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Distributed Systems
and Networks Lab

Spire:
Intrusion-Tolerant SCADA for the Power Grid

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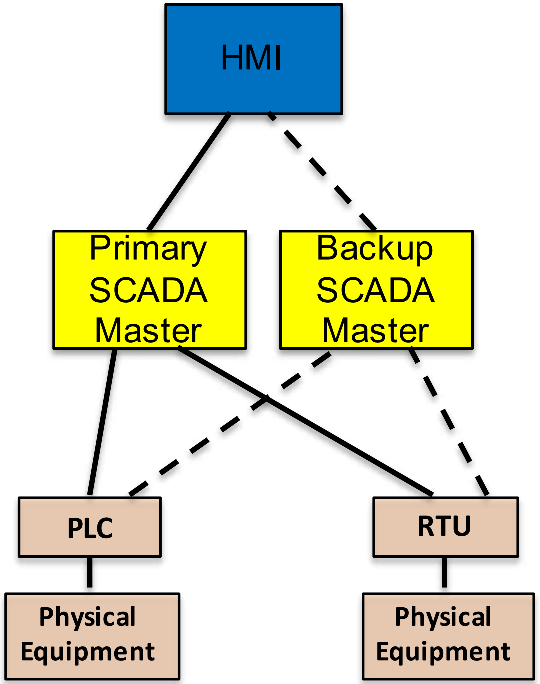
SCADA is Vulnerable on Several Fronts

The move to IP makes SCADA vulnerable on several fronts:

- SCADA system compromises
  - SCADA Master – system-wide damage
  - RTUs, HMIs – limited local effects
- Network level attacks
  - Routing attacks that disrupt or delay communication
  - Isolating critical components from the rest of the network



- Therefore, SCADA systems must ensure continuous availability and correct operation in the presence of compromises and attacks at both the system and network level

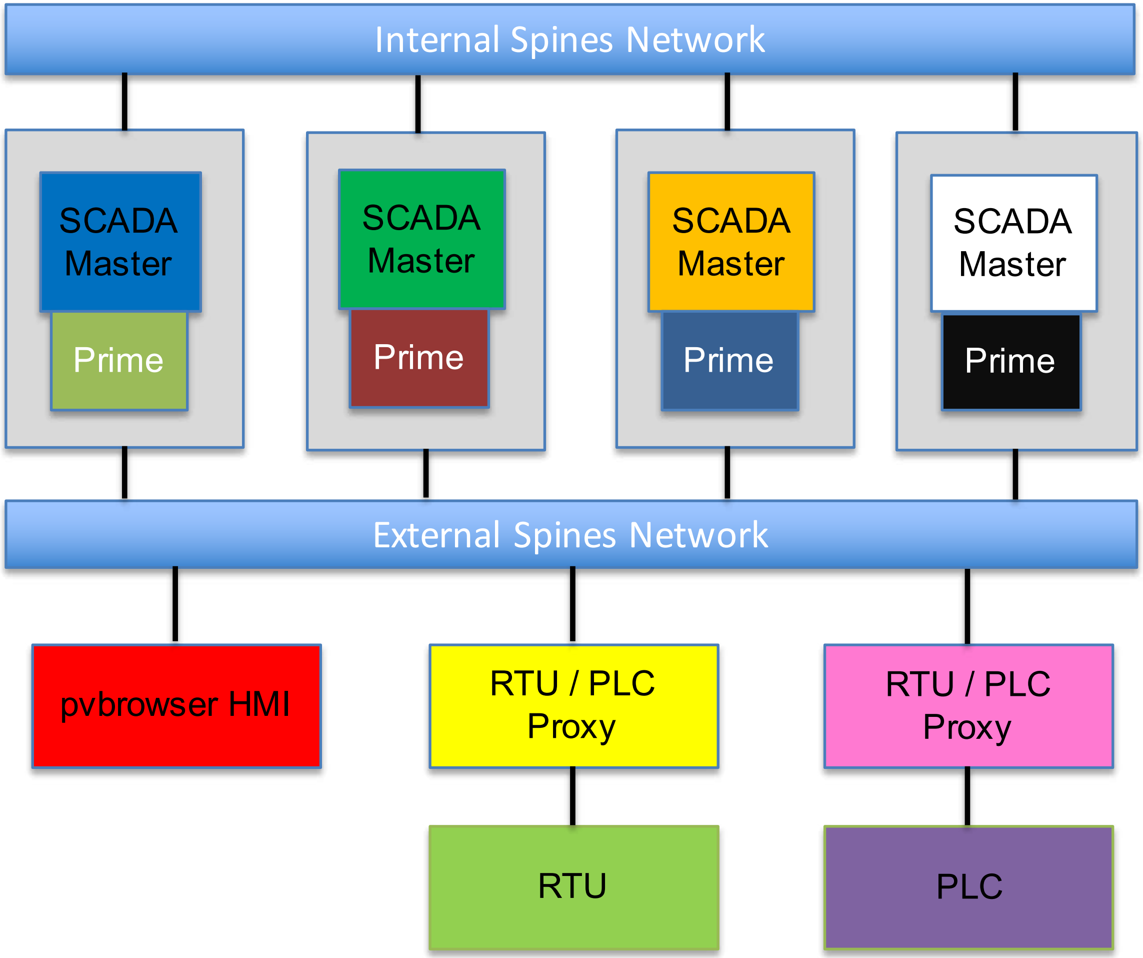
Spire Overview

- Spire is a SCADA system that continues to work even if some critical components have been compromised
- Intrusion tolerance as the core design principle protecting several different layers of the system:
  - Intrusion-tolerant network
  - Intrusion-tolerant consistent state
  - Intrusion-tolerant SCADA Master
- Combines proven open-source components with new system components built from scratch to provide a **complete** top-to-bottom solution
- Open Source - http://dsn.jhu.edu/spire

Spire Components

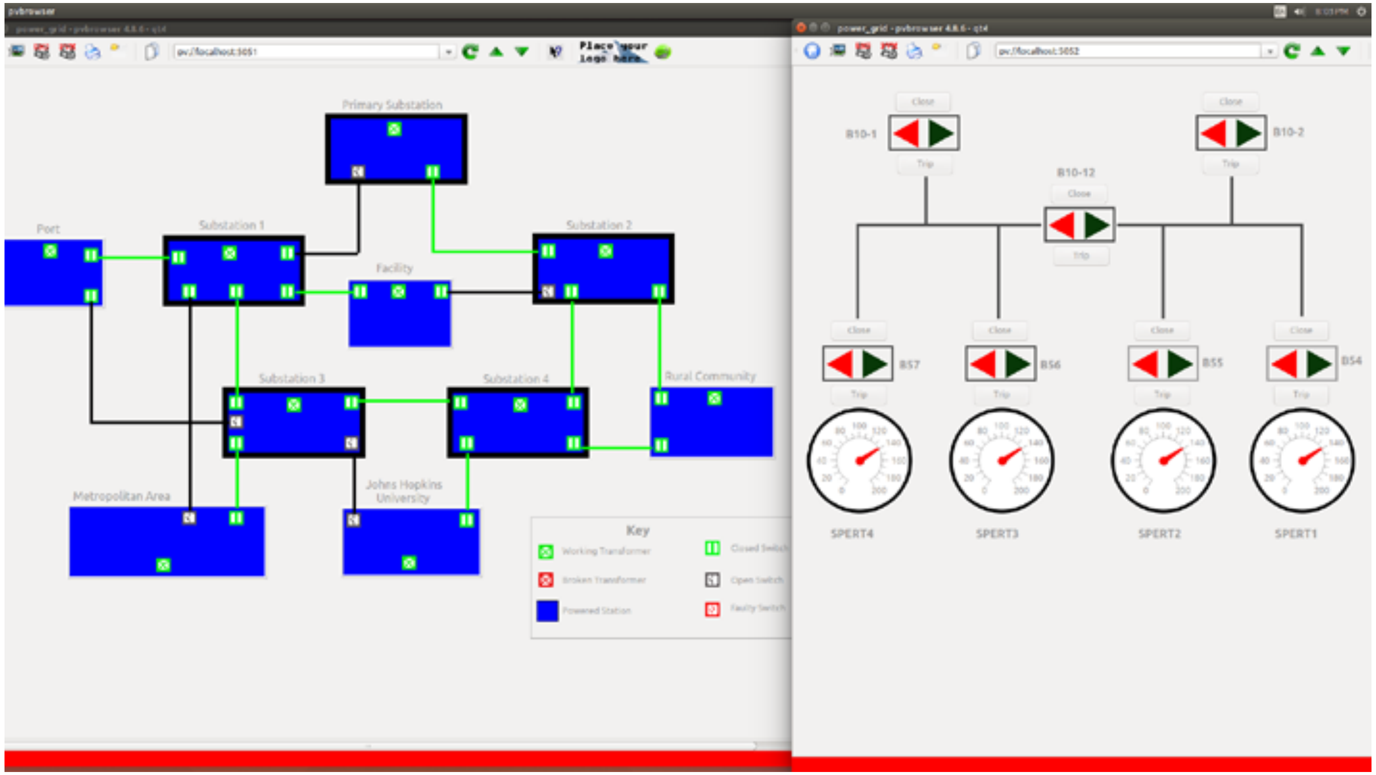
- **Spines** (http://spines.org)
  - Intrusion-Tolerant Network
- **Prime** (http://dsn.jhu.edu/prime)
  - Intrusion-Tolerant Replication – BFT with performance guarantees under attack
- **SCADA Master** (http://dsn.jhu.edu/spire)
- **PLC/RTU Proxy** (http://dsn.jhu.edu/spire)
- **Pvbrowser-based HMI** (https://pvbrowser.de/pvbrowser/index.php)
  - Rainer Lehrig and his group
- **OpenPLC** (http://www.openplcproject.com)
  - PLC Emulation – (Thiago Alves, Tommy Morris) University of Alabama, Huntsville
- **Multicompiler** (https://github.com/securesystemslab/multicompiler)
  - Diversity (Michael Franz group at UC Irvine, Immunant)

Spire Architecture: Single Control Center

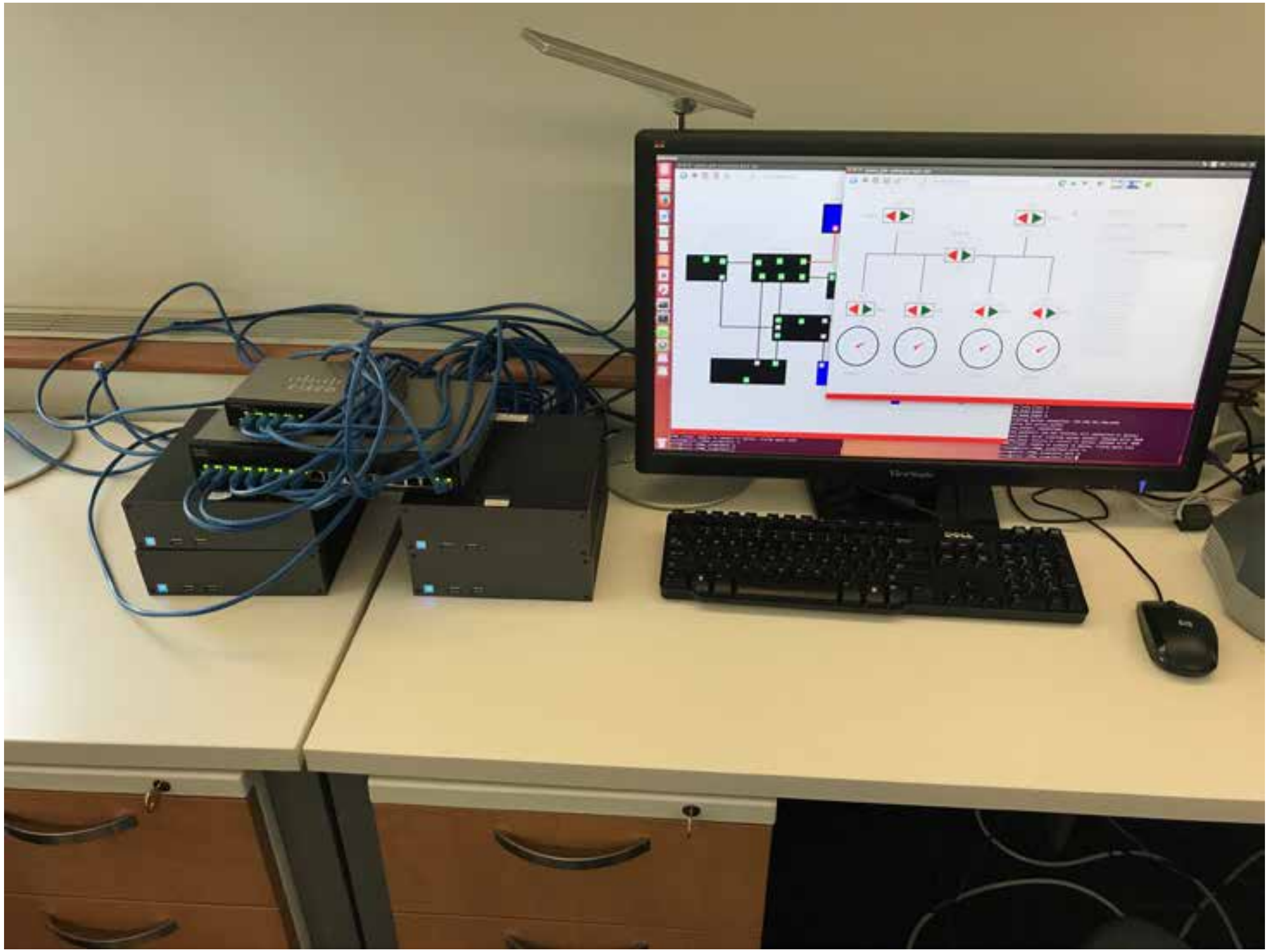


pvbrowser-based HMI

- Pvbrowser is an open source SCADA software solution
  - Used in real-world deployments: Romanian power distribution system covering 10,000 km^2 with 50 power switches



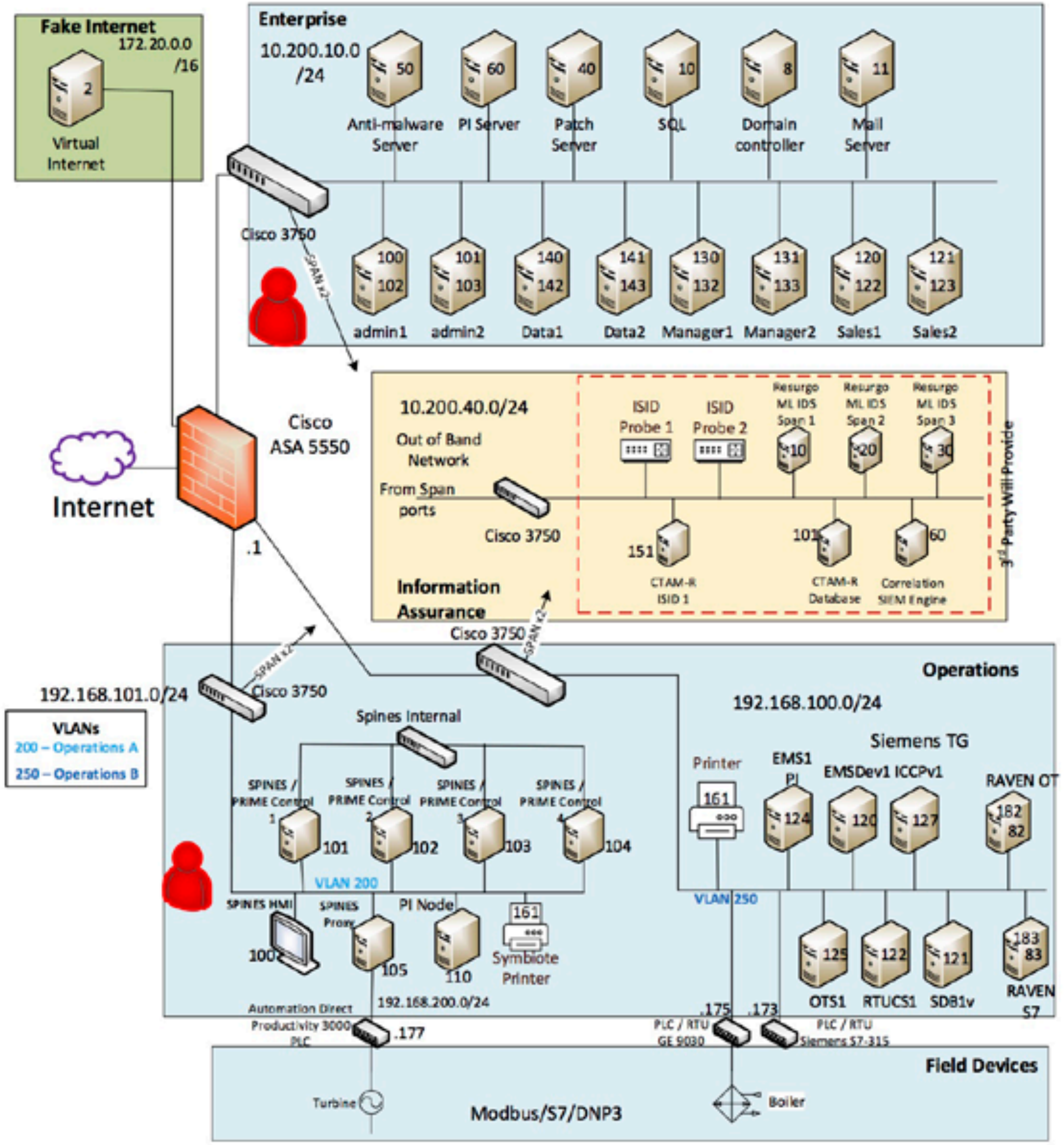
Spire in Action



Spire as used in the DoD ESTCP experiment March-April 2017

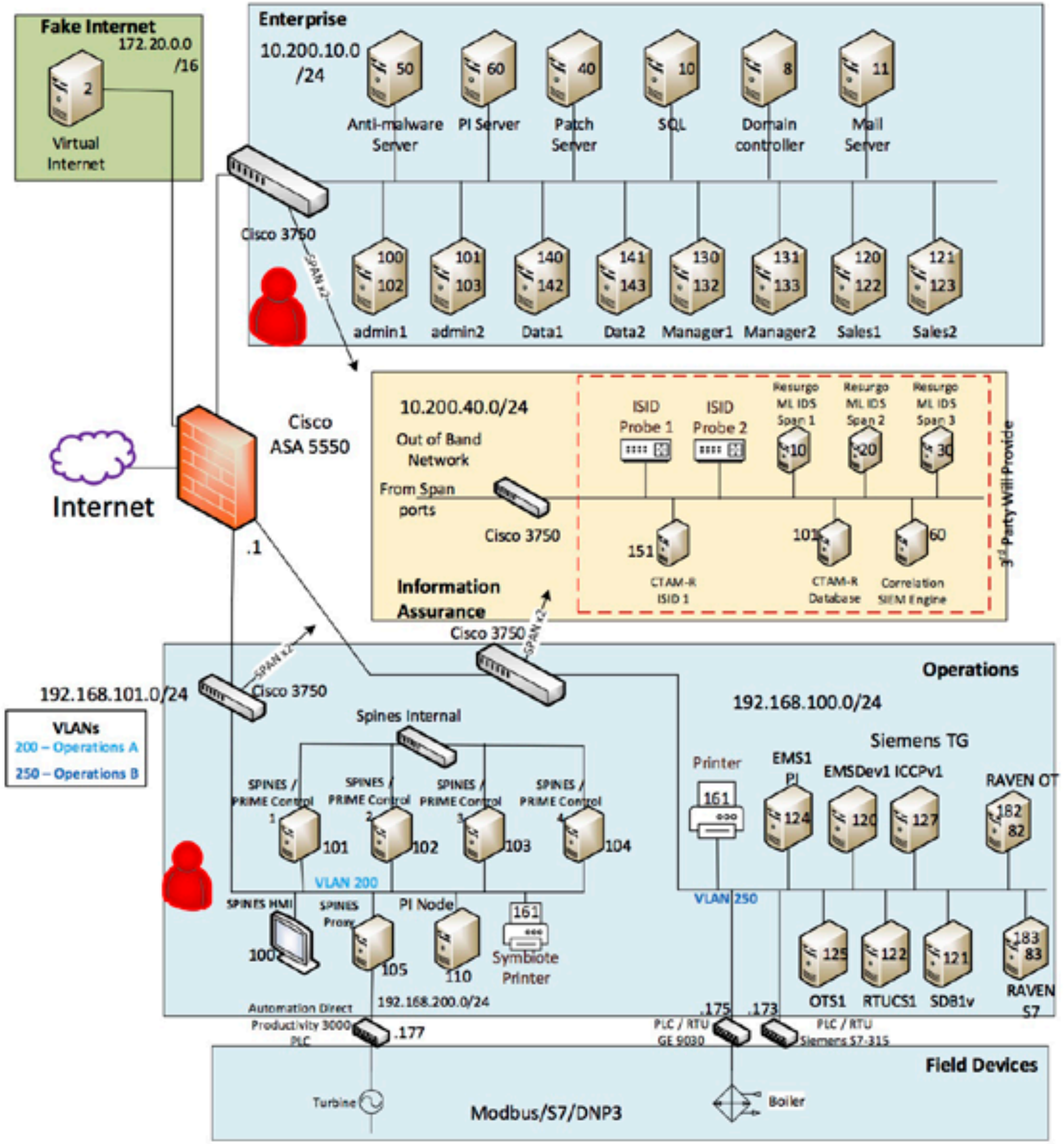
DoD ESTCP Experiment

- DoD ESTCP project at Pacific Northwest National Labs
  - Conducted by Resurgo
  - 3/27/17 to 4/7/17
- Comparing NIST-compliant SCADA architecture with Spire
  - Each attacked by Sandia National Labs red team



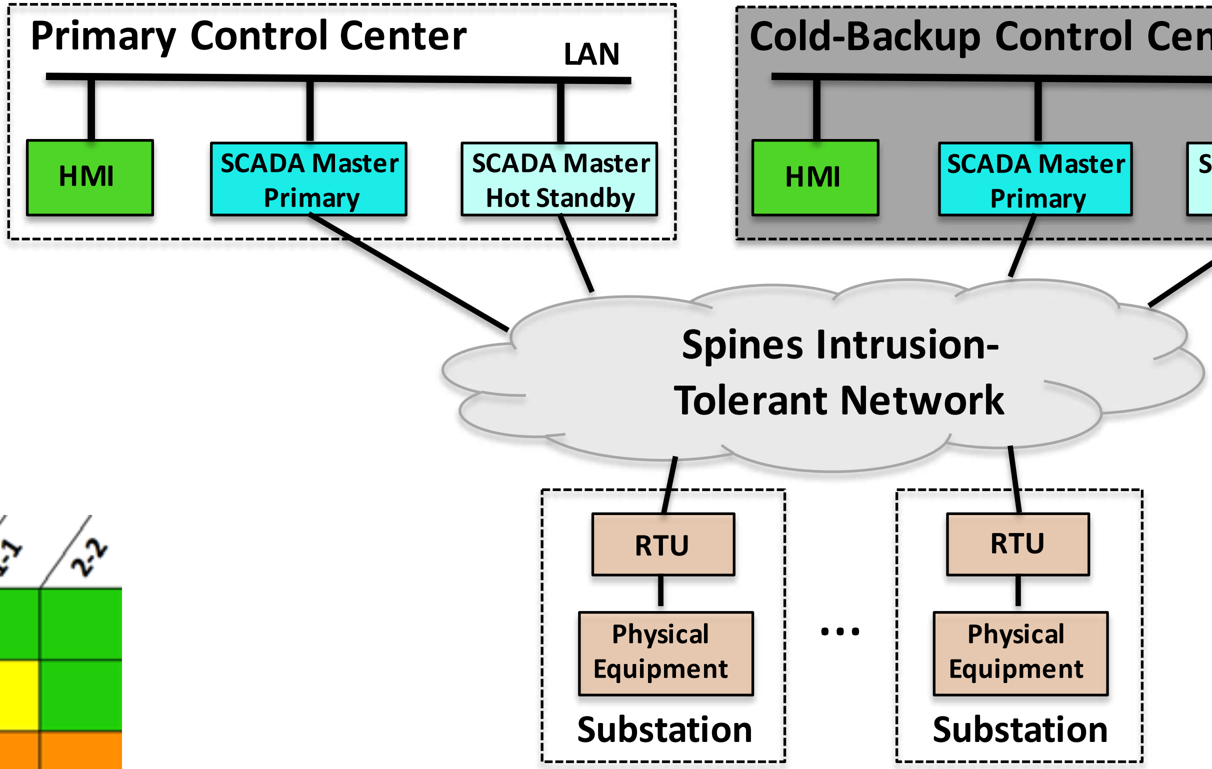
DoD ESTCP Results

- NIST-compliant system completely taken over
  - MITM attack from corporate network
  - Direct access to PLC from operational network
- Spire completely unaffected
  - Attacks in corporate and operational network
  - Given complete access to a replica and code
  - Red team gave up after several days



Current SCADA Systems

2-2



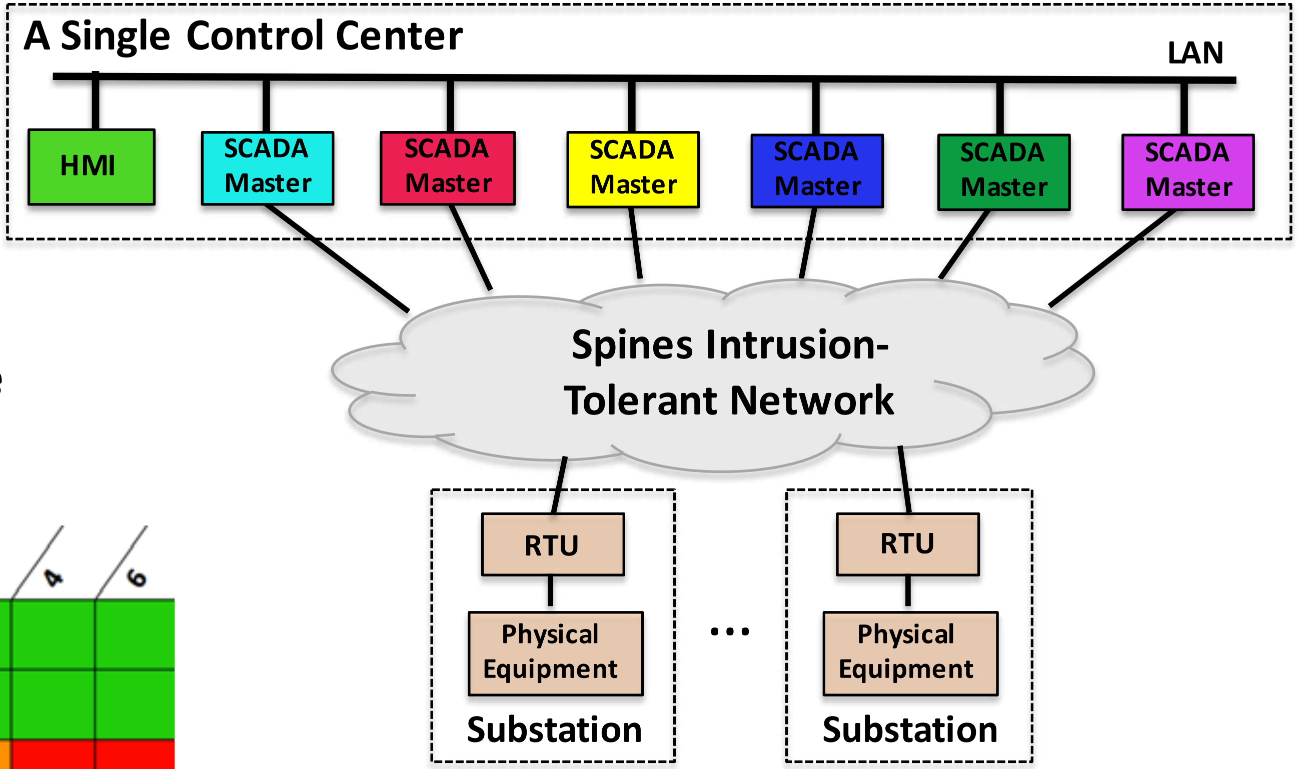
	1	2	1-1	2-2
All Correct	🟩	🟩	🟩	🟩
Proactive Recovery (PR)	🟨	🟩	🟨	🟩
Disconnected/Downed Site	🟥	🟥	🟧	🟧
Disconnected/Downed Site + PR	🟥	🟥	🟧	🟧
Intrusion	▨	▨	▨	▨
Intrusion + PR	▨	▨	▨	▨
Disconnected/Downed Site + Intrusion	▨	▨	▨	▨
Disconnected/Downed Site + Intrusion + PR	▨	▨	▨	▨

🟩	Bounded Delay
🟨	Bounded Delay, except when rejuvenating any correct replica
🟧	Eventual Progress – Human in the loop. Potentially powering up cold backup control center
🟥	Eventual Progress – No bound. Network has to heal, crash has to be repaired, and/or intrusion needs to be cleansed
▨	Incorrect System

Intrusion Tolerance State-of-the-Art in Research

6 (progress: 4)

- 3f+2k+1 total replicas
- 2f+k+1 connected correct replicas required to provide bounded delay



	1	2	1-1	2-2	4	6
All Correct	🟩	🟩	🟩	🟩	🟩	🟩
Proactive Recovery (PR)	🟨	🟩	🟨	🟩	🟩	🟩
Disconnected/Downed Site	🟥	🟥	🟧	🟧	🟥	🟥
Disconnected/Downed Site + PR	🟥	🟥	🟧	🟧	🟥	🟥
Intrusion	▩	▩	▩	▩	🟩	🟩
Intrusion + PR	▩	▩	▩	▩	🟨	🟩
Disconnected/Downed Site + Intrusion	▩	▩	▩	▩	🟥	🟥
Disconnected/Downed Site + Intrusion + PR	▩	▩	▩	▩	🟥	🟥

🟩	Bounded Delay
🟨	Bounded Delay, except when rejuvenating any correct replica
🟧	Eventual Progress – Human in the loop. Potentially powering up cold backup control center
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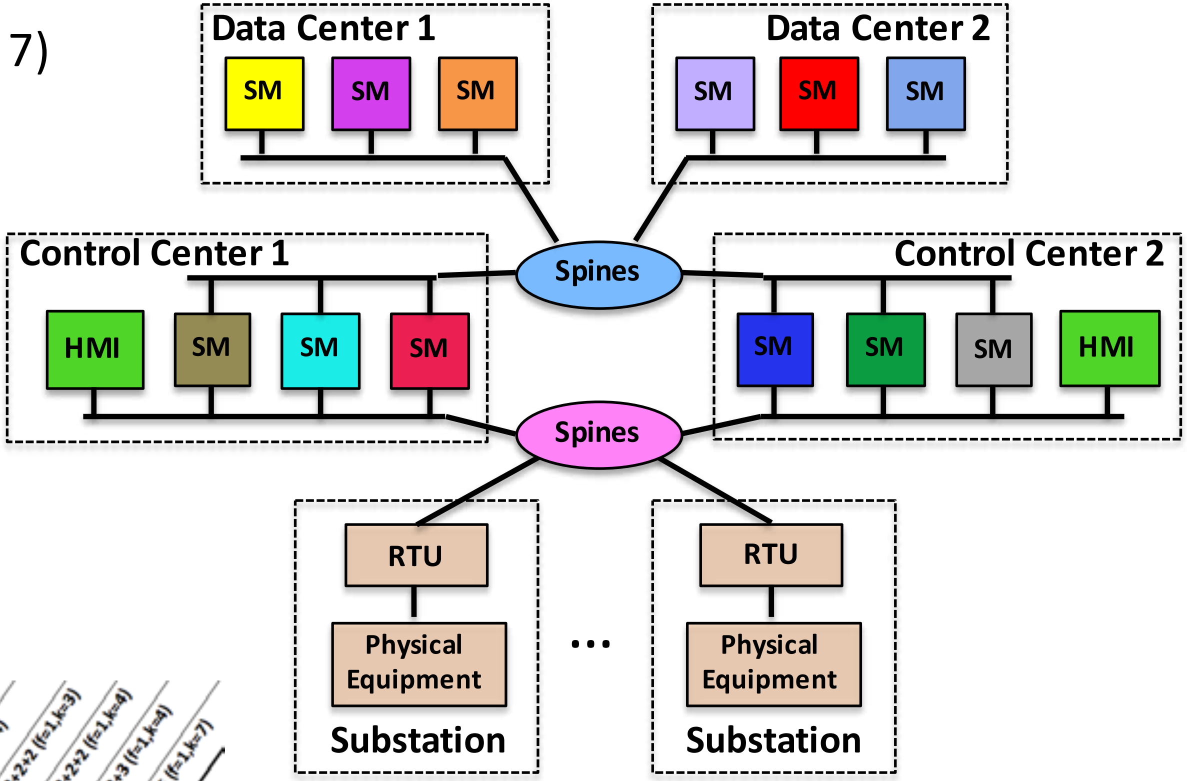
▩	Incorrect System

Novel Resilient Configurations (7/7)

3+3+3+3 (progress: 7)

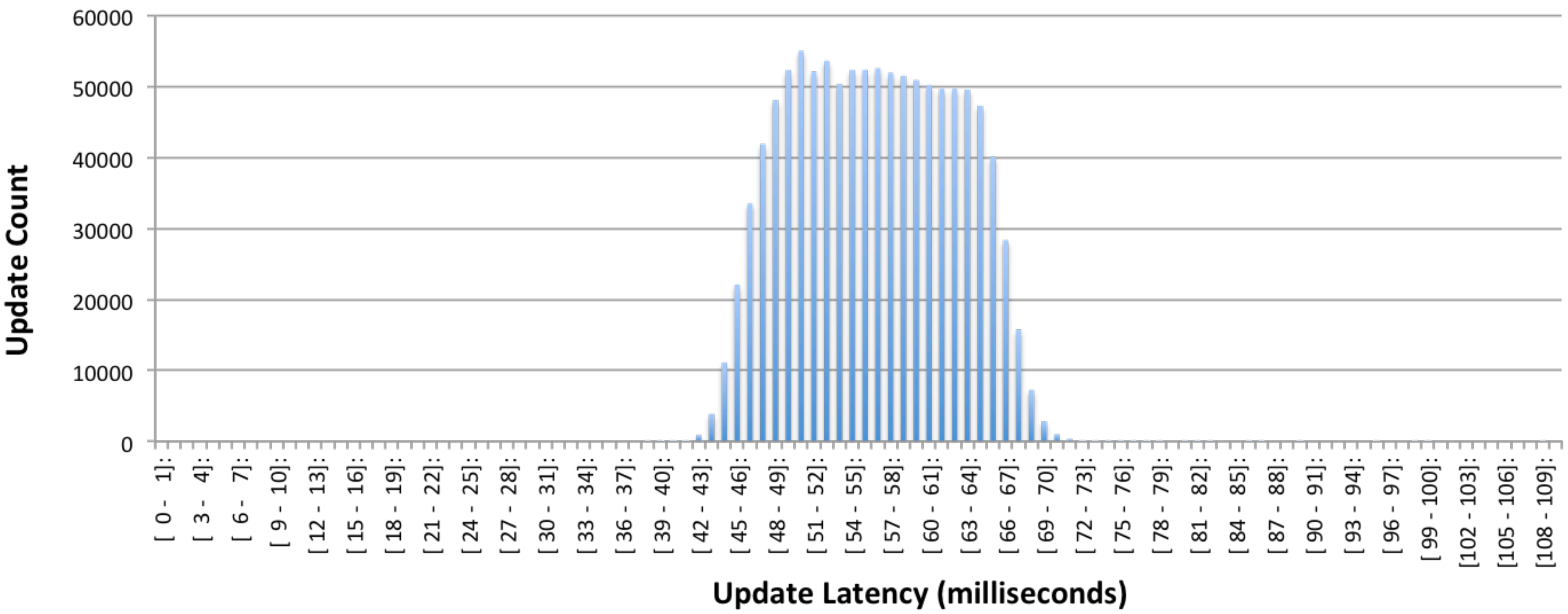
- **Complete solution for 4 total sites: (2 control centers, 2 data centers)**
- **Sweet-spot balancing the number of data center sites, the number of total replicas, and the communication overhead**



	1	2	1-1	2-2	4	6	4-4	6-6	3+3 (f=1,k=1); x+y	2+2+2 (f=1,k=1)	2+2+2+2 (f=1,k=2)	4+4+4 (f=1,k=4)	2+2+2+2+2 (f=1,k=3)	3+3+2+2+2 (f=1,k=4)	3+3+3+3 (f=1,k=4)	6+6+6 (f=1,k=7)
All Correct	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Proactive Recovery (PR)	🟨	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Disconnected/Downed Site	🟥	🟥	🟧	🟧	🟥	🟥	🟧	🟧	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Disconnected/Downed Site + PR	🟥	🟥	🟧	🟧	🟥	🟥	🟧	🟧	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩
Intrusion	⬛	⬛	⬛	⬛	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Intrusion + PR	⬛	⬛	⬛	⬛	🟨	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Disconnected/Downed Site + Intrusion	⬛	⬛	⬛	⬛	🟥	🟥	🟧	🟧	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
Disconnected/Downed Site + Intrusion + PR	⬛	⬛	⬛	⬛	🟥	🟥	🟧	🟧	🟥	🟥	🟨	🟨	🟦	🟩	🟩	🟩

🟩	Bounded Delay
🟦	Bounded Delay, except when one control center is down and the other control center has only one uncompromised replica and that replica is currently rejuvenating
🟨	Bounded Delay, except when rejuvenating any correct replica
🟧	Eventual Progress – Human in the loop. Potentially powering up cold backup control center
🟥	Eventual Progress – No bound. Network has to heal, crash has to be repaired, and/or intrusion needs to be cleansed
⬛	Incorrect System

Wide Area: Update Latency Histogram



- 30-hour wide-area deployment of 3+3+3+3 configuration
  - Control centers at JHU and SVG, data centers at WAS and NYC
  - 10 emulated RTUs sending periodic updates
  - 1.08 million updates (108K from each RTU)
  - Over 99.999% of updates delivered within 100ms (56ms average)

The Spire Forum

- Forum focused on Open Source Intrusion-tolerant control systems for the power grid
- Please join the Spire forum if interested
- http://dsn.jhu.edu/spire

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