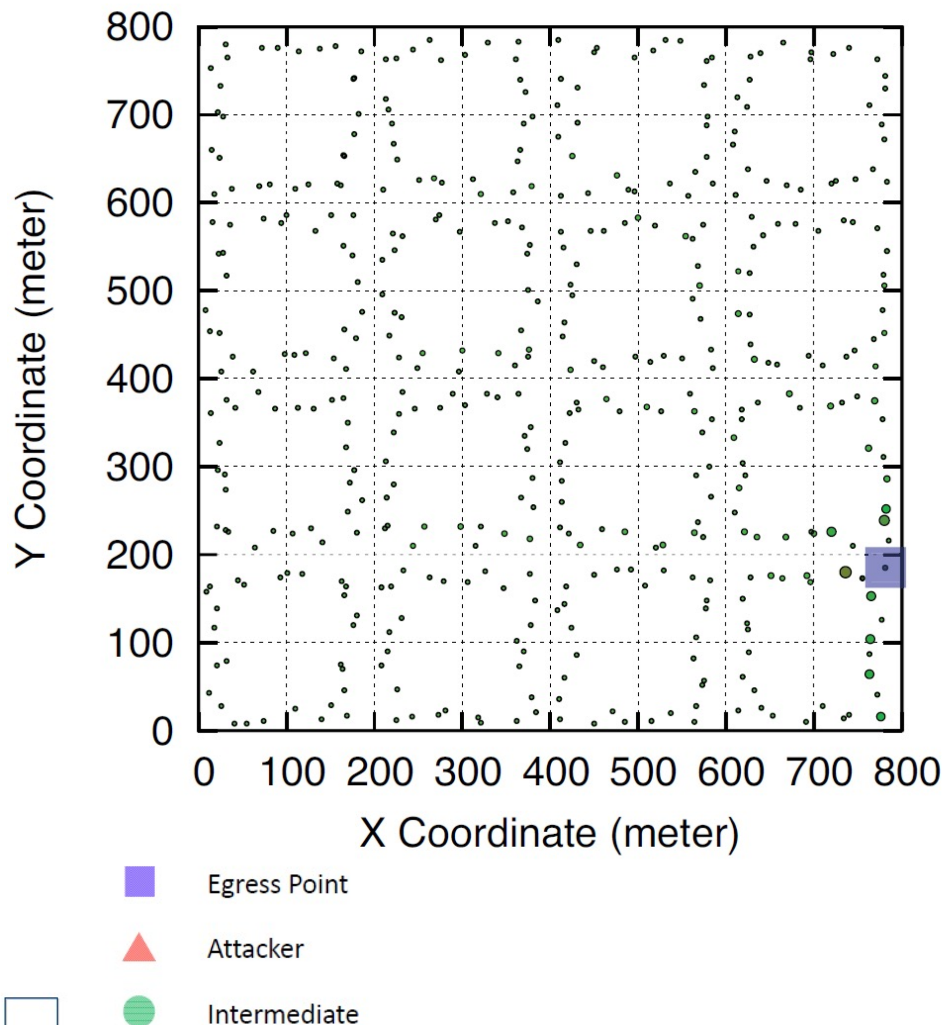
C12.22 Trace Service





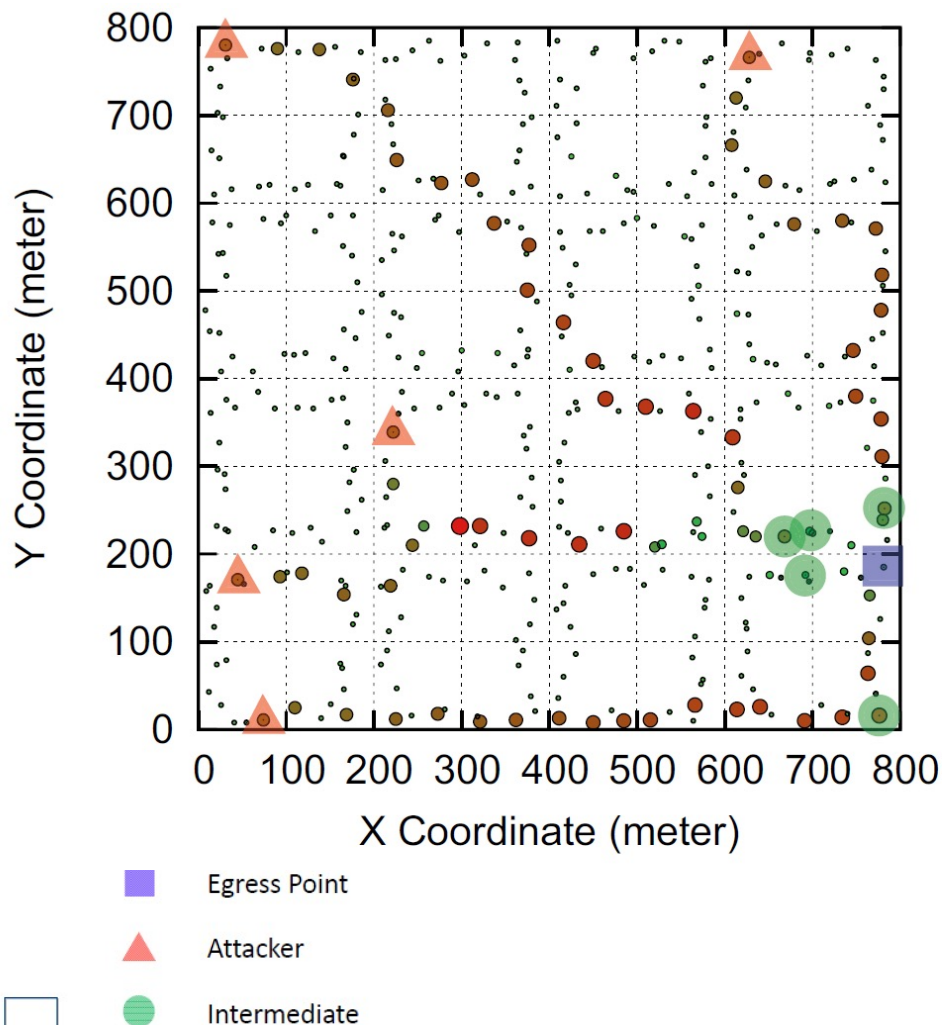
- Amplification
  - Increased volume of traffic
- Reflection
  - Spoofed source address (the victim's address)

Attacking Experiment



- 4x4 blocks, 448 meters
- ZigBee wireless network, 1 Mb/s bandwidth

Attacking Experiment



- 4x4 blocks, 448 meters
- ZigBee wireless network, 1 Mb/s bandwidth
- 5 attackers
- Victim: the single egress point (meter gateway)

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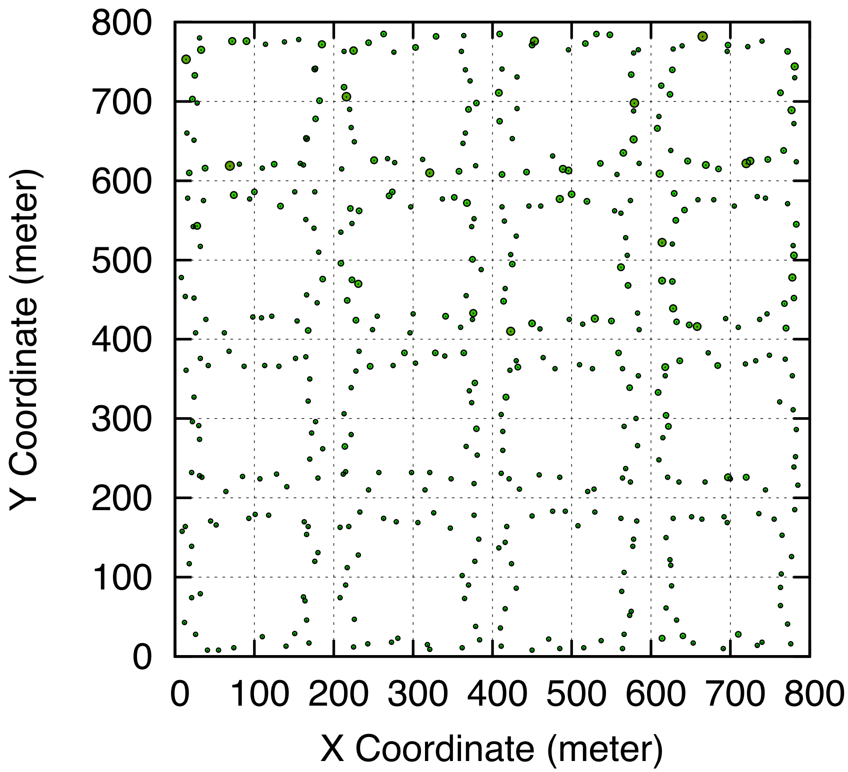
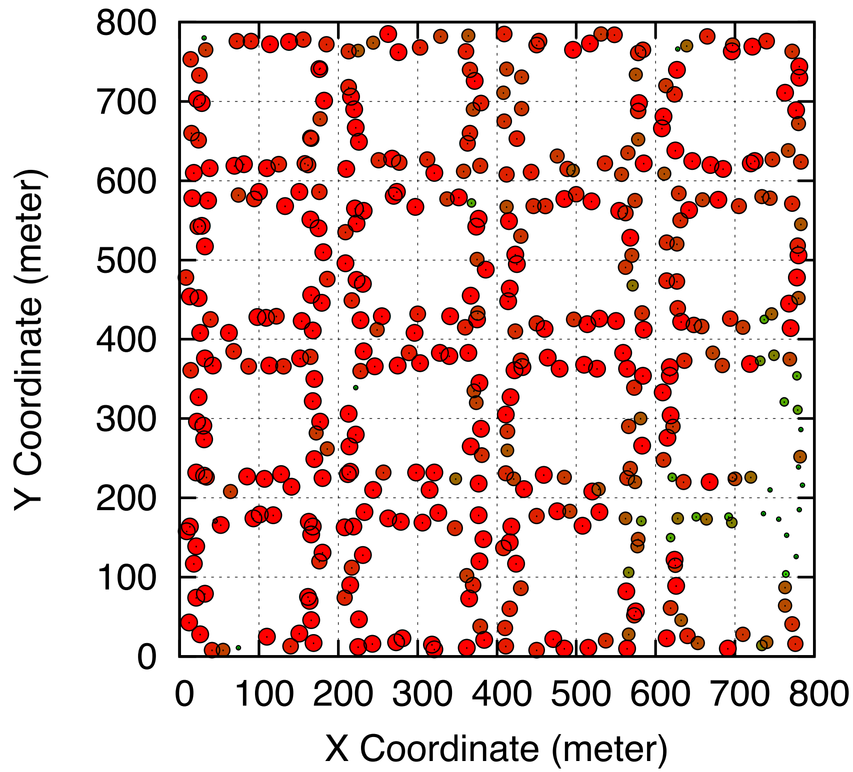
Experimental Results – Packet Loss



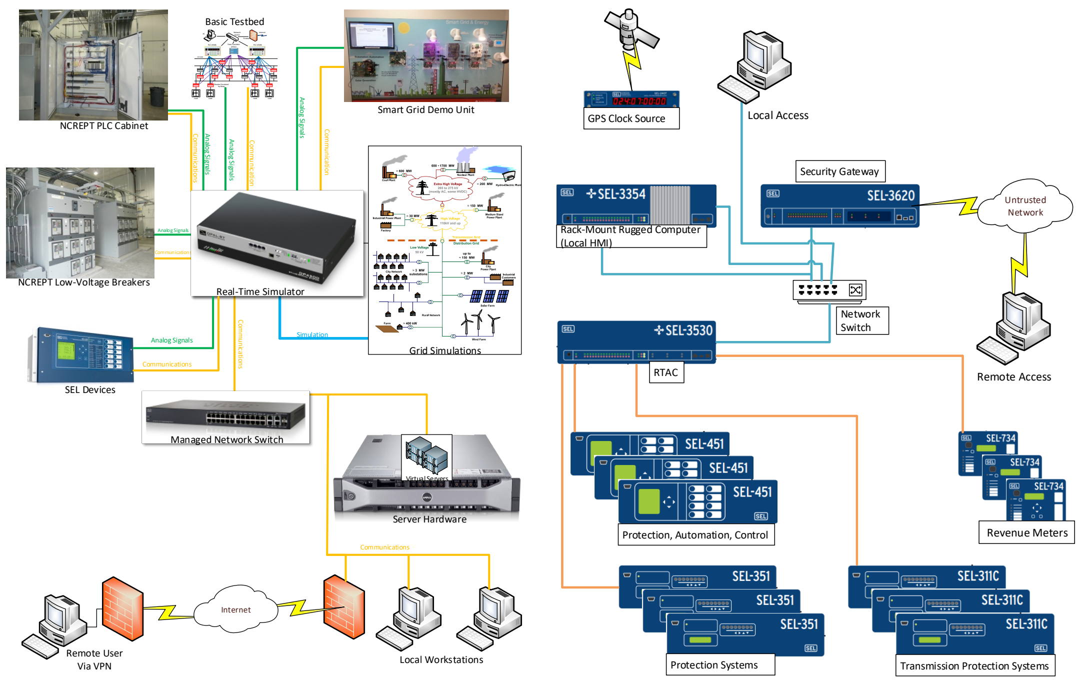
Normal



Under DDoS Attack

Packet Loss Rate 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

Univ. of Arkansas Efforts in Smart Grid Cyber Security



Cybersecurity Testbed

The National Center for Reliable Electric Power Transmission (NCREPT)

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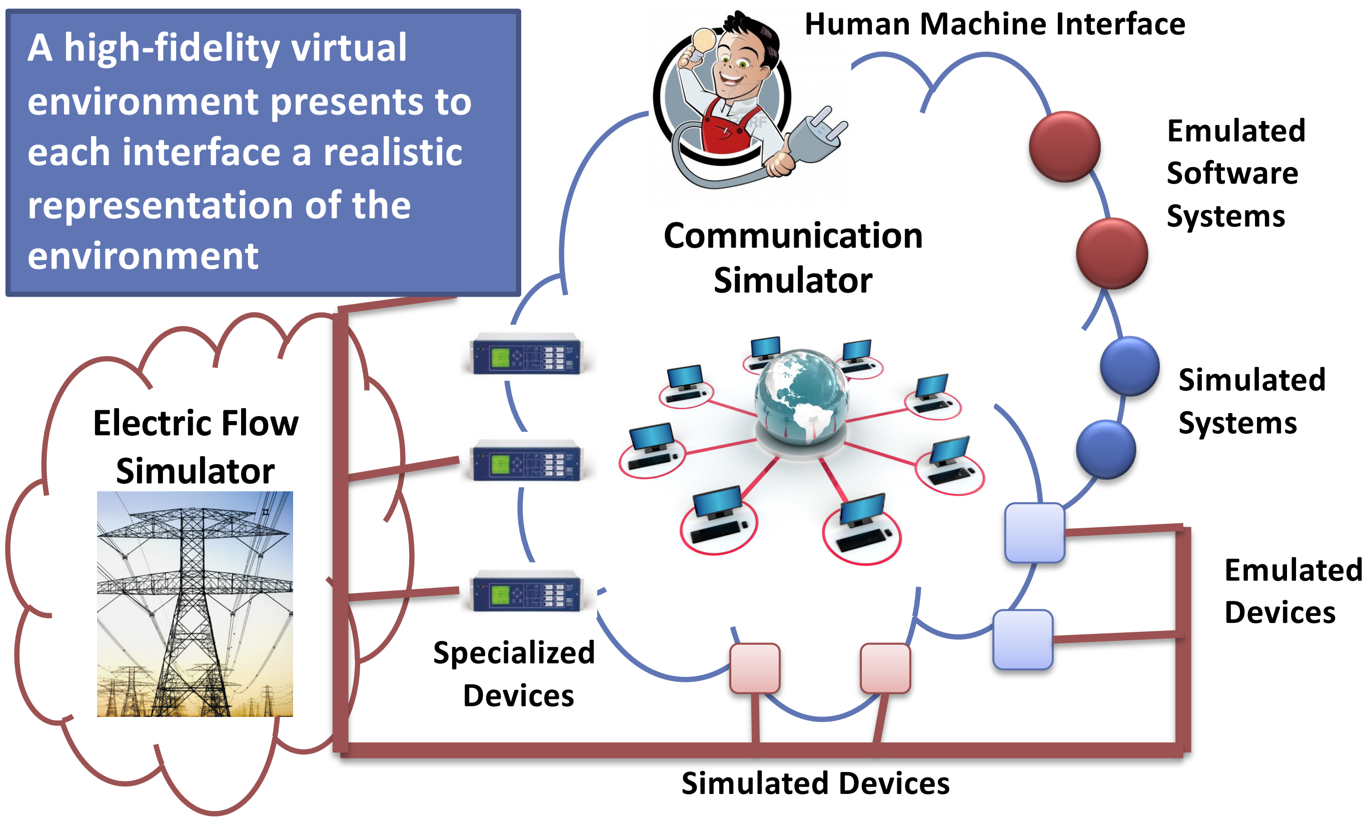
Ongoing/Future work: Can we make the whole greater than the sum of the parts?

A high-fidelity virtual environment presents to each interface a realistic representation of the environment



We need an infrastructure that includes all this reality, but also *models* of real stuff.

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Conclusion

- Goal: To build a more secure, resilient, and safe cyber-environment for industrial control systems
- Enable a cyber secure and resilient ICS in power grid with SDN
  - A novel SDN architecture in microgrid
  - Innovative SDN-based security applications
  - testbed using parallel simulation and virtual-machine-based emulation