Towards a Resilient US Power Grid

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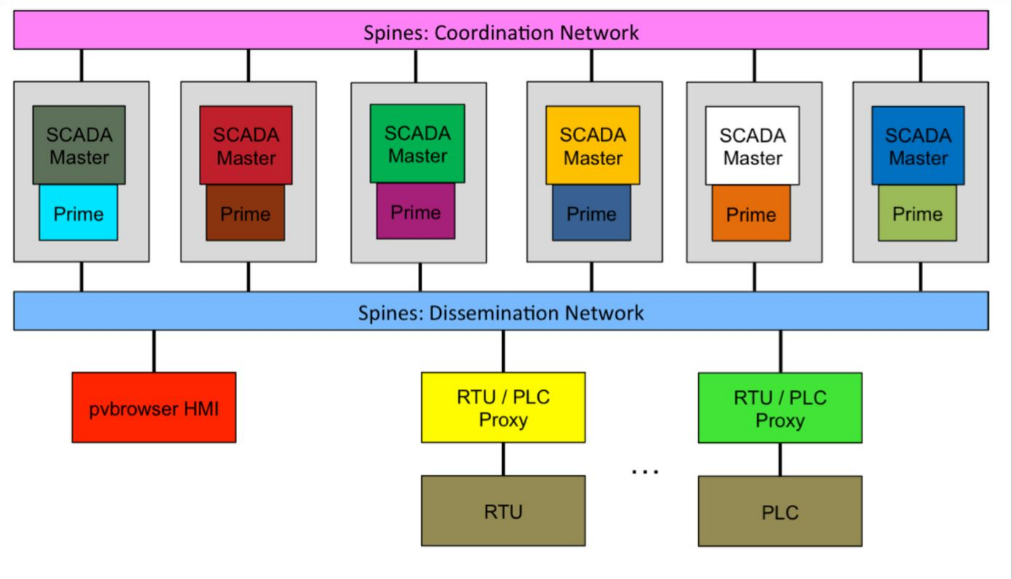
The goal of our project is to find errors in Spire's protocol that can be exploited by an attacker to cause a fatal slowdown or a total system failure.

The Spire System

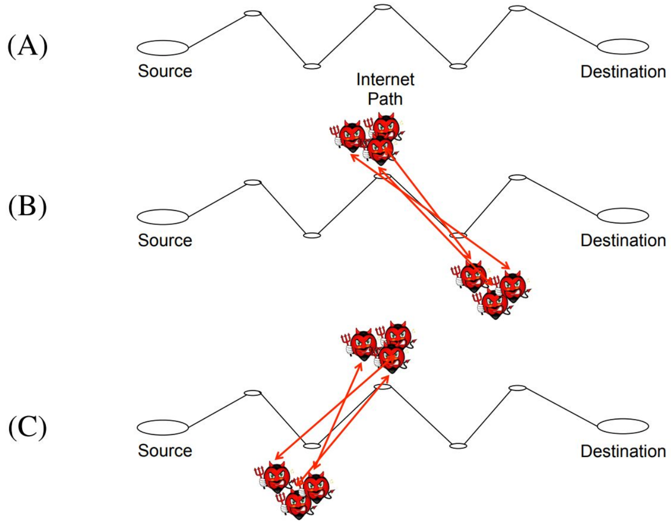
The goal of Spire is to create an intrusion-tolerant, reliable system to operate the power grid that is exposed to the open internet.



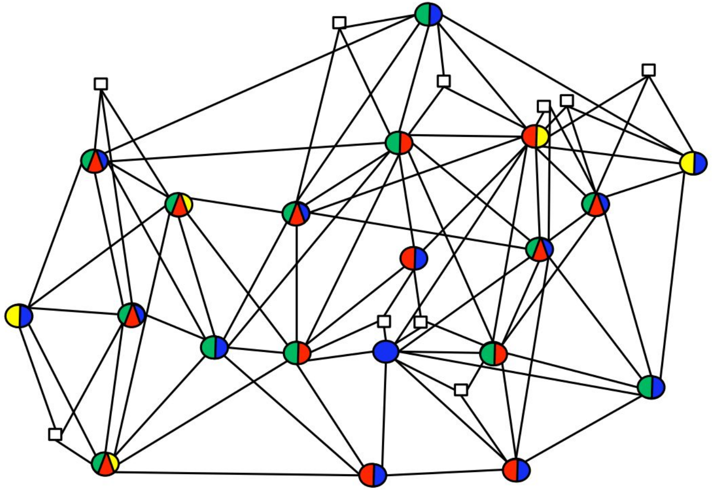
Spines

An Intrusion Tolerant Network

Conventional Infrastructure



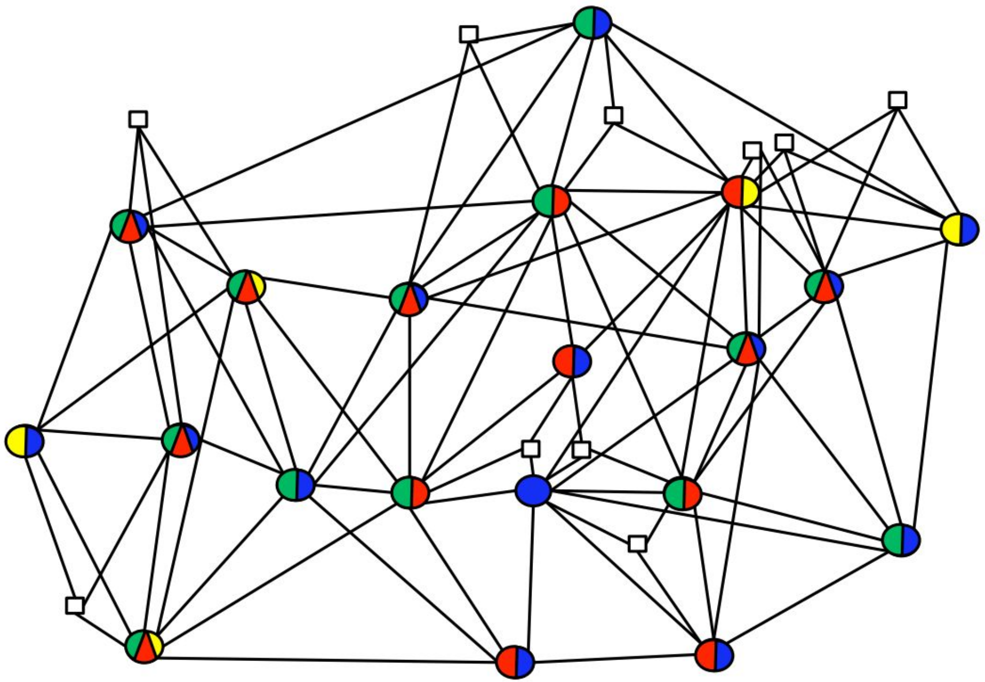
- Overlay network built on top of existing IP infrastructure
  - Multi-homing



Spines

An Intrusion Tolerant Network

- Intrusion Tolerance
  - Fairness Principle
  - Flooding



Prime

How to Create a Reliable System?

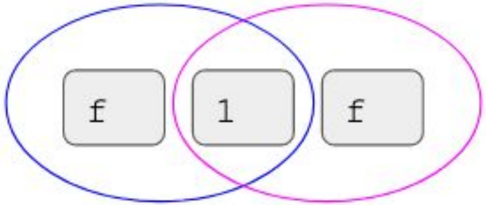
- Problems to Solve:
    - What happens if our server goes down?
    - What happens if our server is compromised by an attacker?

The Answer: REDUNDANCY

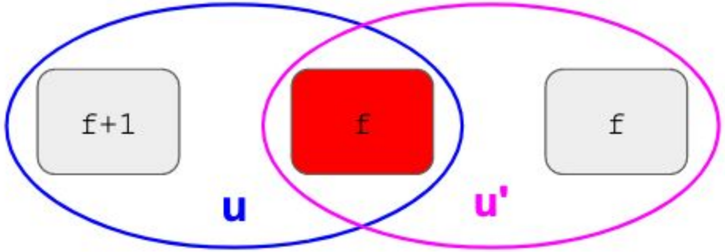
Prime

How many replicas do we need?

- Fail Stop Failure
    - A replica becomes completely unresponsive
- Handling Fail Stop Failure: $N \geq 2f + 1$



- Byzantine Failure
    - A replica responds in any unexpected way
    - Harder to account for in a system
- Handling Byzantine Failure: $N \geq 3f + 1$



Prime

Consensus Algorithms

- We seek 3 things:
  - 1) Termination
  - 2) Integrity
  - 3) Agreement
- Prime guarantees that we achieve these properties in a timely manner.
  - Older protocols did not enforce a timeliness condition

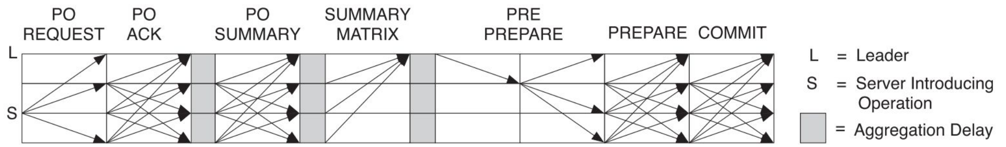


Fig. 3. Operation of Prime with a malicious leader that performs well enough to avoid being replaced ($f = 1$).

Prime: Deep Dive

3 Things:

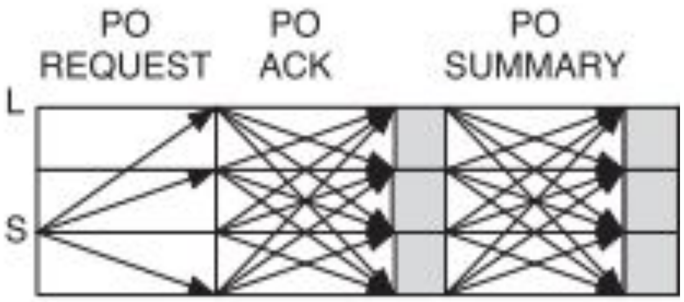
Integrity

Agreement

Termination

Prime Protocol: Pre-Ordering

- Pre-Order Requests: Servers send their client updates to all other servers with a unique sequence number.
- Acknowledgement: Servers acknowledge that they have received a pre-order requests.
- Summary: Servers send summaries of their believed current state of the system.



Prime Protocol: Suspect Leader

- Timeliness of Agreement
- Leader leads the ordering process
- Slow leader = slow execution
- Turnaround Time
  - RTT PING
- A leader is replaced if it is significantly slower than the average replica.

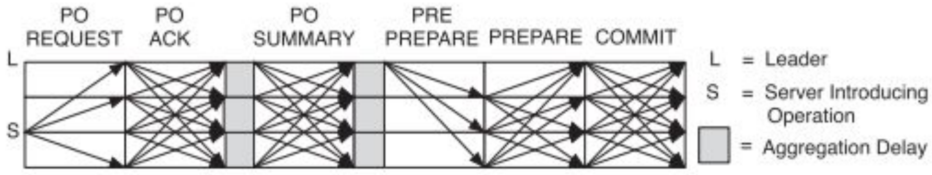
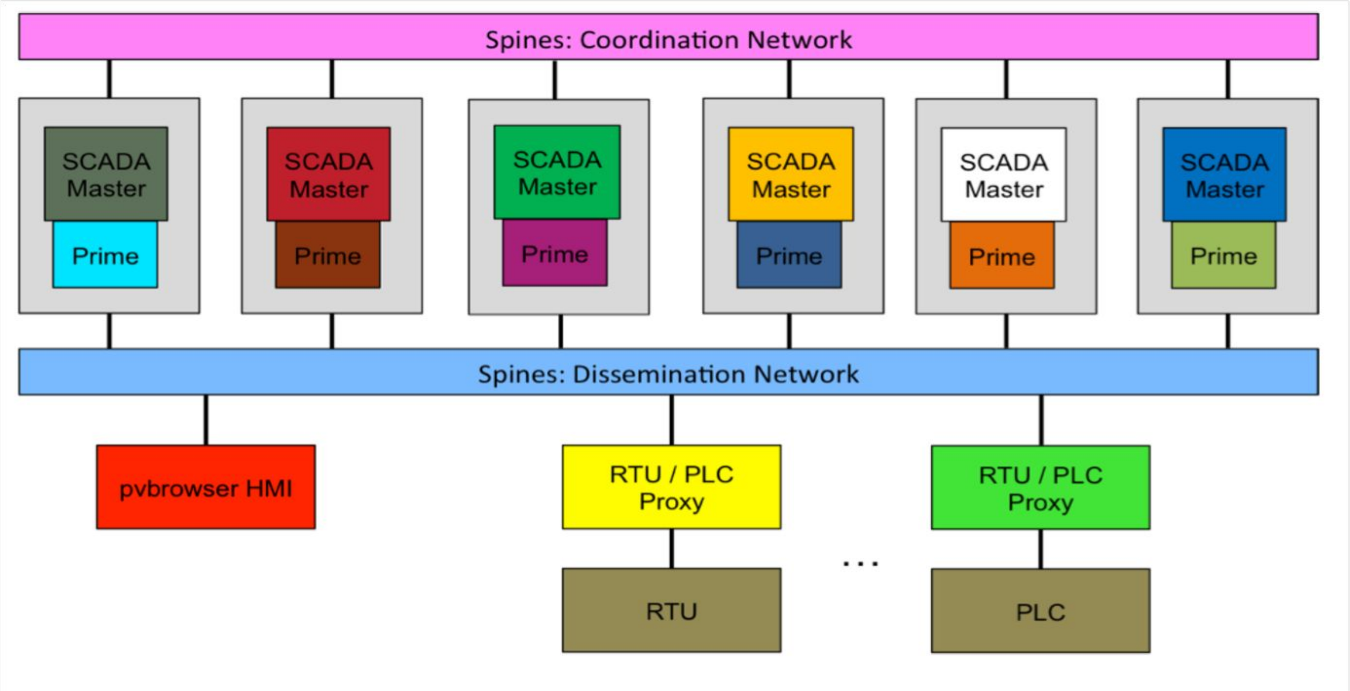


Fig. 2. Fault-free operation of Prime ($f = 1$).

Our Test Bed Environment



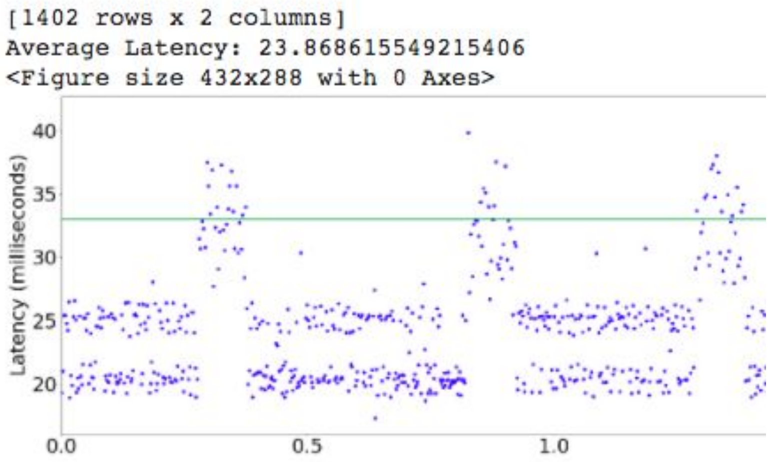
Planning Our Attacks

- Attack Types
  - Internal vs. External
  - Failstop vs. Byzantine
- Combine strategies!
- Measuring Results
  - Latency
  - Resource levels
  - Number of leader changes

RTT Ping DoS Attack

Our Motivation

- Replay packet spam attack showed regular latency spikes
- Isolate and spam that message



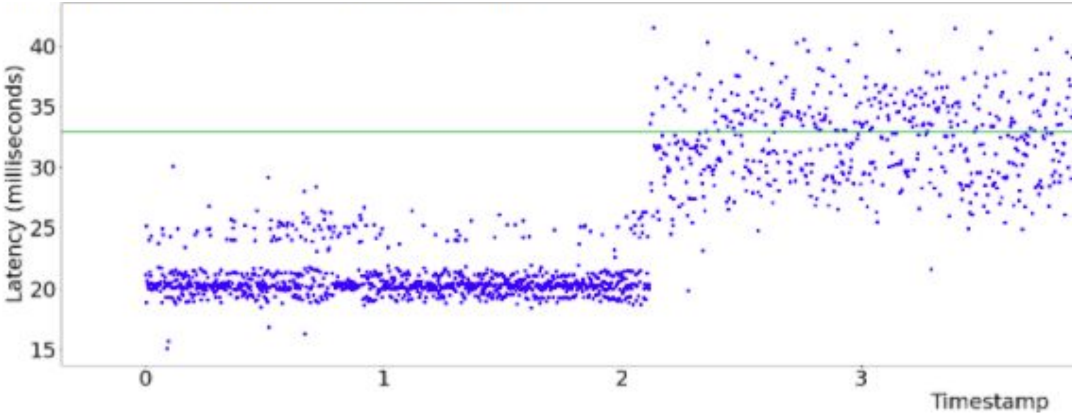
Time (seconds) vs. Latency (ms) for Prime Replay DoS Attack using Prime Client

The Approach

- The culprit: RTT_PING packet type
- Wait until faulty replica generated a RTT_PING packet
- Save packet, send packet to every server repeatedly

Results

- Regularly raised latency above target
- Attack limited by Spines network timeliness protocol



Time (sec) vs. Latency (ms) during RTT_PING Attack using Prime Client

Average Latency: 31.8 ms
10th Lowest (During Attack): 23.9 ms
10th Highest (During Attack): 40.7 ms

Follow The Leader Attack

Prime Suspect Leader Protocol

- The suspect leader sub protocol is incorporated into the prime system to mitigate leader attacks.
- Allows replicas to measure turnaround time of the leader.
  - If leader_tat > accepted_tat, then that leader is suspicious
- Non leaders can reach a consensus to remove a leader.

Our Approach

- Target each current leader with excessive messages using a compromised replica
- Cause a delayed round trip time which will force the leader to be changed
- Cause each leader to be changed to the next leader quickly

Causing a Single Leader Change

- Modifications to Faulty Prime from a RTT Ping DOS attack to targeting a single leader

```
while (1) {
        UTIL_Broadcast(mess);
}
```

→

```
for  (i = 0; i < 1000000; i++) {
        UTIL_Send_To_Server(mess, 1);
}
```

Choosing the Messages

- Most efficient is sending RTT_Ping
  - Why? Leader replies to rtt ping
- We send other messages to non leader replicas
  - we broadcast all messages, other than ping (ie act normally for any other message we handle)

Targeting any Leader to Cause Repeated Changes

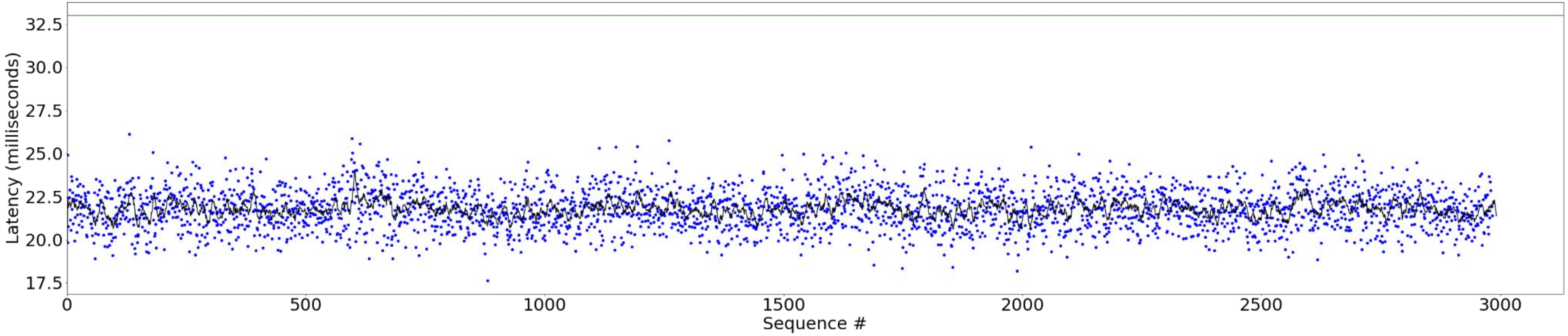
- Target the current leader using the current view
  - (View - 1)Mod6 + 1
- Ping the leader repeatedly while broadcasting all other messages (normal behavior)
- Successful at targeting the current leader while the current view is up to date

Too Many Pongs

- Every Ping will result in a Pong
  - Too many pongs to process
  - View is not updated efficiently, can’t keep track of current leader
- Filter out all message types other than New Leader Proof, New Leader, and Ping Messages when in normal state
  - Pings are used to spam
  - New Leader messages update the view

SPIRE System Baseline

Average Latency (ms): 21.78
Latencies above 33 ms: 0.00%
Latencies above 100 ms: 0.00%

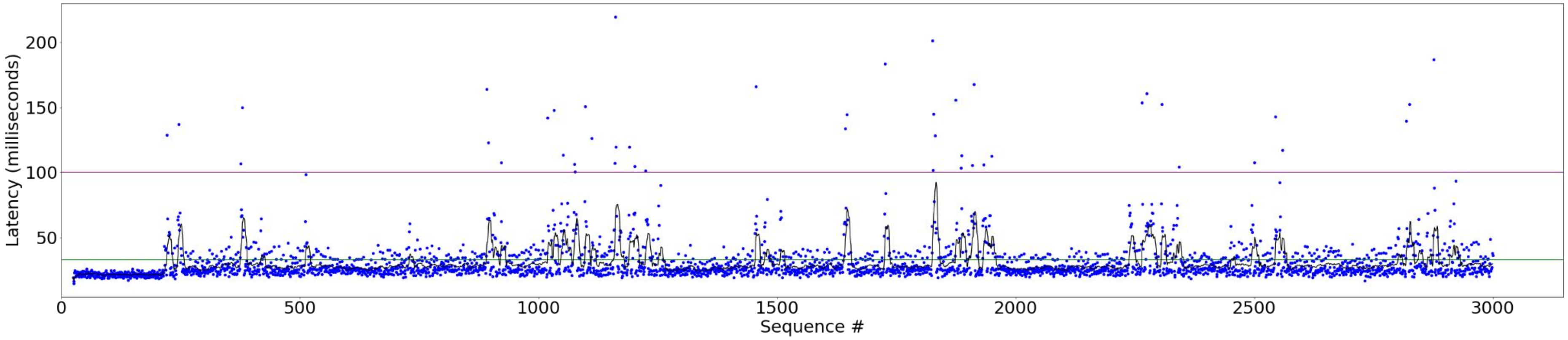


Demo Time!

Follow the Leader - 100% current

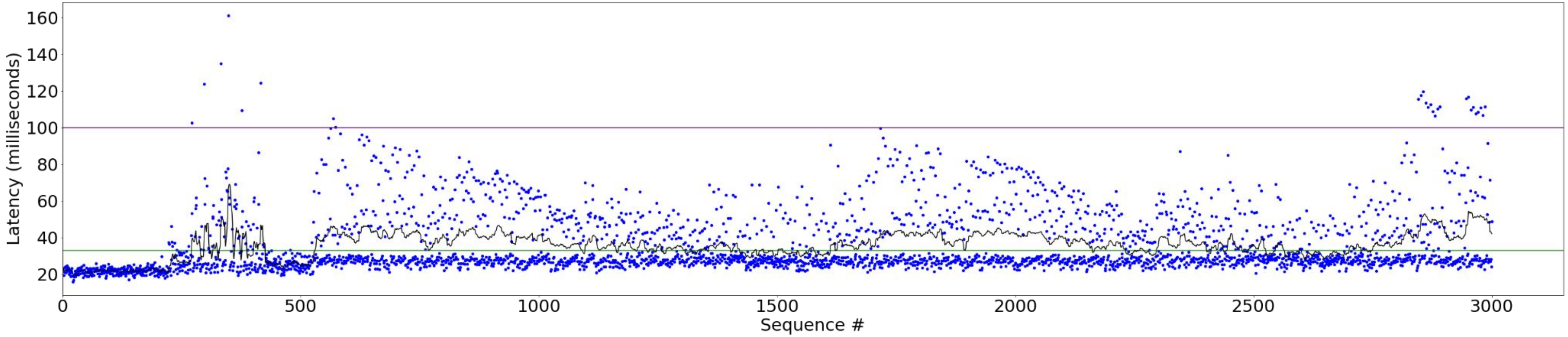
- This is the attack we just demonstrated!

Average Latency (ms):	31.97
Latencies above 33 ms:	25.63%
Latencies above 100 ms:	1.50%



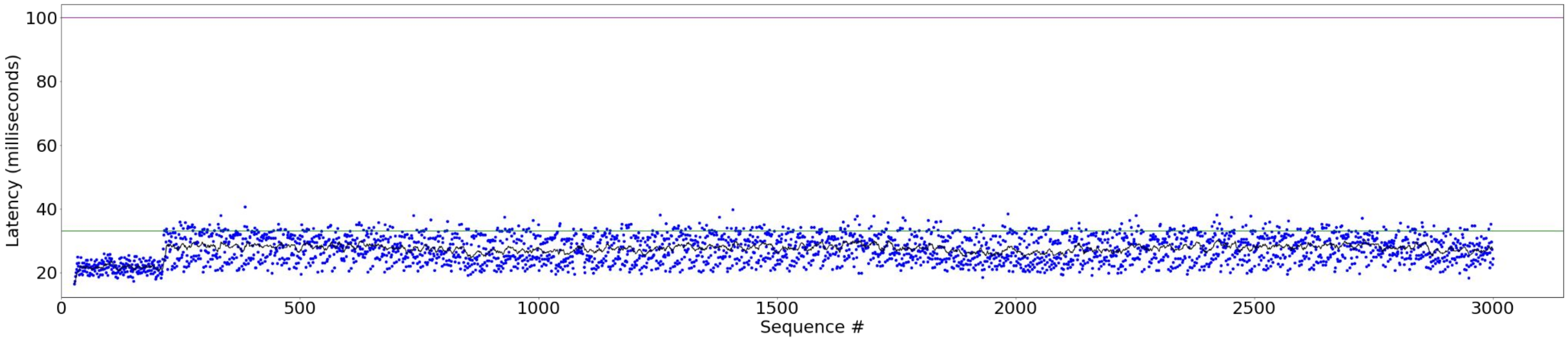
Follow the Leader + Scada1 in Proactive Recovery

Average Latency (ms):	37.62
Latencies above 33 ms:	33.06%
Latencies above 100 ms:	0.90%



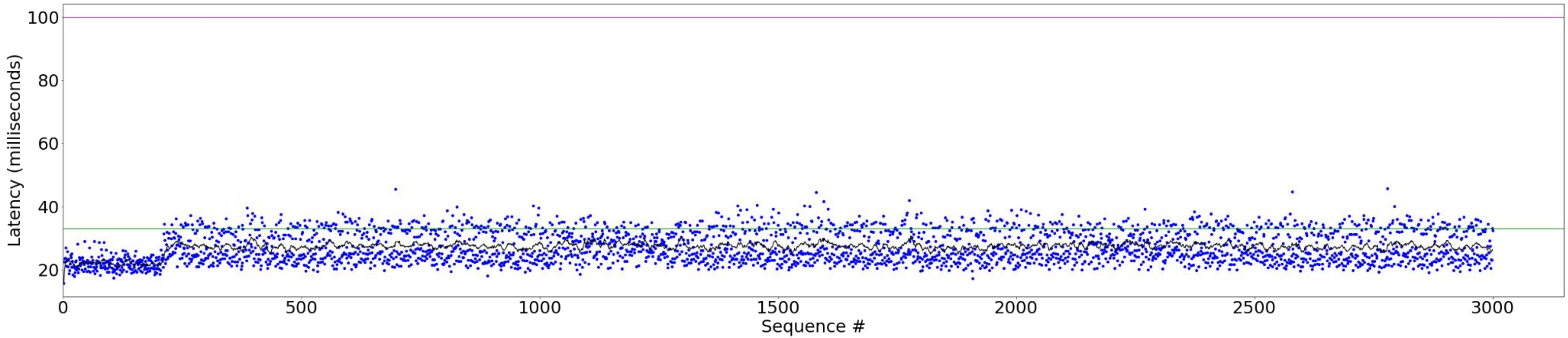
Follow the Leader - 50% current, 50% next

Average Latency (ms):	27.70
Latencies above 33 ms:	10.37%
Latencies above 100 ms:	0.00%



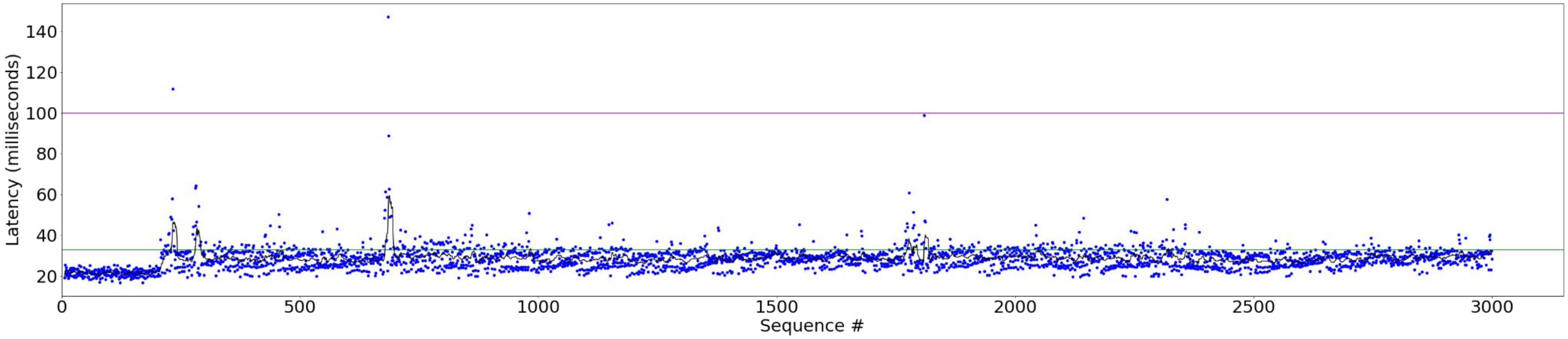
Follow the Leader - 75% current, 25% next

Average Latency (ms):	27.49
Latencies above 33 ms:	16.80%
Latencies above 100 ms:	0.00%



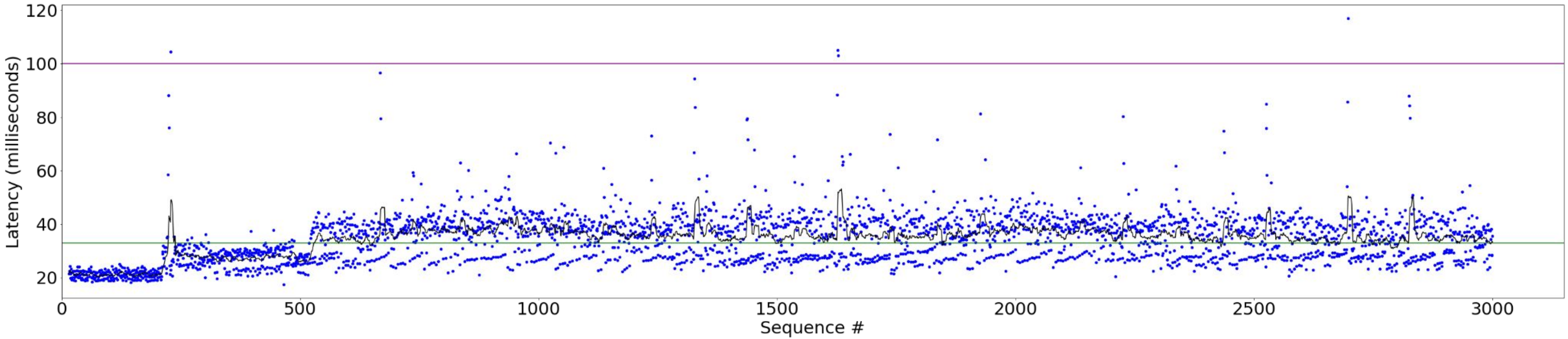
Follow the Leader - 90% current, 10% next

Average Latency (ms):	29.07
Latencies above 33 ms:	12.60%
Latencies above 100 ms:	0.07%



Follow the Leader - 90%/10% + Scada1 in Proactive Recovery

Average Latency (ms):	36.44
Latencies above 33 ms:	54.87%
Latencies above 100 ms:	0.13%

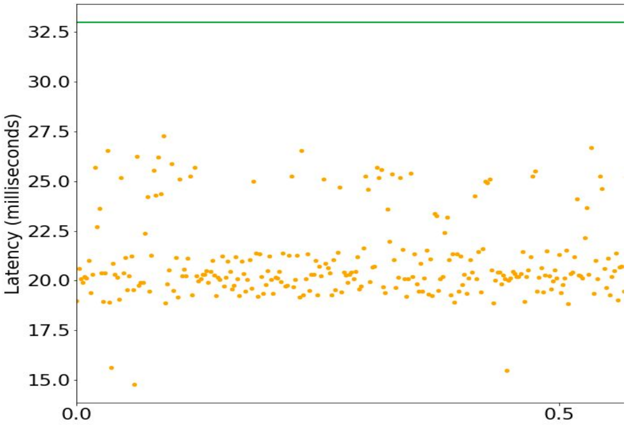


Questions?

Pre-Order Memory Consumption Attack

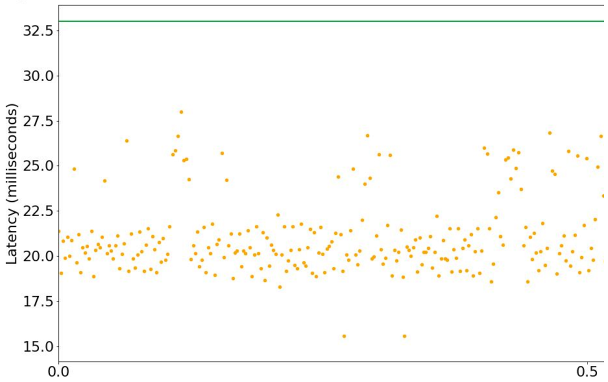
Previous Sequence Number Attacks

Improper Sequence Number Update



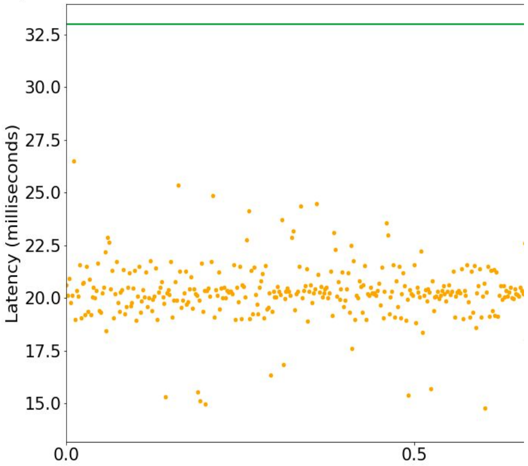
Average Latency: 21.1036558908

No Sequence Number Update



Average Latency: 20.8574664536

Spam 10,000 / message



Average Latency: 20.24648035190615

The BACKGROUND

- The key is **INTEGRITY.**
- Every replica must save update information until it is executed
- All updates must be executed in order
- A replica can only flush old updates once they have been executed

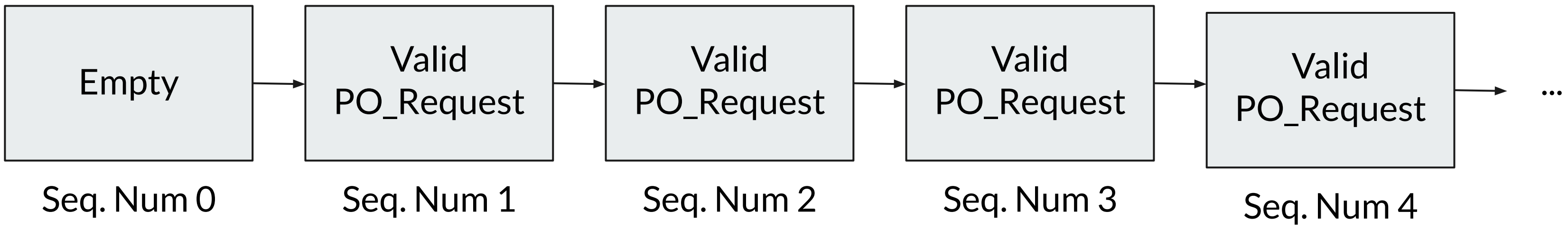
```
a = 0
a = 5
a += 1
```

VS.

```
a = 0
a += 1
a = 5
```

The Attack

- Skip a sequence number, lengthen data structure to eat up RAM
- Generate valid PO_Requests and send to all replicas
- Assure we always have a client update to order



Demo Time!

Problems We Faced

- Assure list of updates does not grow infinitely and consume memory
- We store our own PO_Requests, would also eat our memory
- Work around catch up protocol
- Implementation Bugs

Results

- With Spam, **16GB of RAM** is consumed in **under 15 minutes**
- Spam and no-spam variants
  - Spam variant works quickly, can be detected
  - No-spam variant works more slowly, goes undetected by IDS
- Non-spam attack variant goes undetected by NIDS
- Once RAM limit is reached, replicas become increasingly unresponsive
- Implementation bugs

Questions?

Future Steps

- PO Request Attack
    - Increase Reliability
    - Test with Intrusion Detection System
- Follow the Leader Attack
    - Control Leader while in Proactive Recovery

Mitigation

- Memory Attack: Bound the memory that one server can consume on another server
  - Bounded queue of updates
- Follow the Leader Attack:
  - Rate Limiting

Thank You!

Yair Amir
Sahiti Bommareddy
Daniel Qian
Jerry Chen
And, the rest of the SFRC class

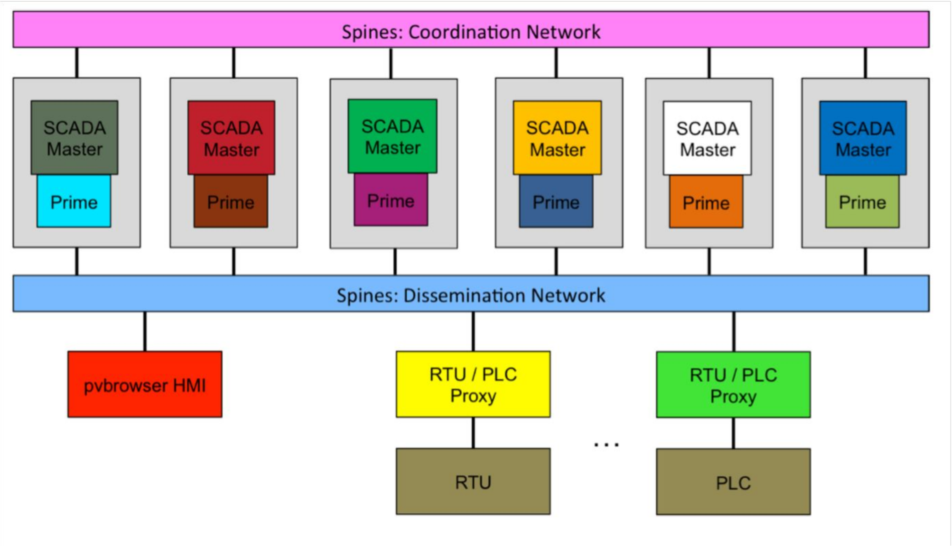
Questions?

(Conclusion) … So were we successful?

TL;DR - The Spire System

- Spines creates an intrusion-tolerant reliable network that isn't vulnerable to conventional network attacks (DOS, MITM, BGP Hijacking)

- Prime ensures that our distributed system maintains correctness while executing commands in a timely manner.



Follow the Leader - 50% current, 50% next (a closer look)