JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

Distributed Systems
and Networks Lab

Spire: Intrusion-Tolerant SCADA for the Power Grid

Amy Babay*, Thomas Tantillo*, Trevor Aron, Yair Amir

June 25, 2017

Distributed Systems and Networks Lab

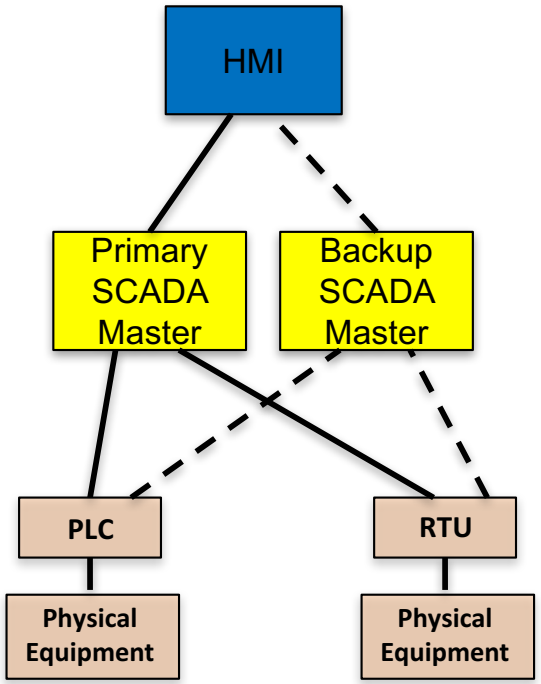
Department of Computer Science

Johns Hopkins University

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, PLCs – limited local effects
  - HMIs
- 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

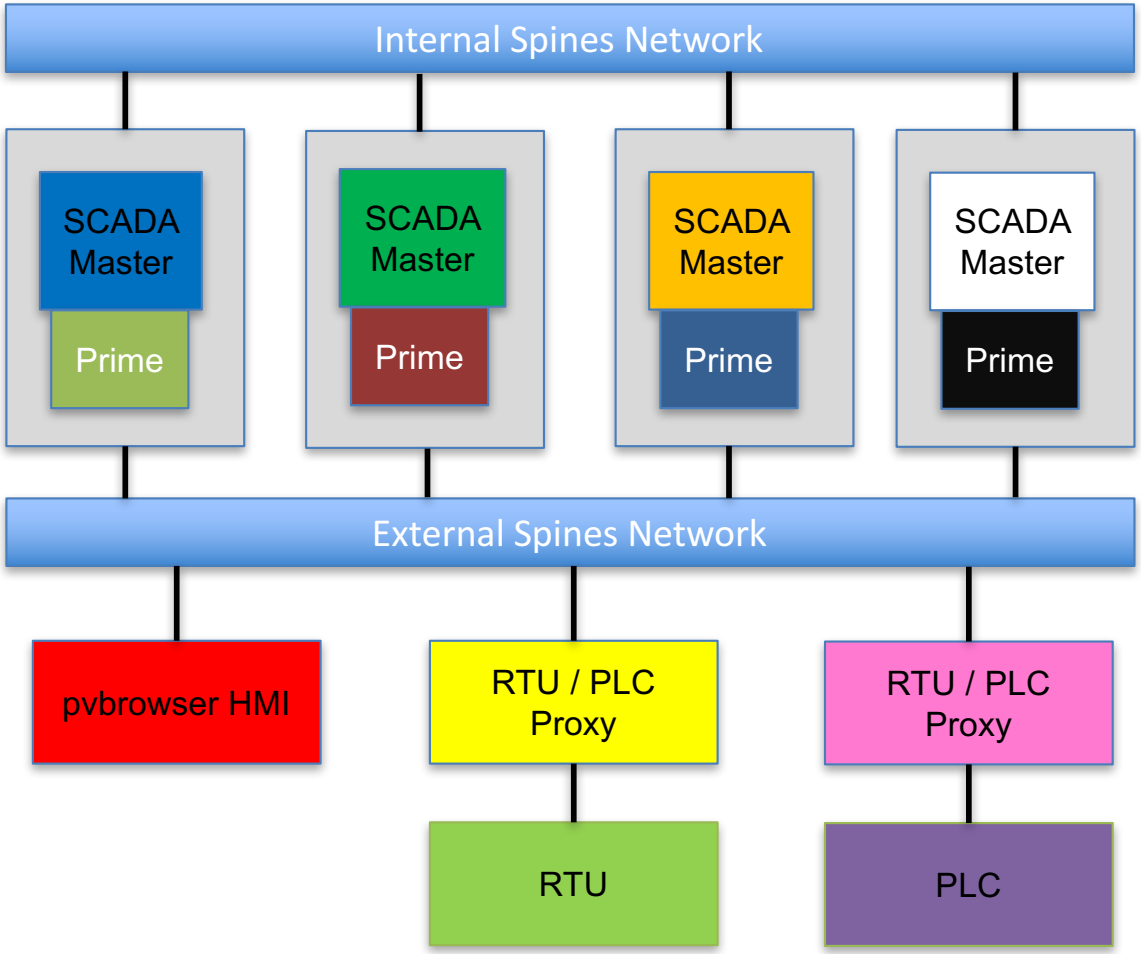
Spire Overview

- 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 from a distributed systems perspective
- Open Source - http://dsn.jhu.edu/spire

Spire Components

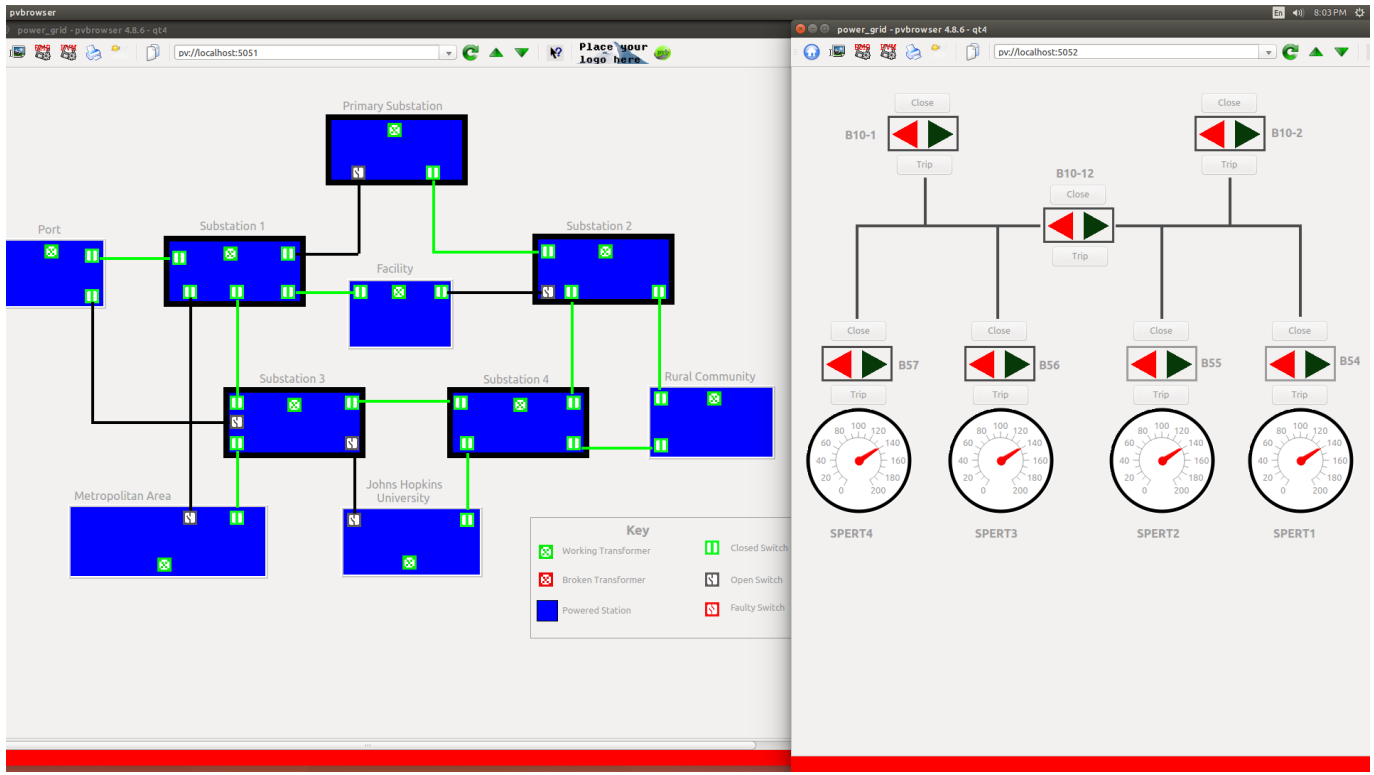
- **Spines** (http://spines.org)
  - Intrusion-Tolerant Network
- **Prime** (http://dsn.jhu.edu/prime)
  - Intrusion-Tolerant Replication – BFT with performance guarantees under attack
- **SCADA Master** (http://dsn.jhu.edu/spire)
- **PLC/RTU Proxy** (http://dsn.jhu.edu/spire)
- **Pvbrowser-based HMI** (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

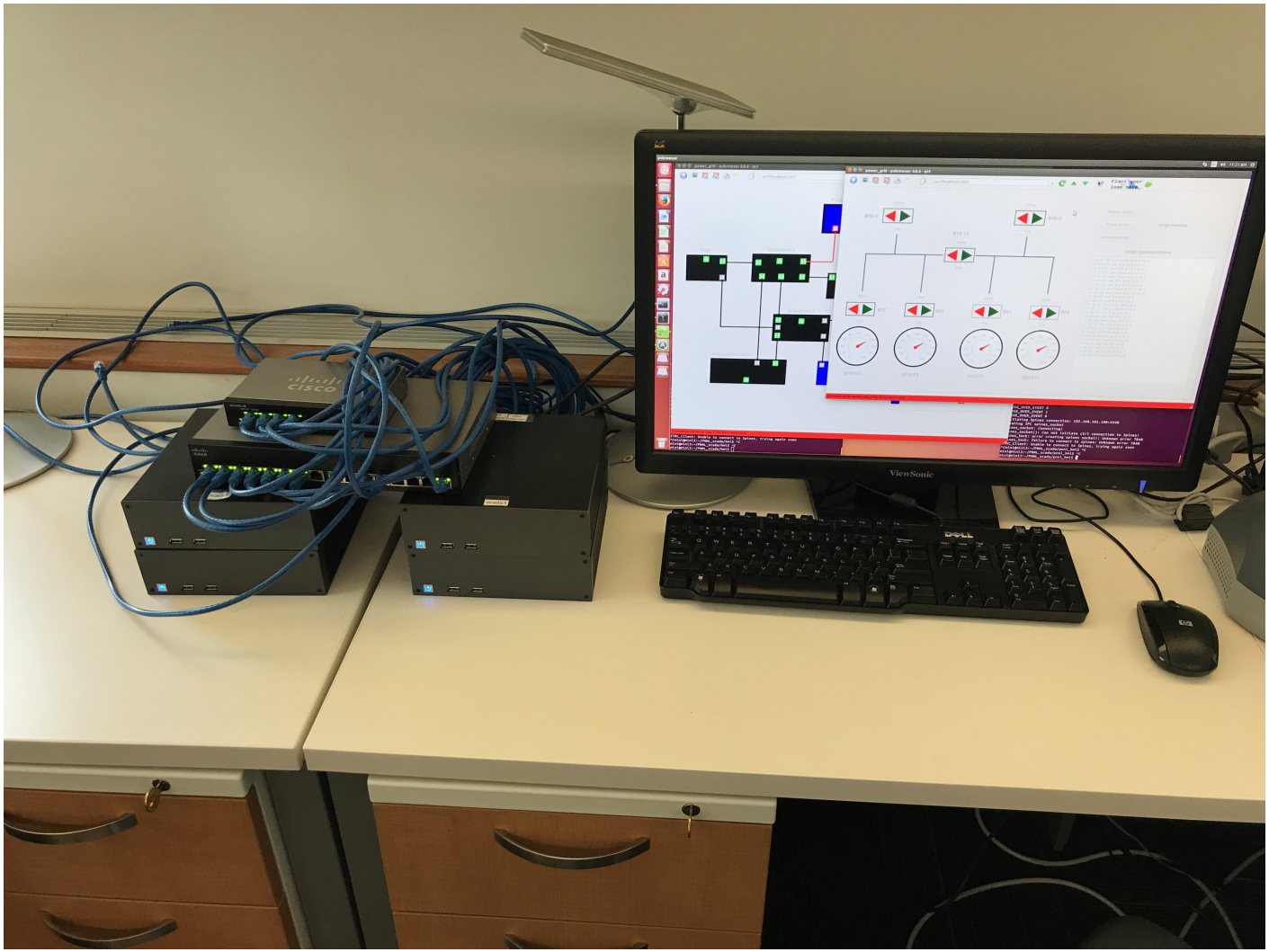


pvbrowser-based HMI

- 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's HMIs is based on pvbrowser



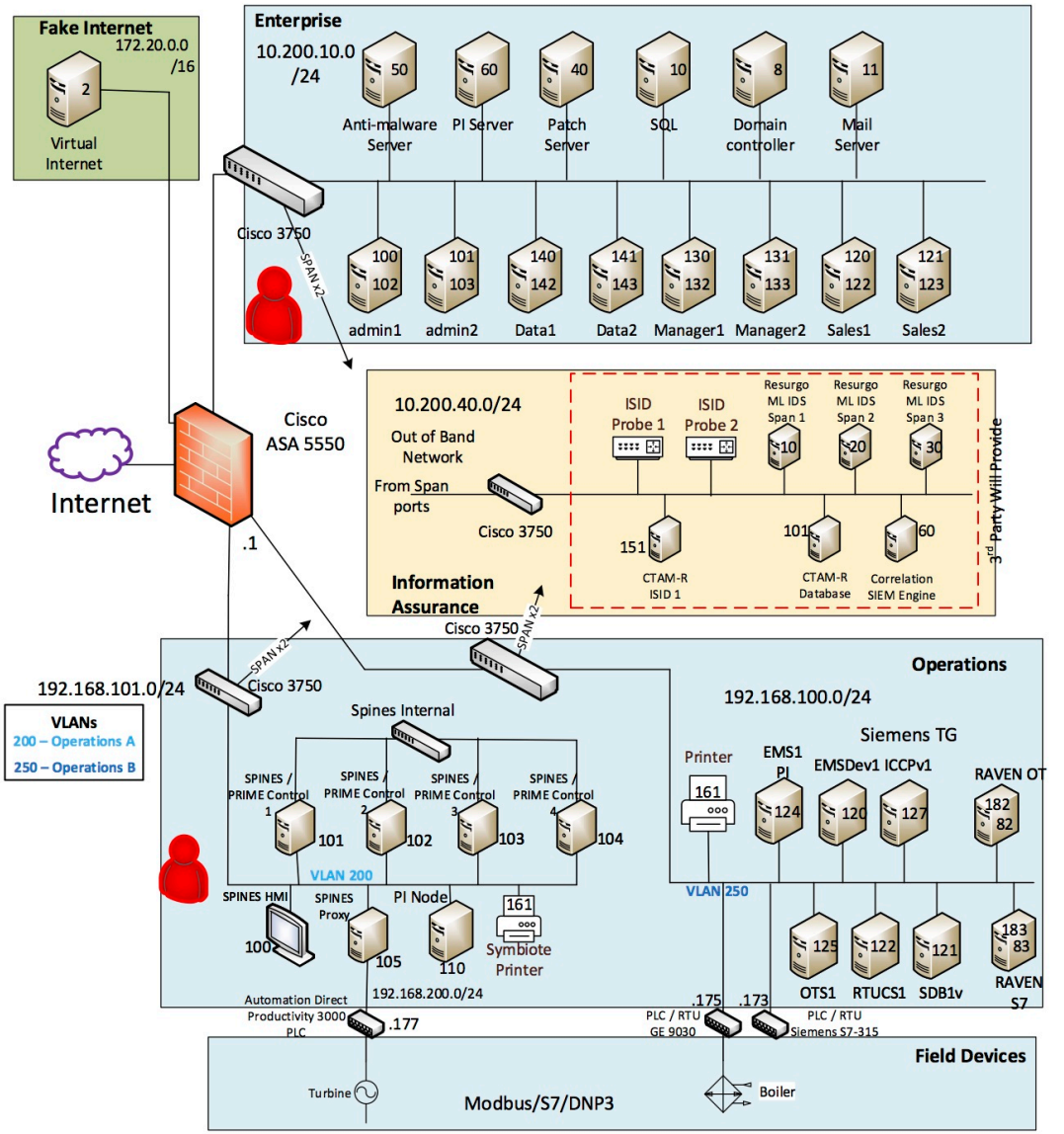
Spire in Action



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

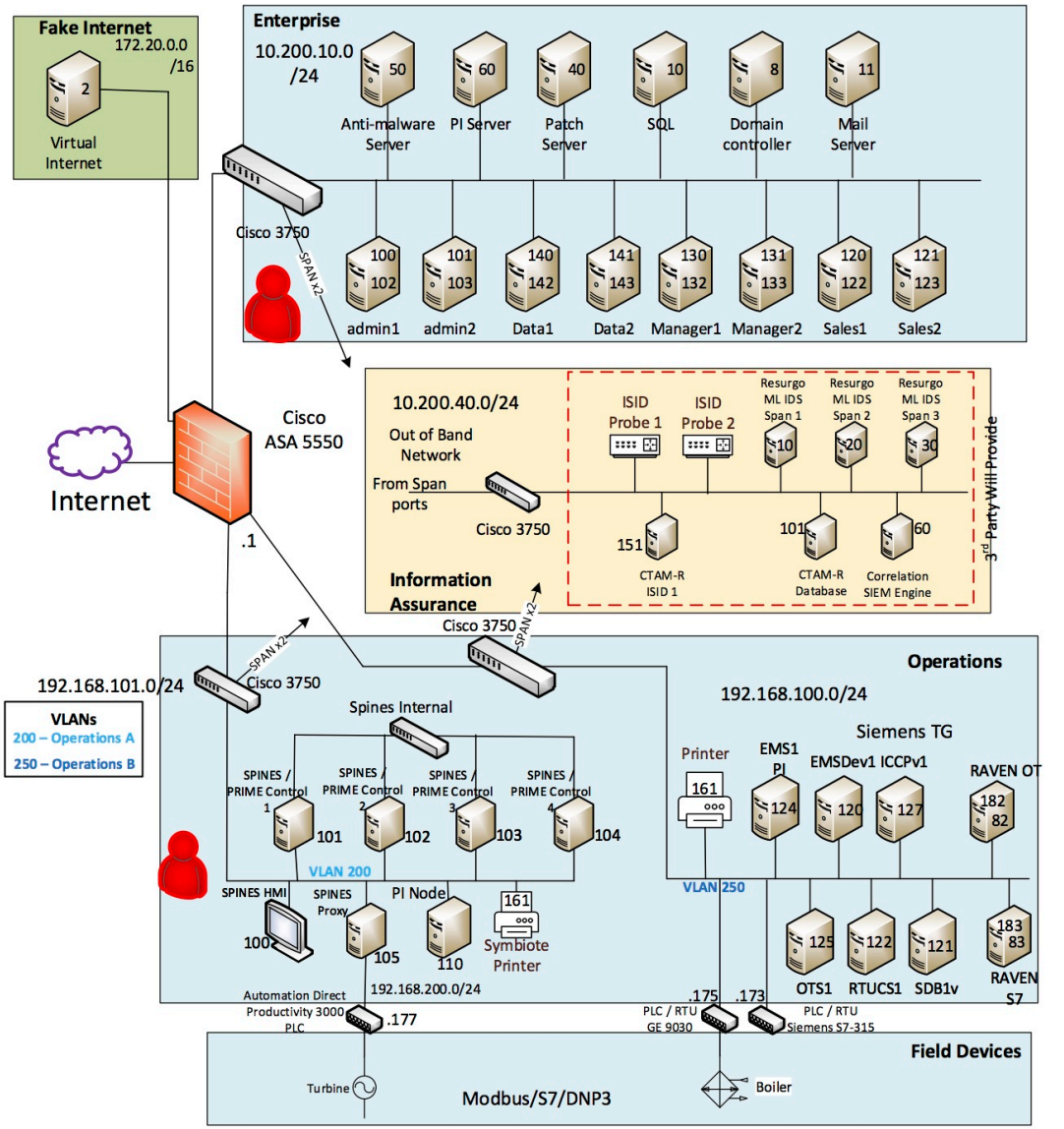
DoD ESTCP Experiment

- 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

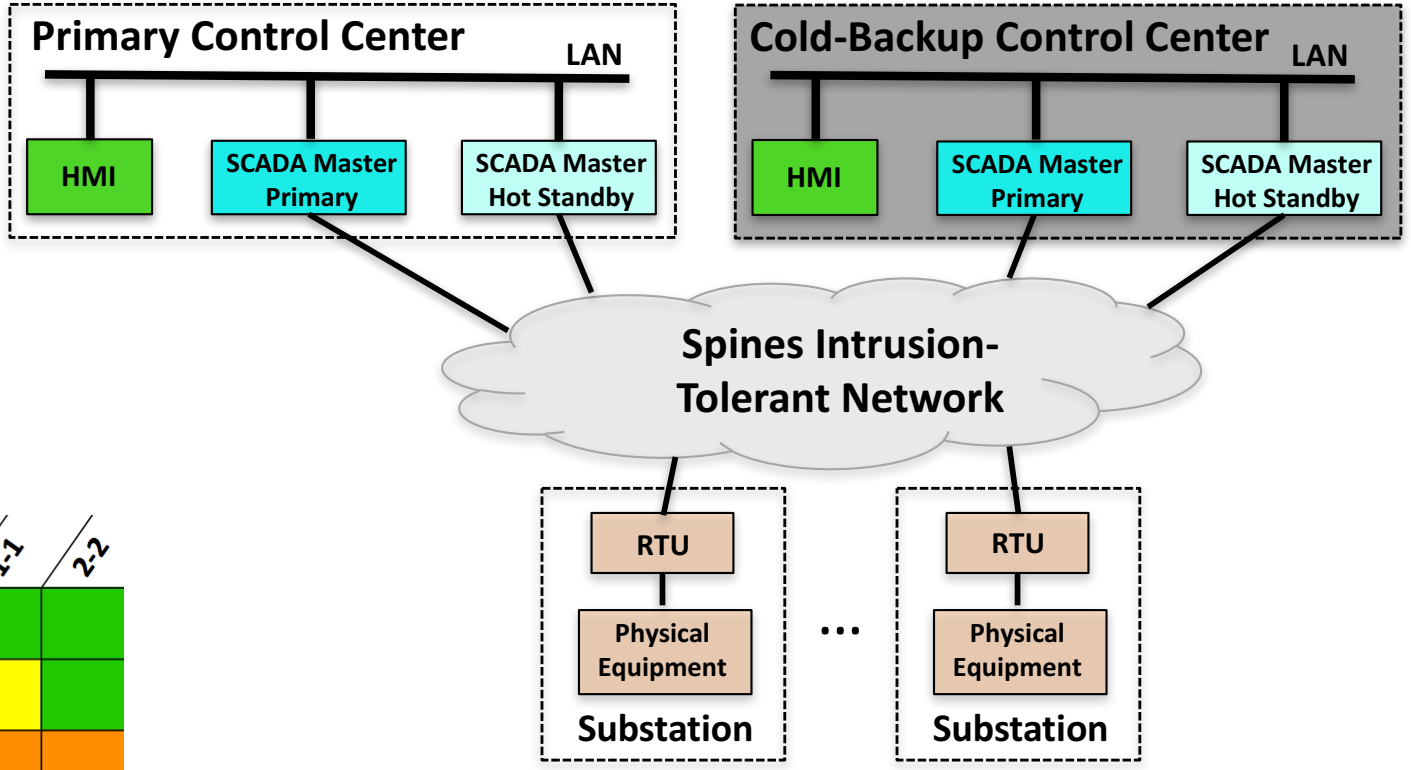


Beyond a Single Site

- To protect against sophisticated network attacks, Spire supports multiple control sites
- Since it is expensive to construct control sites, Spire is able to operate with two control sites plus additional sites that can be served by commodity data centers (that lack the ability to communicate with RTUs and PLCs in the field)

Current SCADA Systems

2-2



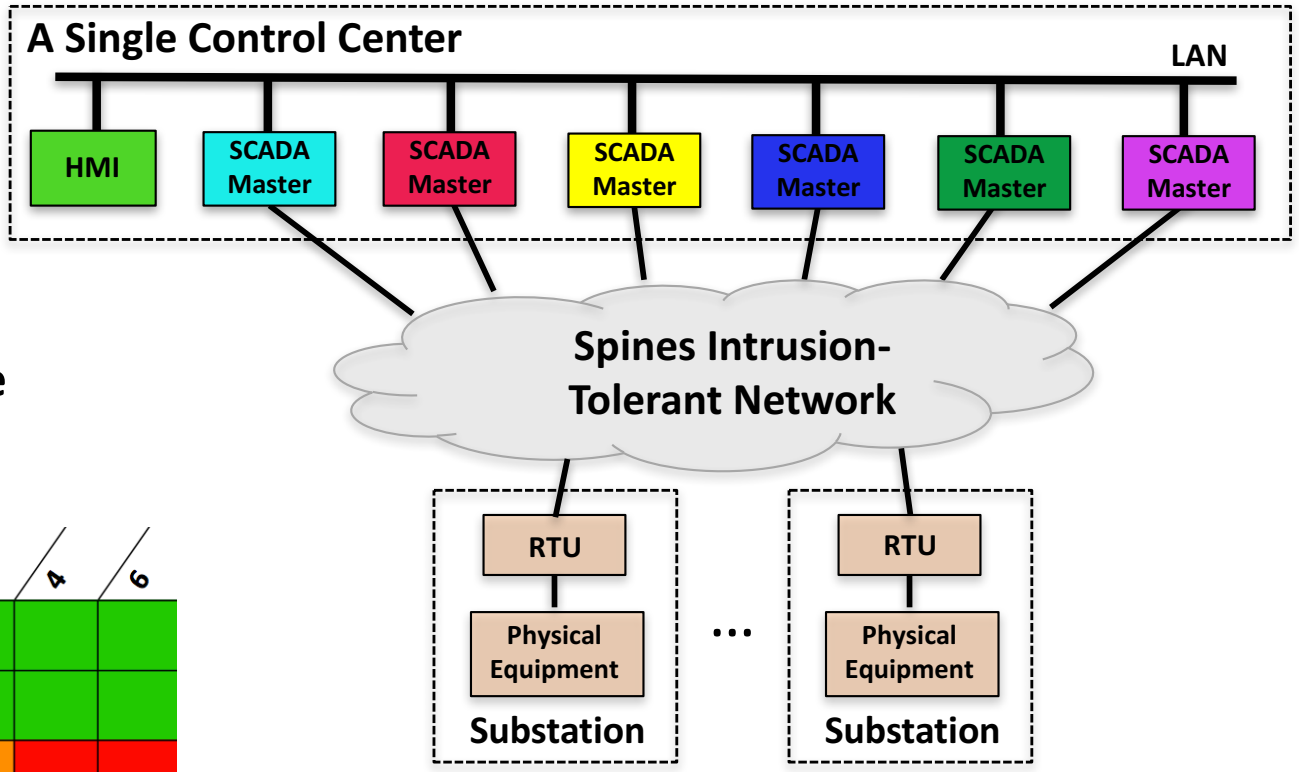
	1	2	1-1	2-2
All Correct				
Proactive Recovery (PR)				
Disconnected/Downed Site				
Disconnected/Downed Site + PR				
Intrusion				
Intrusion + PR				
Disconnected/Downed Site + Intrusion				
Disconnected/Downed Site + Intrusion + PR				

- 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**



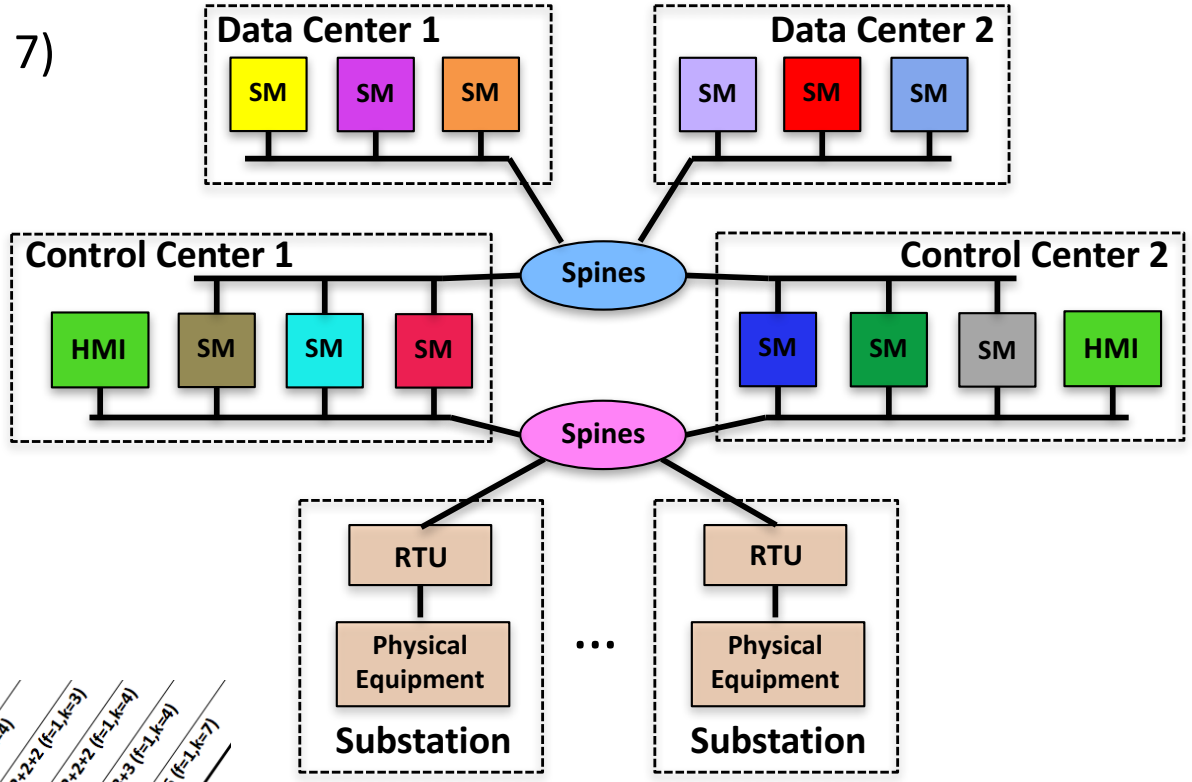
	1	2	1-1	2-2	4	6
All Correct						
Proactive Recovery (PR)						
Disconnected/Downed Site						
Disconnected/Downed Site + PR						
Intrusion						
Intrusion + PR						
Disconnected/Downed Site + Intrusion						
Disconnected/Downed Site + Intrusion + PR						

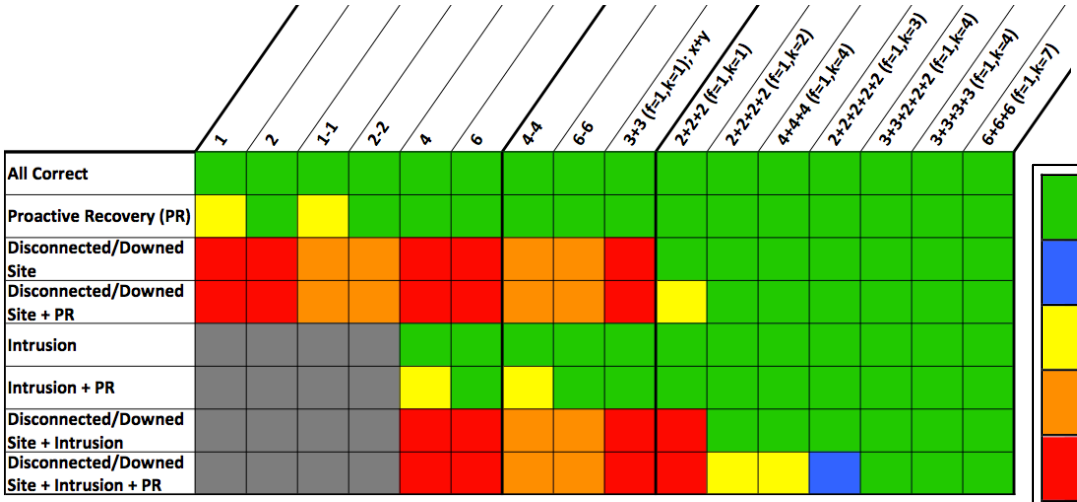
- Bounded Delay
- Bounded Delay, except when rejuvenating any correct replica
- Eventual Progress – Human in the loop. Potentially powering up cold backup control center
- Eventual Progress – No bound. Network has to heal, crash has to be repaired, and/or intrusion needs to be cleansed
- Incorrect System

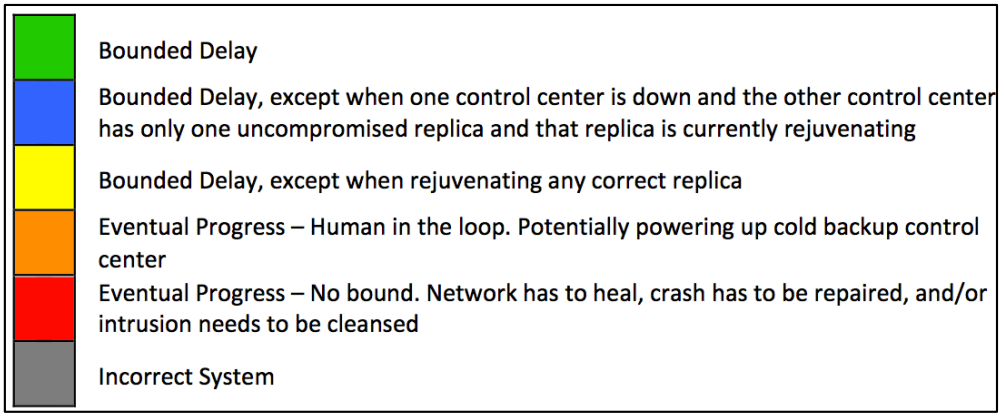
Novel Resilient Configurations (7/7)

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

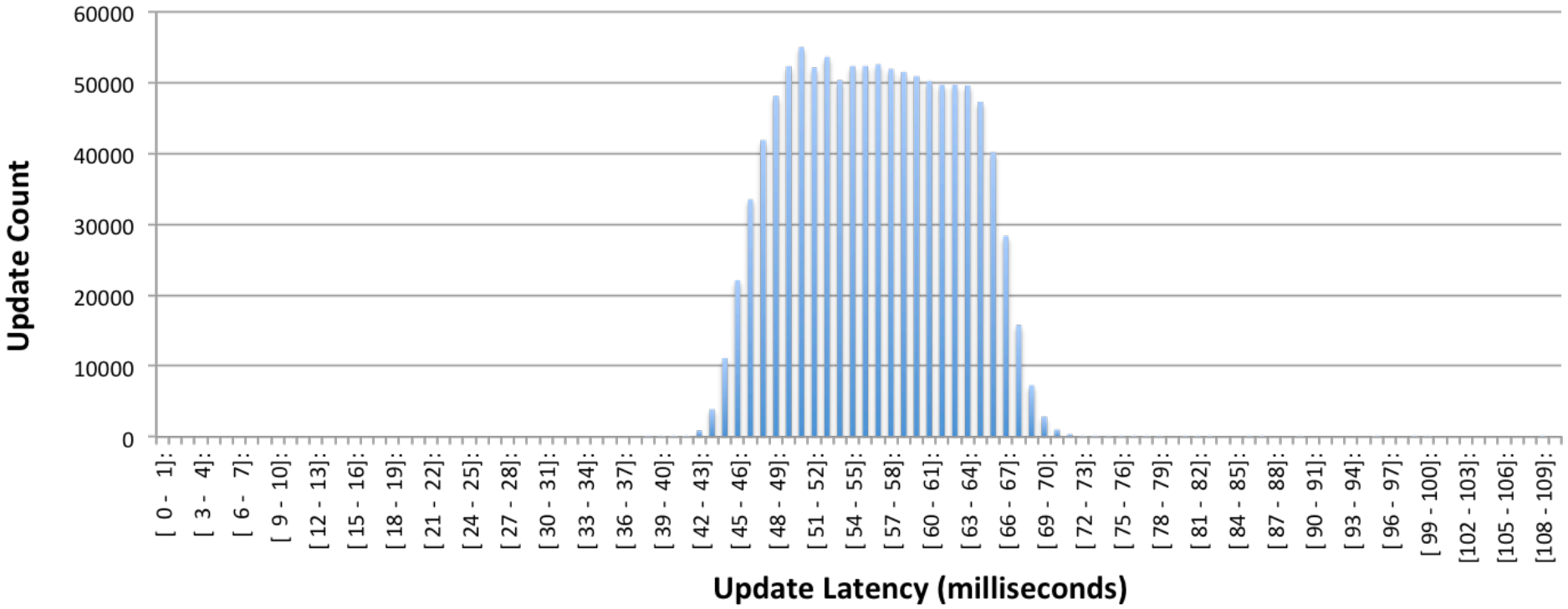
- **Complete solution for 4 total sites:** **(2 control centers, 2 data centers)**
- **Sweet-spot balancing the number of data center sites, the number of total replicas, and the communication overhead**







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

JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

Distributed Systems
and Networks Lab