# Virtual Time Consistency in Smart Grid Test-beds

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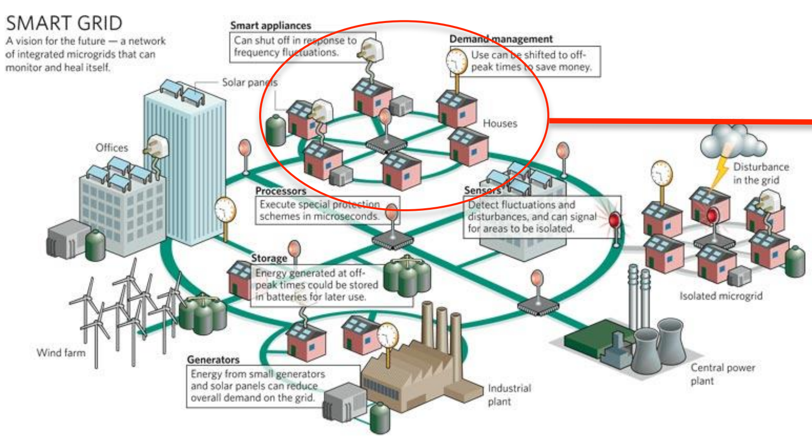
# What purpose for a Test-bed?

Create a model of a physical system that

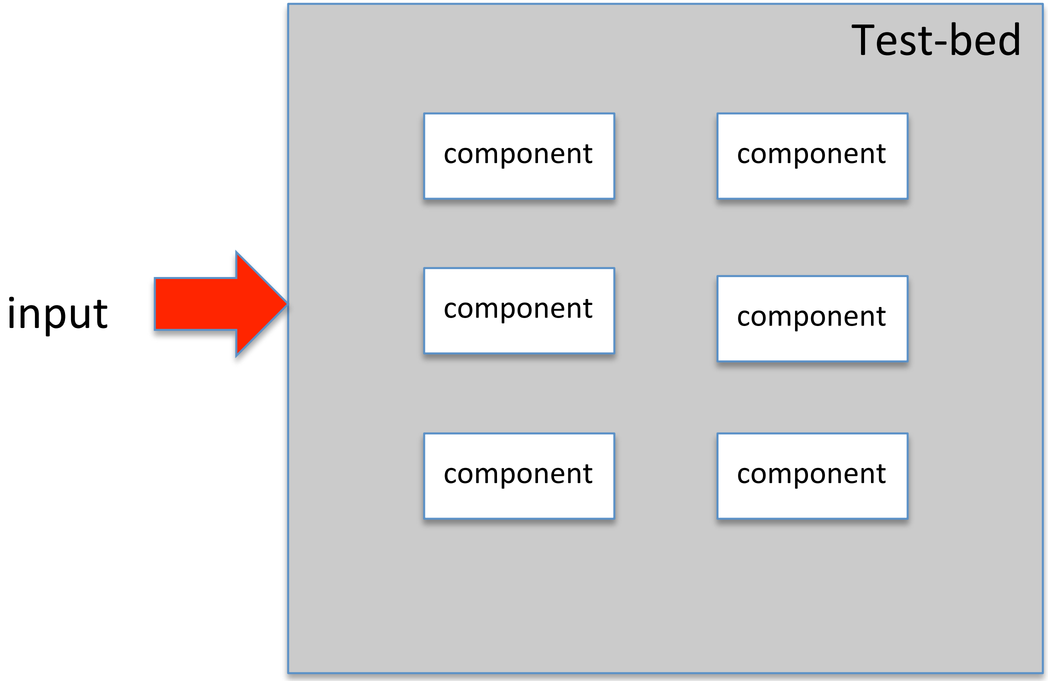
- Captures salient features of interest
- Can be observed through controlled presentation of inputs or boundary conditions




# Test-bed Behavior

We want the test-bed to "act like" the system it models

- Present some input



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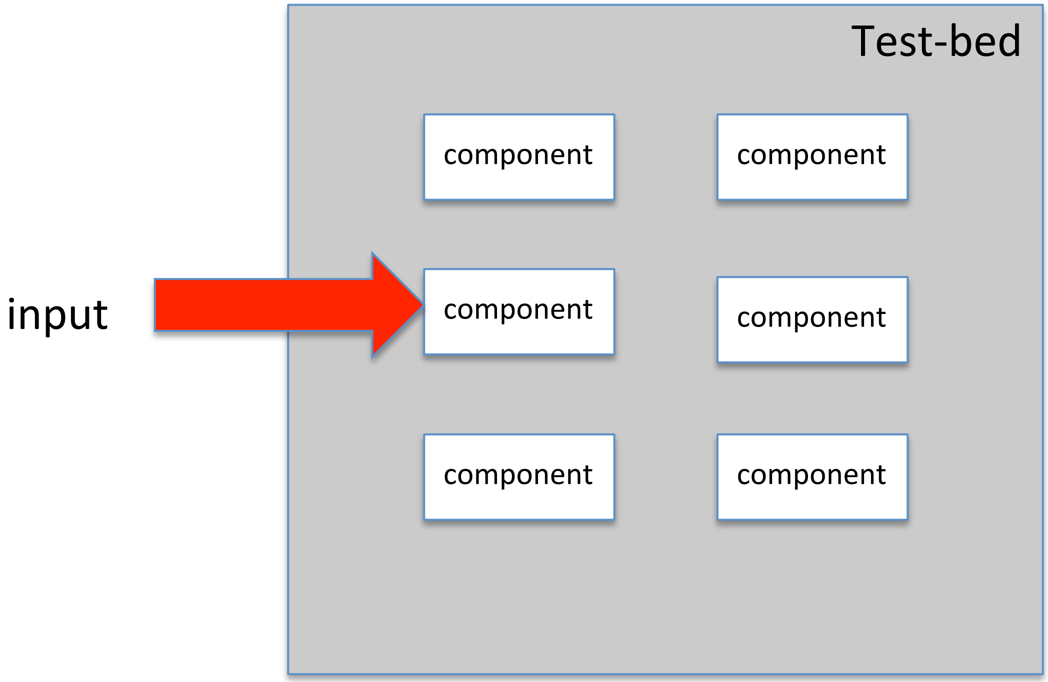
- Input presented to some test-bed component



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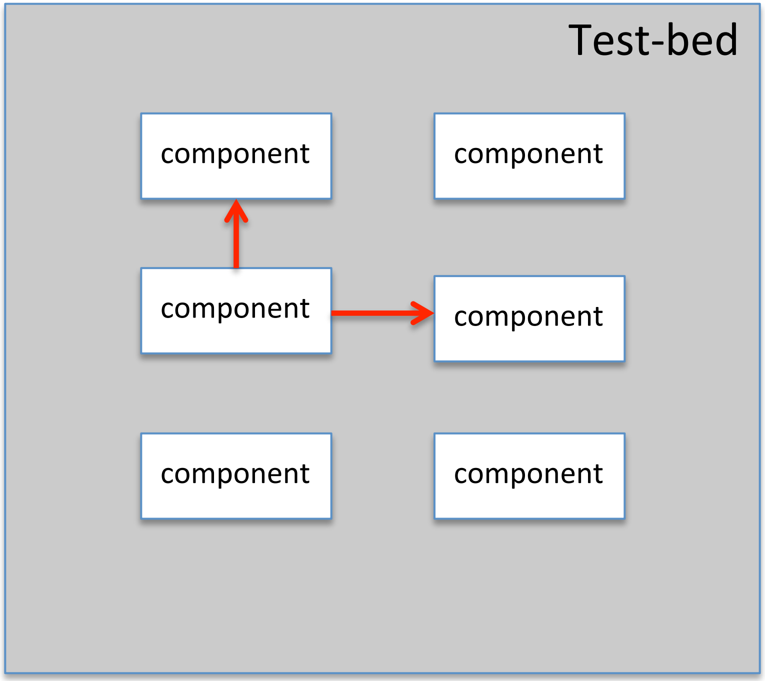
- Initiates some sequence of actions and inputs/ outputs



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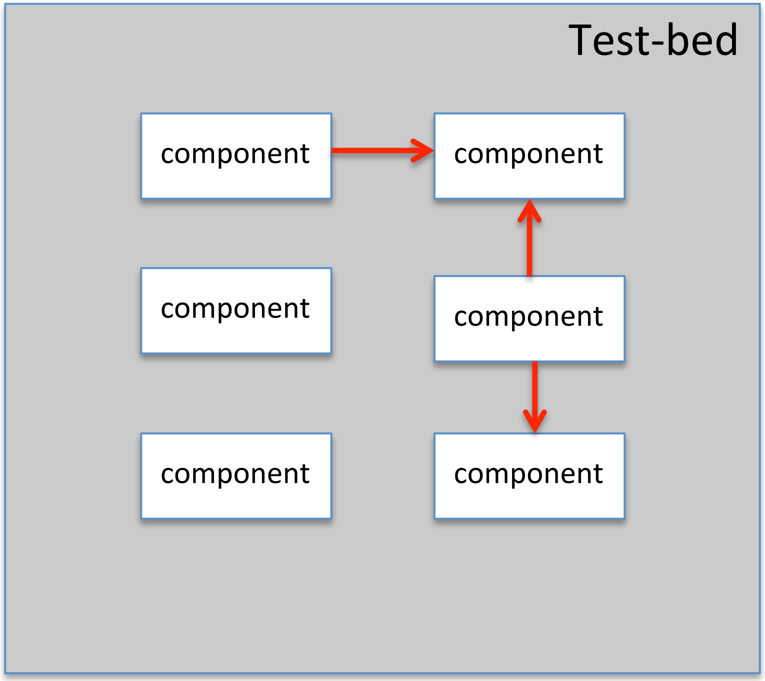

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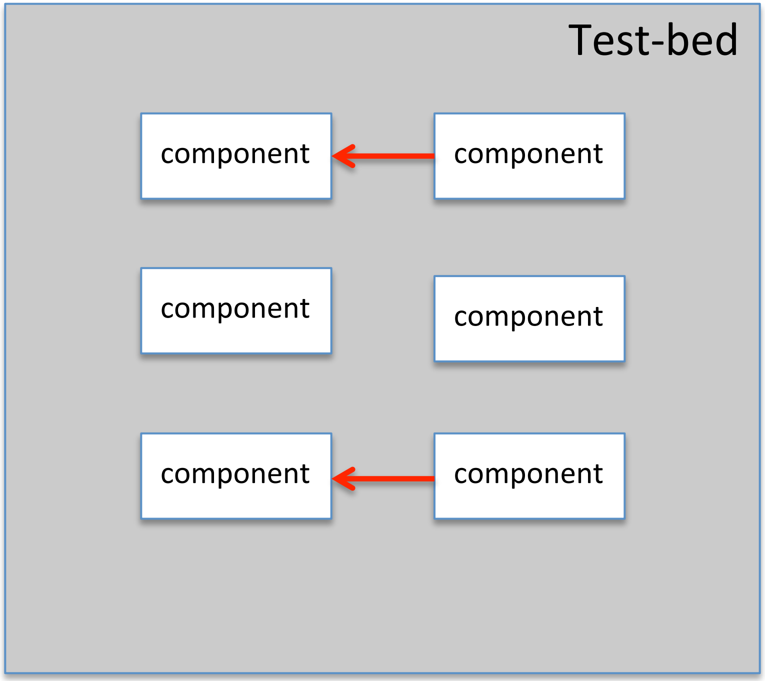

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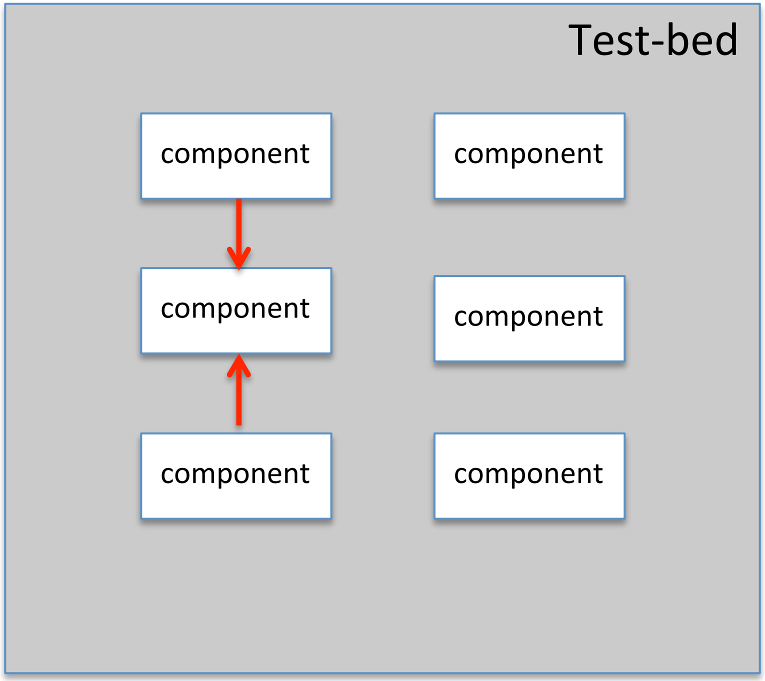

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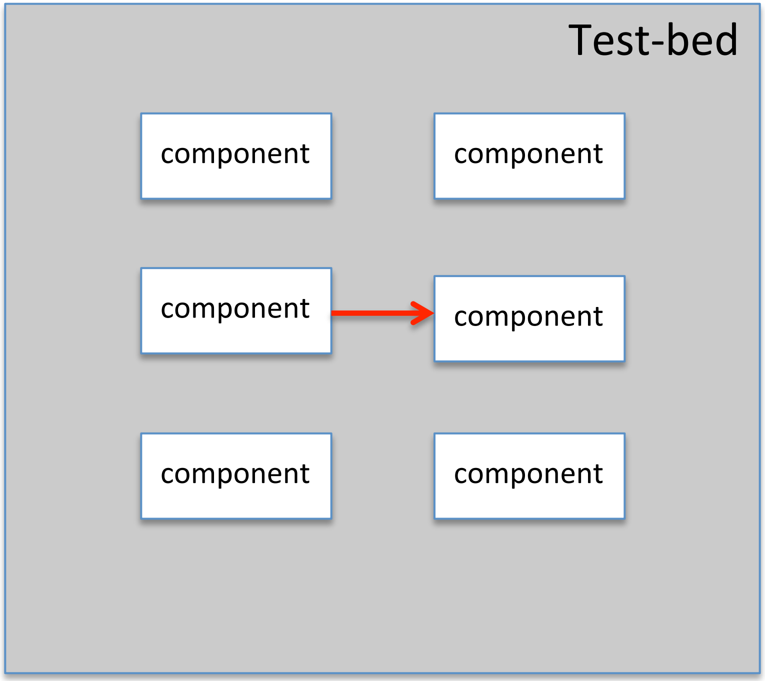

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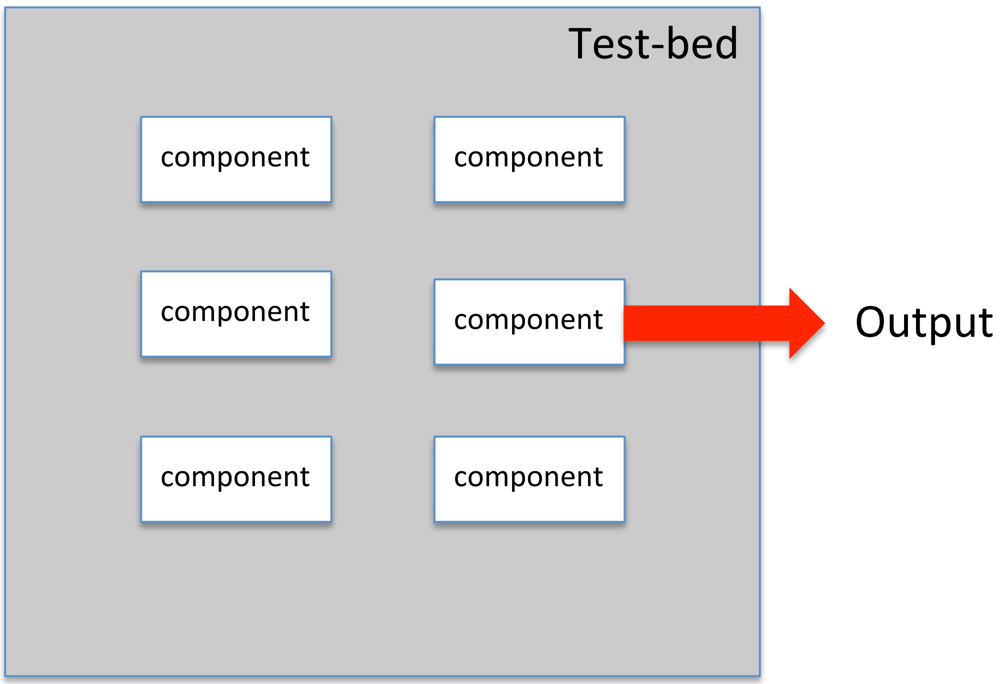


One wants the components to interact in the same way, with the same input/outputs, as in the field, to get the same output

# Test-bed Behavior

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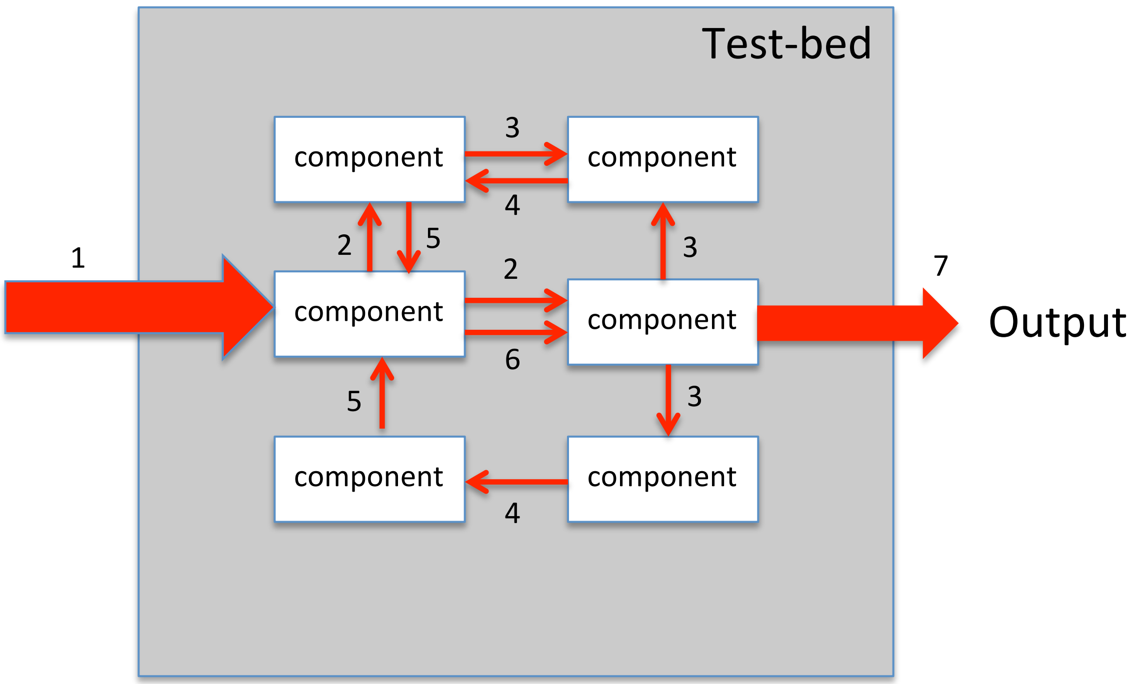


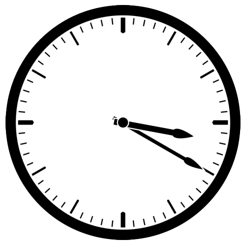

As in the field, sequencing in the test-bed is governed by real-time delays

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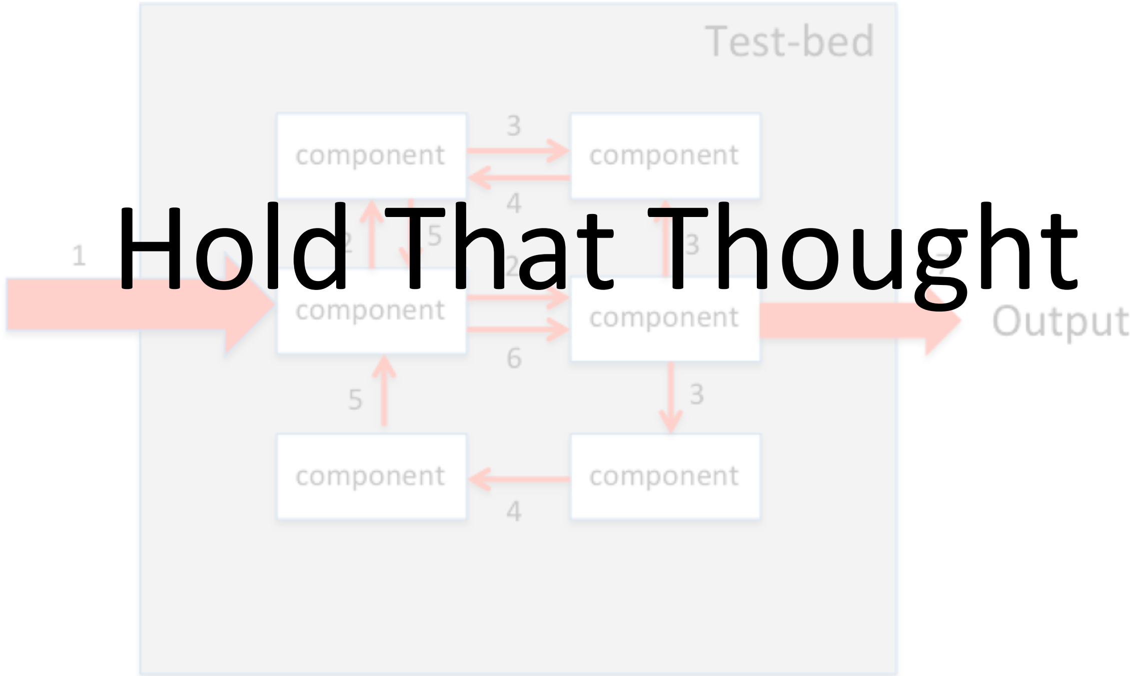


Hold That Thought



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# Our View of a Smart Grid Test-bed

**Devices**

- Meters, relays, PMUs, data aggregators, adaptive multi-channel source, etc.

**Software**

- Control station, data historian, authentication servers, etc.

**Power System Simulators**

- Hardware assisted (e.g., RTDS, Opal-RT)
- Software only, PowerWorld, GridLab-D, OpenDSS, PSAT, etc.

**Device Emulation**

- Xen, QEMU, LXC

**Network Emulation**

- Emulab, CORE, Deter

**Device/Network Simulation**

- ns-3, S3F, OmNet++, etc.

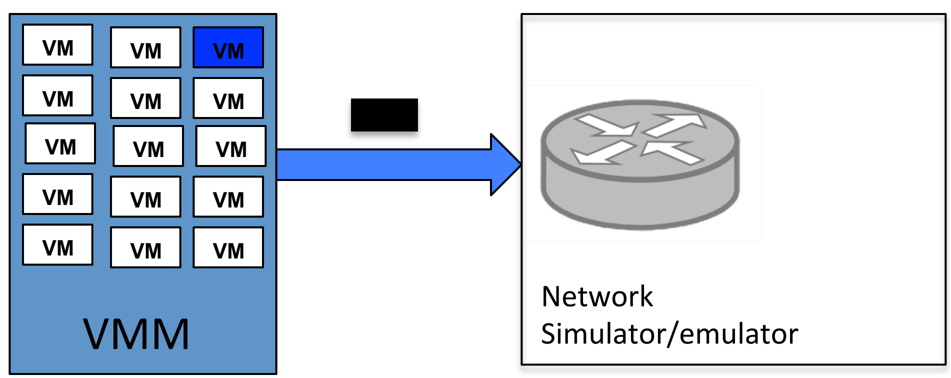
# Keeping it all coordinated…

*Time* matters a lot

Normal emulation execution is *best effort*

Suppose in the modeled system 3 devices all send messages to the same router *at the same time*

- The VMM sends them when it gets around to it…

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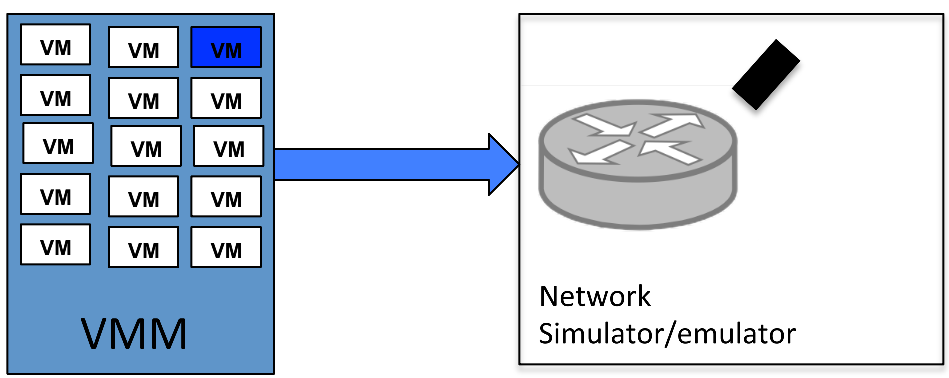


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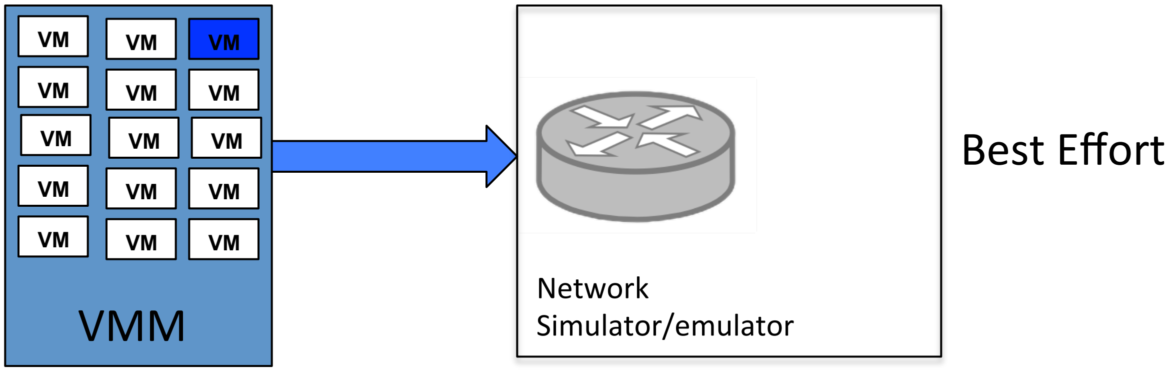

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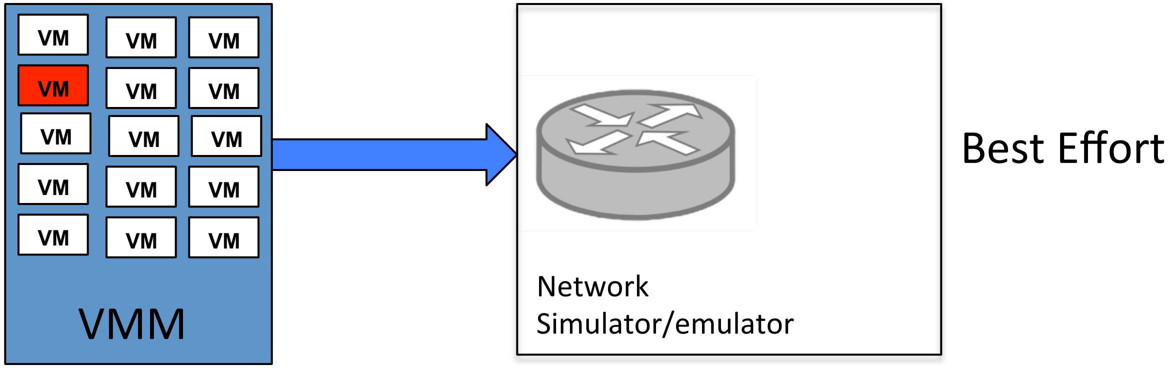

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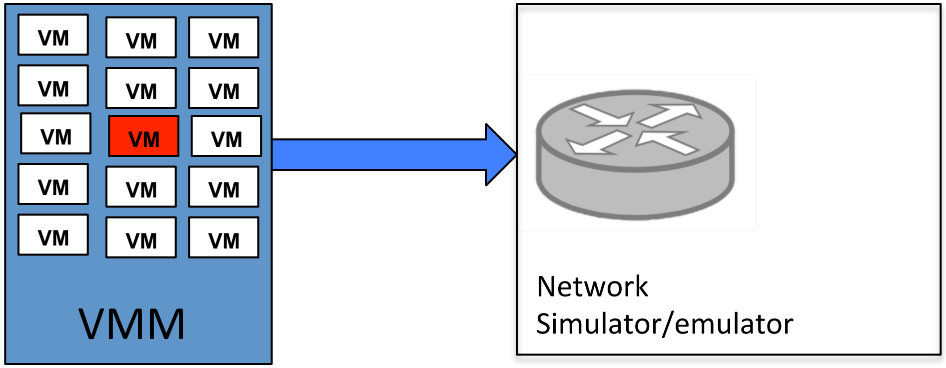


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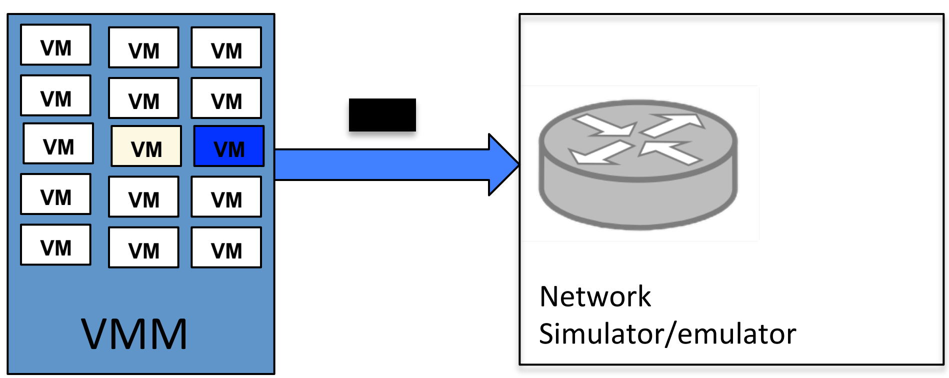


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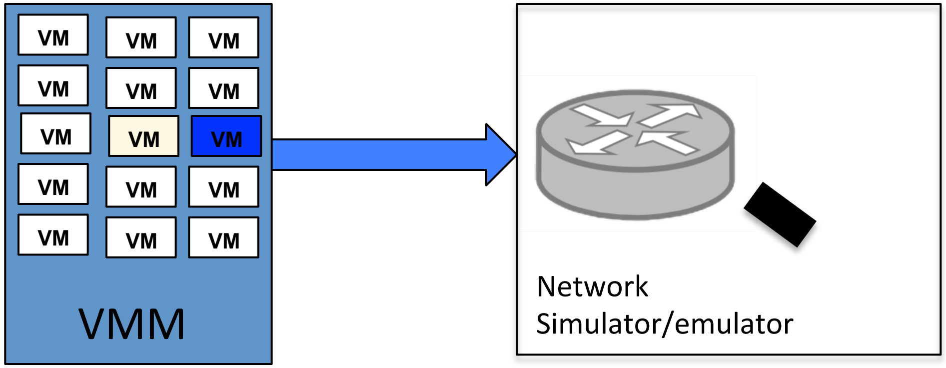


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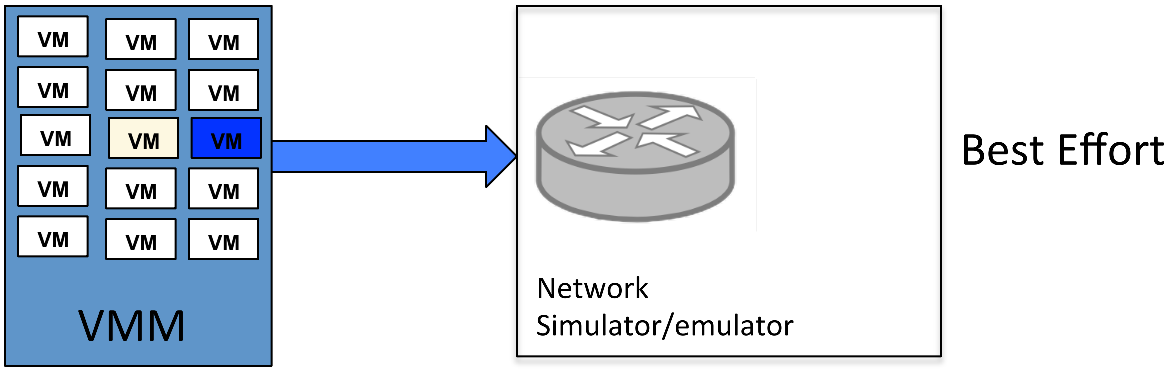

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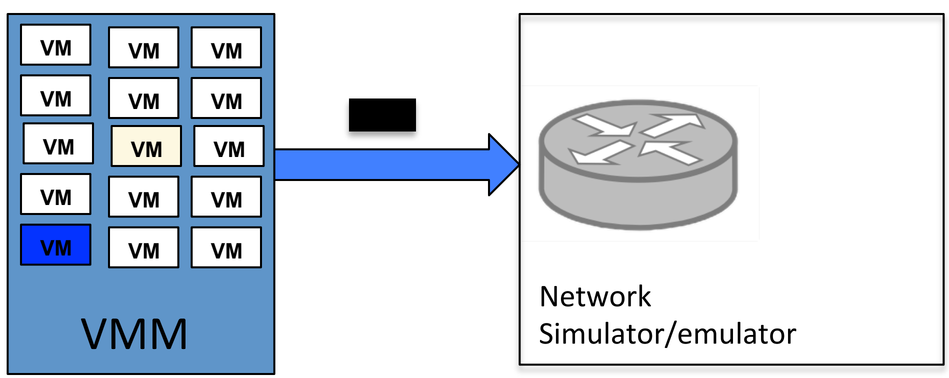


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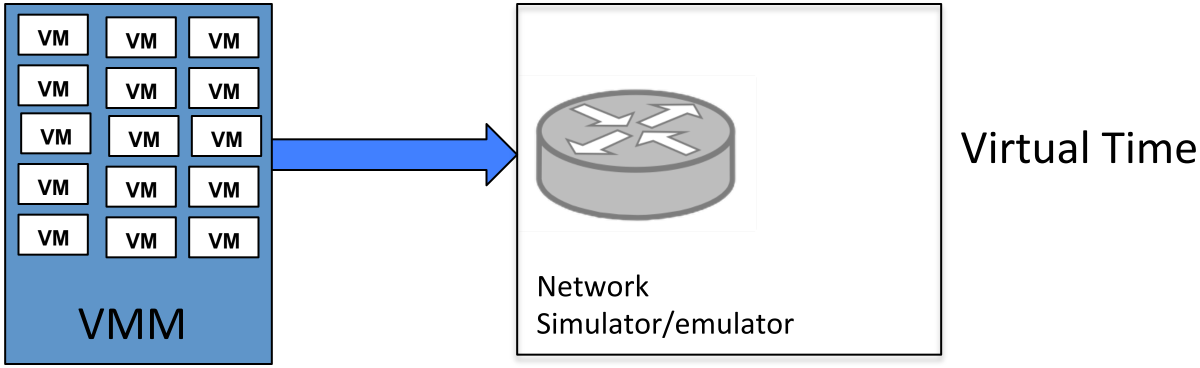

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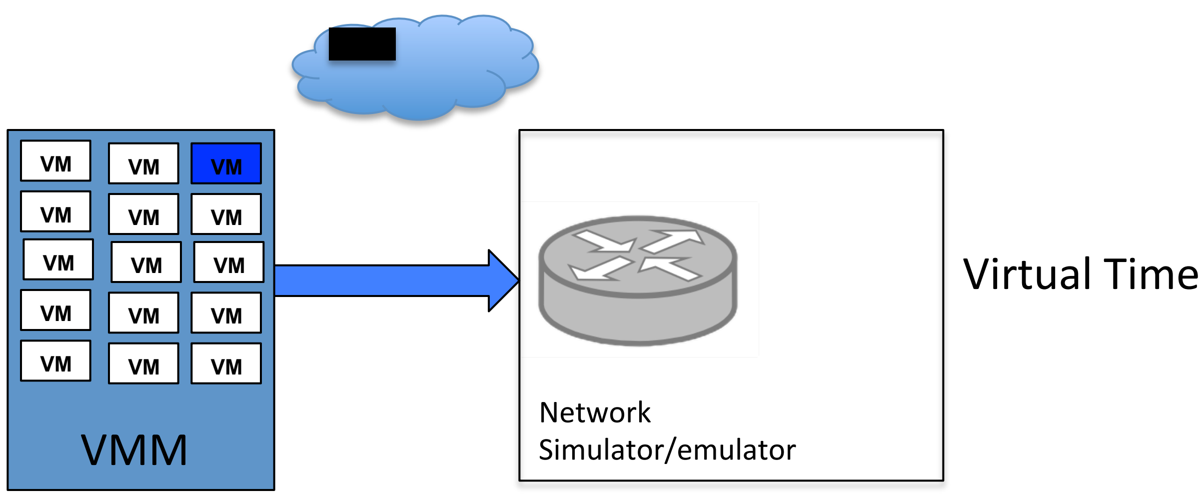

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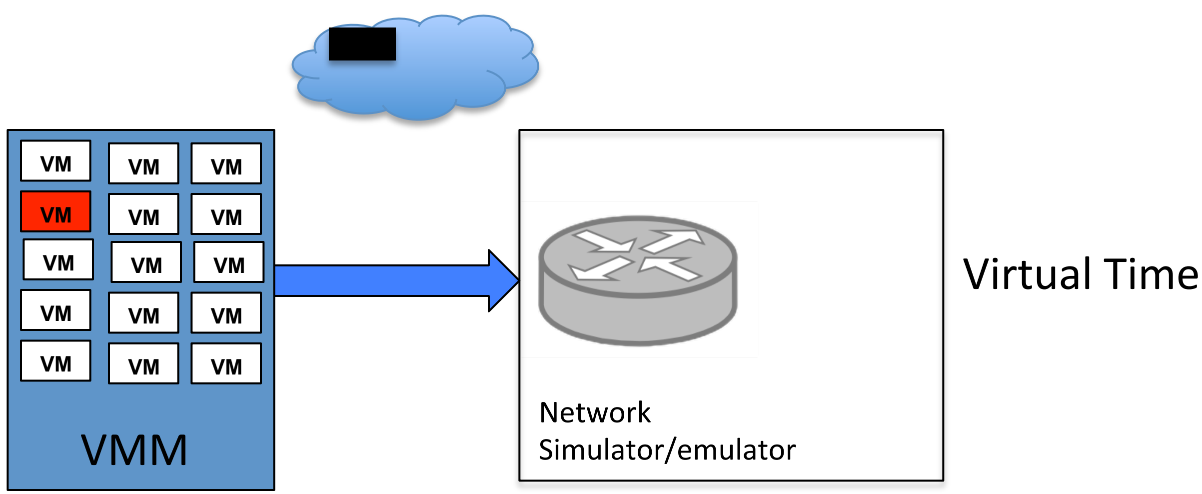

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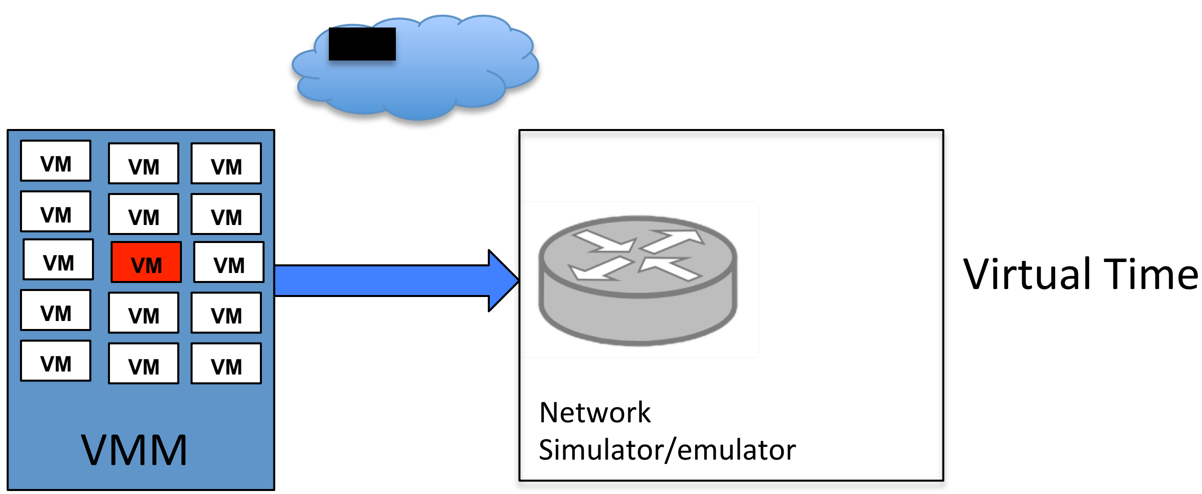

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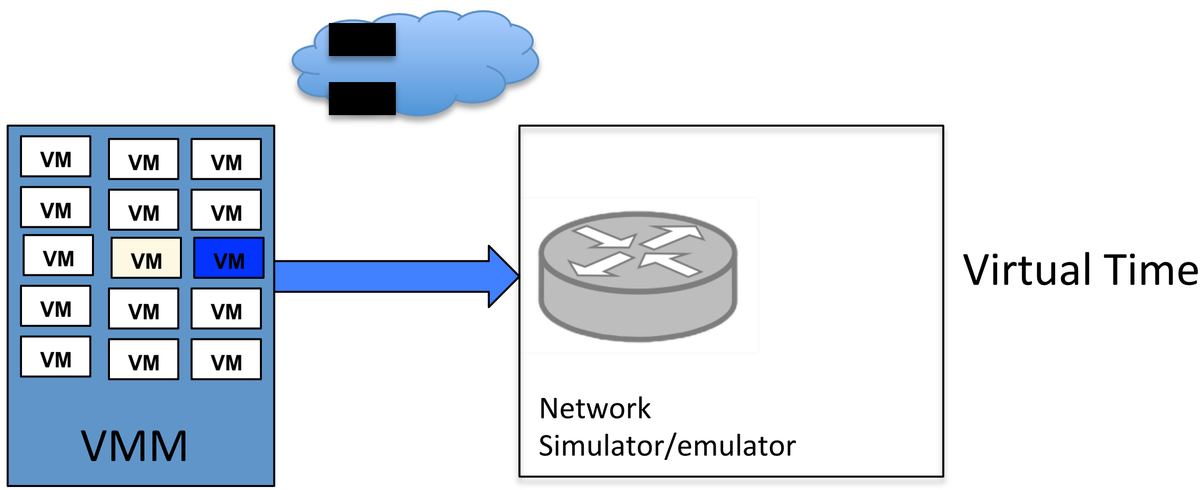

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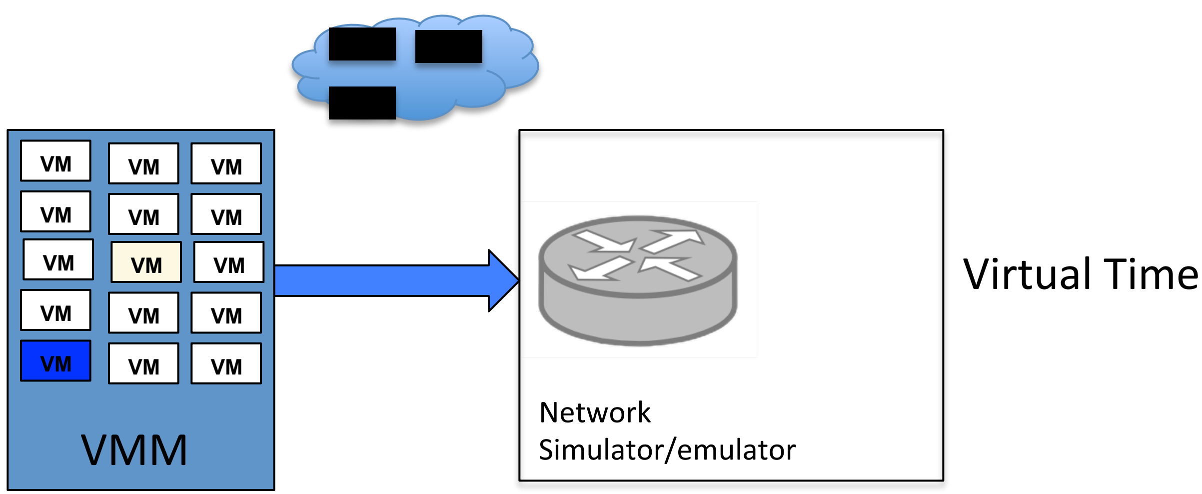

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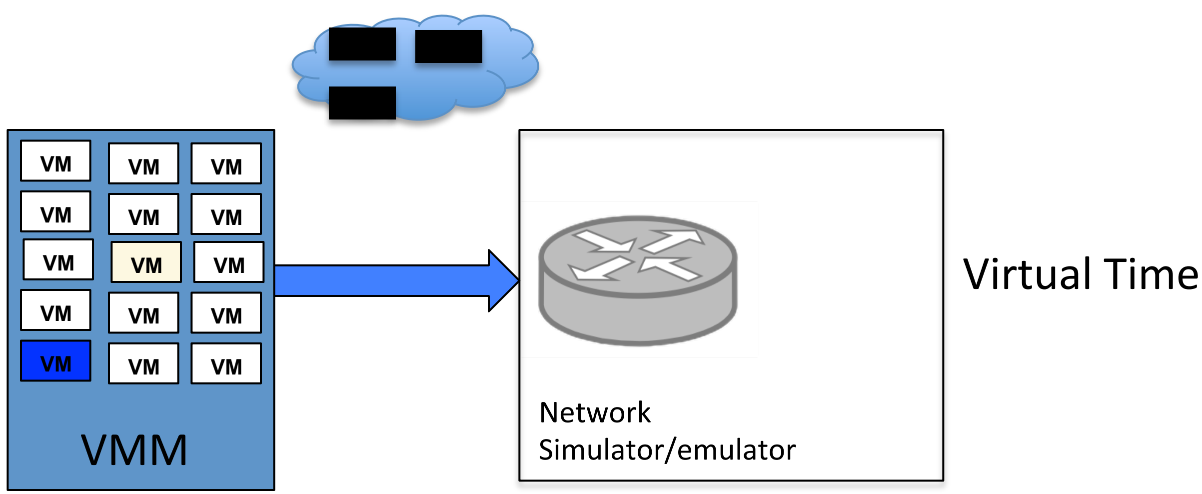

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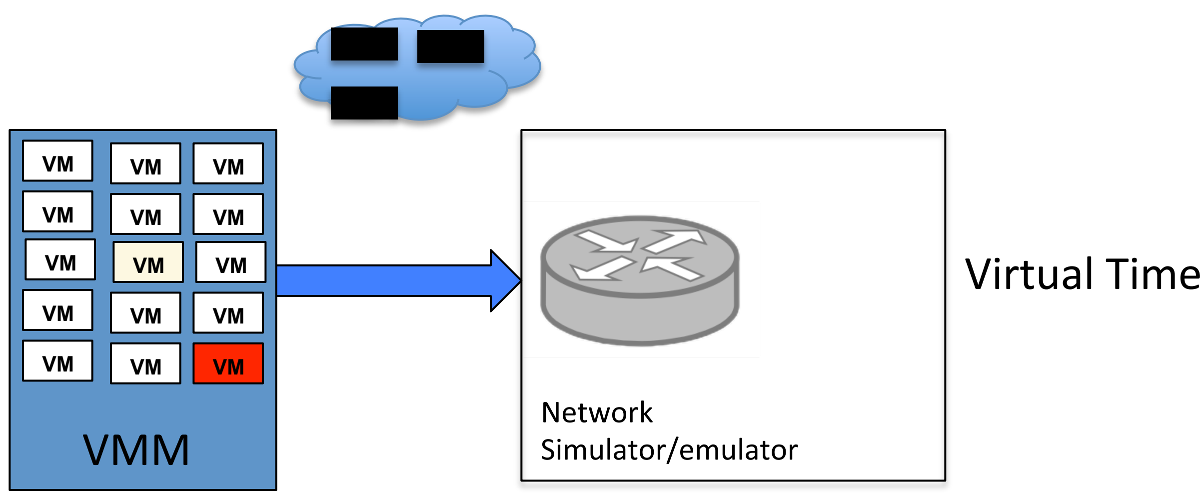

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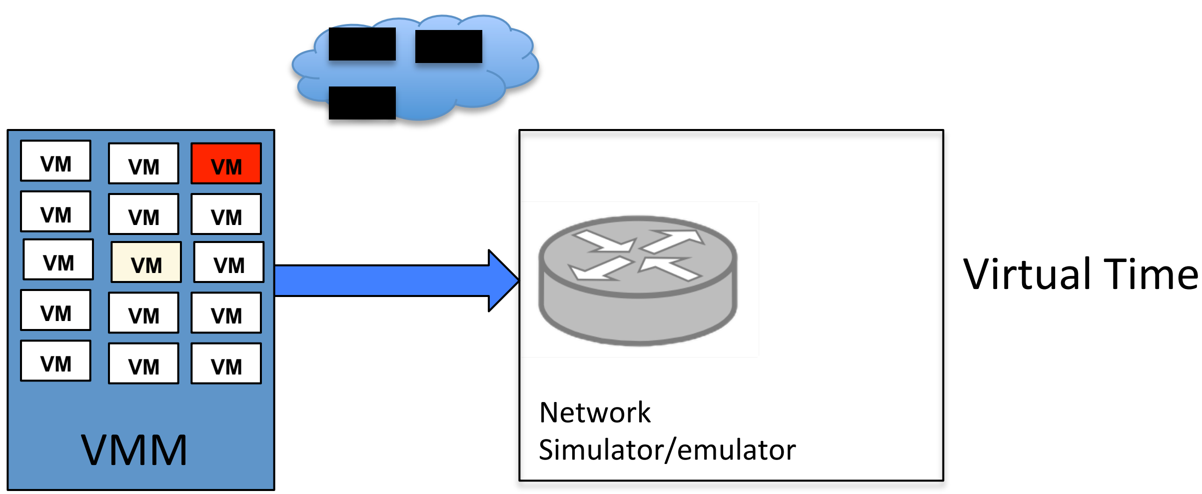

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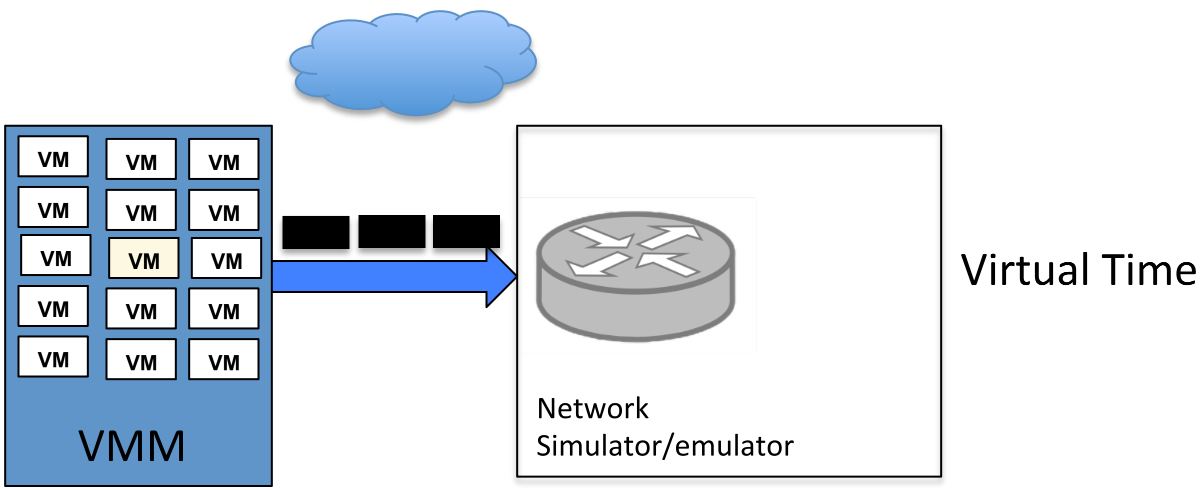
- But if synchronized in **virtual time**, **dispatch is concurrent**



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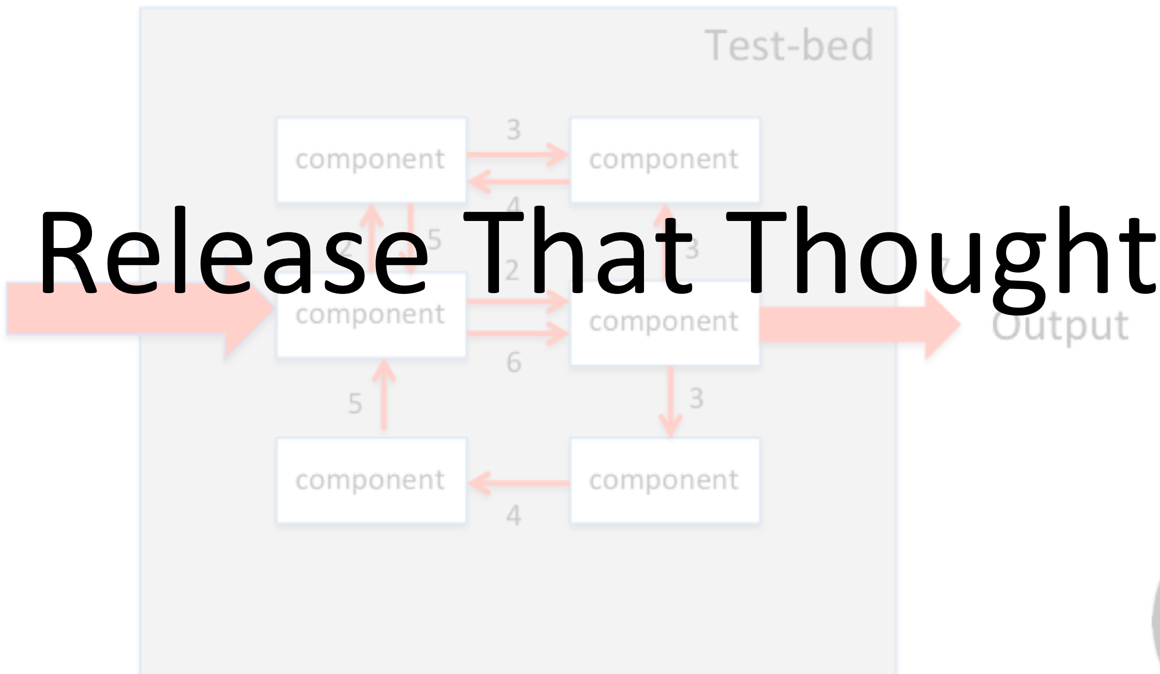


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As in the field, sequencing in the test-bed is governed by real-time delays

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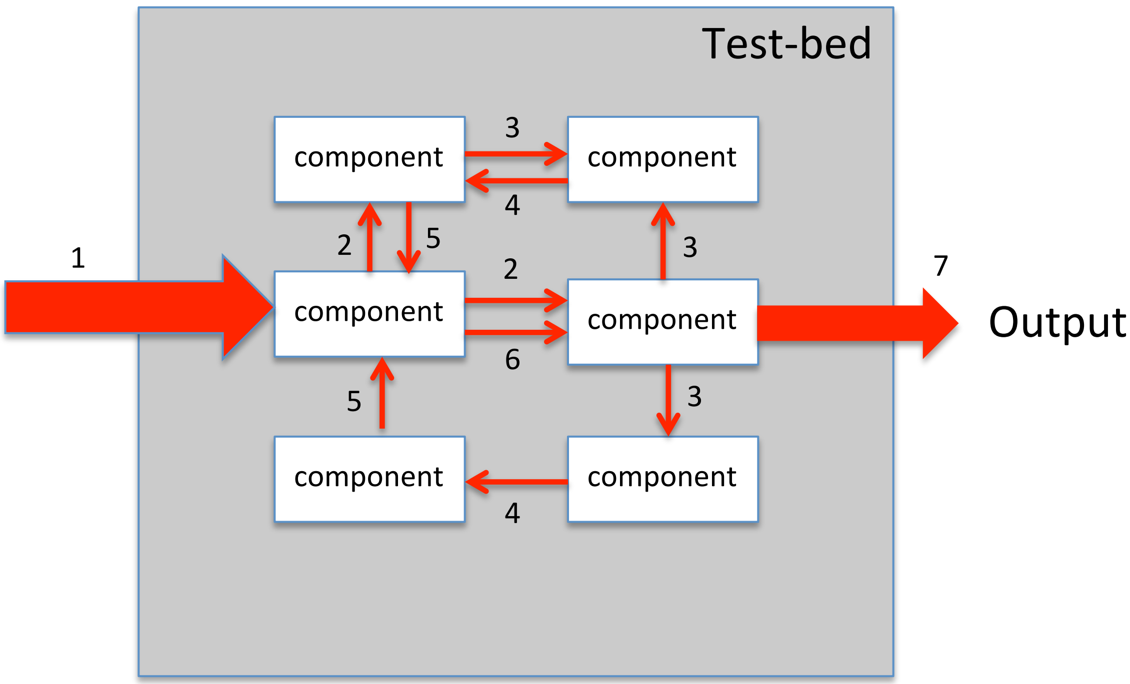
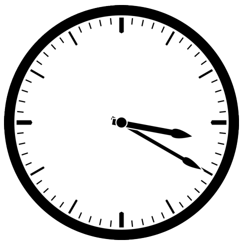


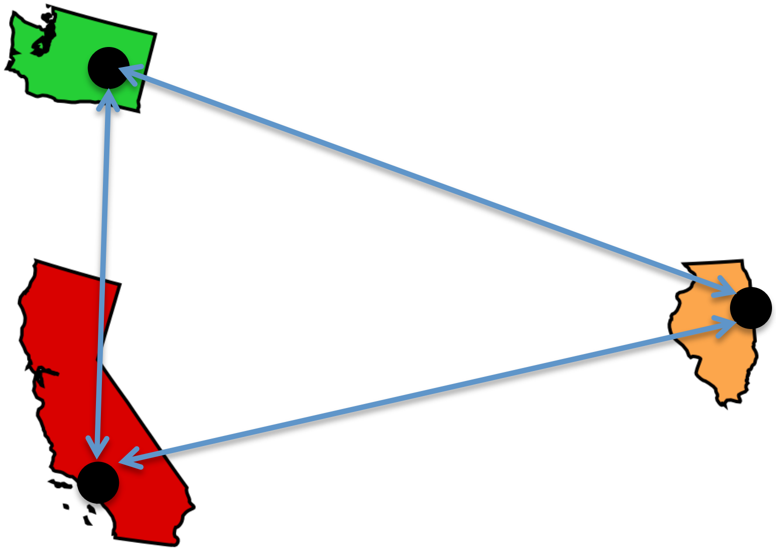



To sequence as in the field, we have to sequence with respect to **Virtual Time**

# Imagine the Possibilities….

With a test-bed embedded in virtual time, you can

- model **larger systems** on smaller test-beds
  - More simulation, fewer devices
- Mask latencies in test-bed federation
  - Run xN slower, turns 50ms real delay into a 50/N ms virtual delay
  - Synchronization



# Virtual Time Sequencing

Every component action needs a **time-stamp**

Every component action needs a **time delay**

Virtual time management framework

- Schedules component actions in virtual time
- Manages inter-component input/output

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Sometimes known as Discrete-Event Simulation

Questions

- How to embed emulation in VT?
- How to embed power system flow simulation in VT?
- How to embed device execution in VT?
- How to coordinate it all?

# Embedding Emulation in Virtual Time

Requires

- calls to clock return *virtual* time
  - Based on measured execution and time dilation factor
- Scheduling
  - Advance virtual machines concurrent w.r.t. virtual time

Examples

- Versions of Xen just shift off clock bits
  - TDF of 2,4,8, etc.
  - Ordinary VM scheduling
- Timekeeper scales time by TDF
  - Advances all LXCs paced by slowest container

# Network Simulation/Emulation Coordination

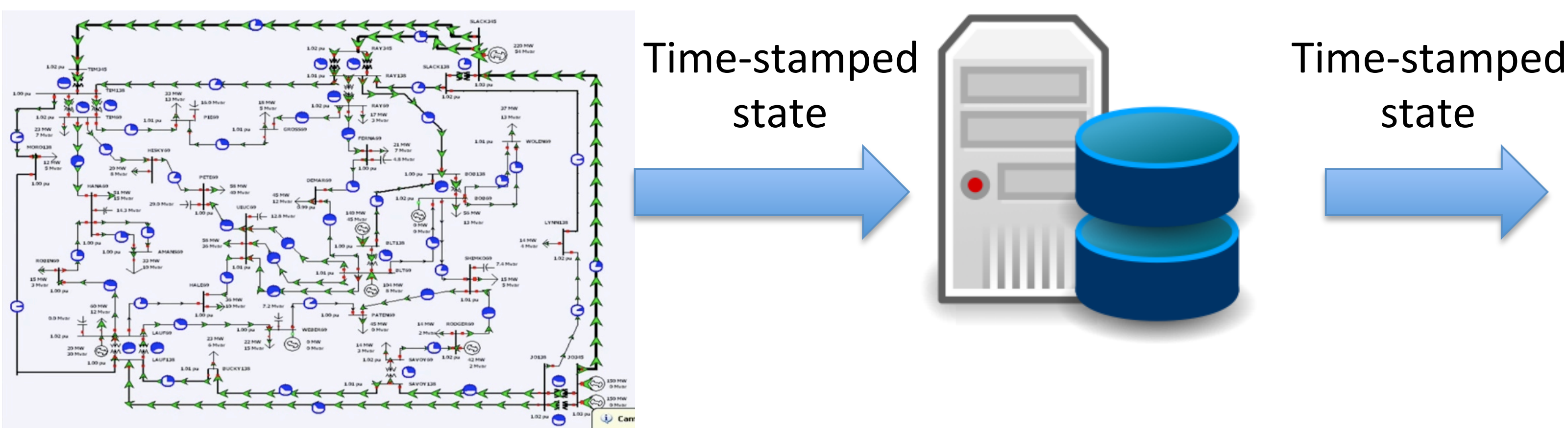
Requires synchronization

- Virtual machines and simulators need to advance at the same rate
  - Best effort interactions within that
- Fine grained synchronization
  - Ensure that no simulator or VM receives a time-stamped communication "in its past"
  - Achieved using synchronization protocols from parallel discrete-event simulation
    - S3F and Timekeeper

# Power System Flow Simulators and Virtual Time

Requirements

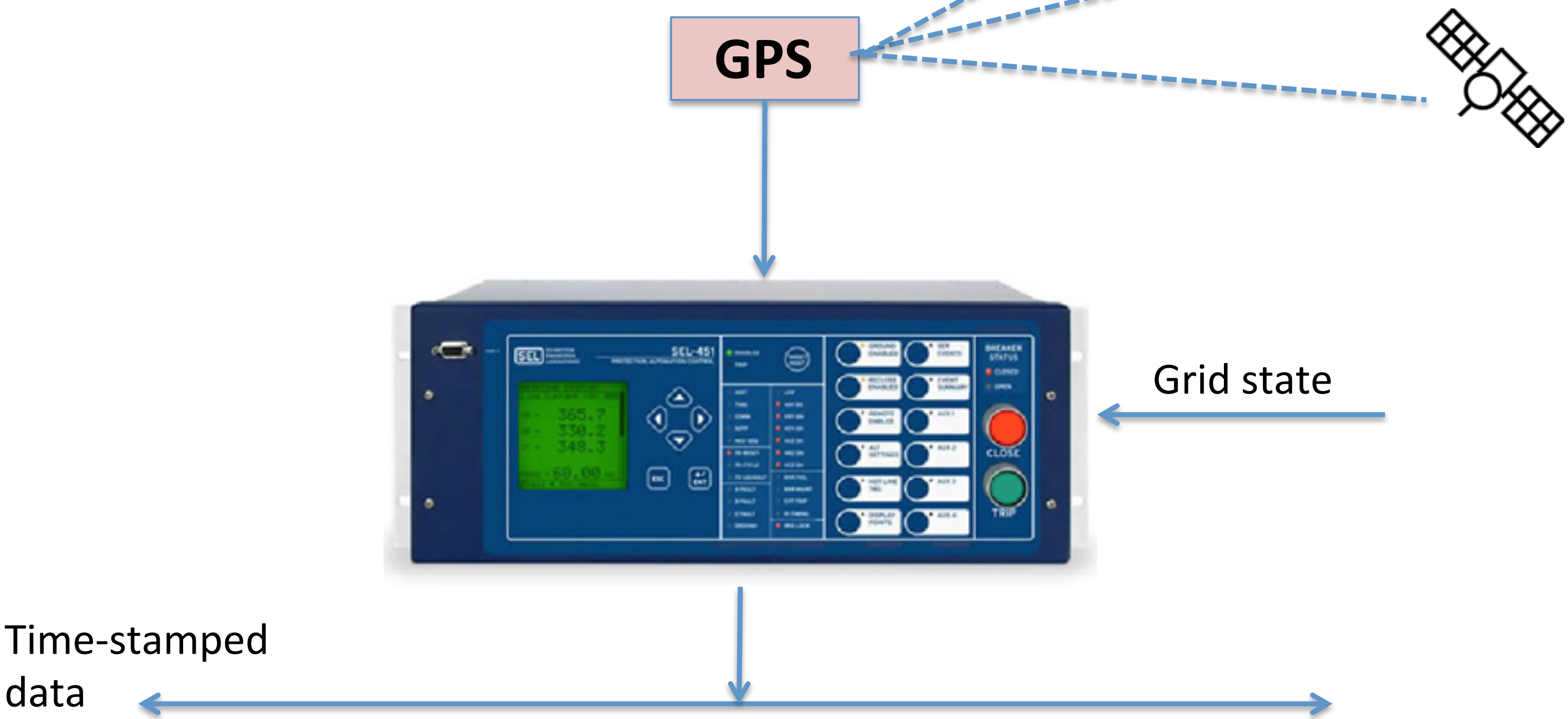
- Export state, with virtual time-stamps
- Pause/Restart, or scaled release execution
- Buffer state



# Device Execution and Virtual Time

No “always works” methodologies

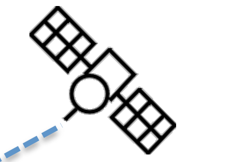
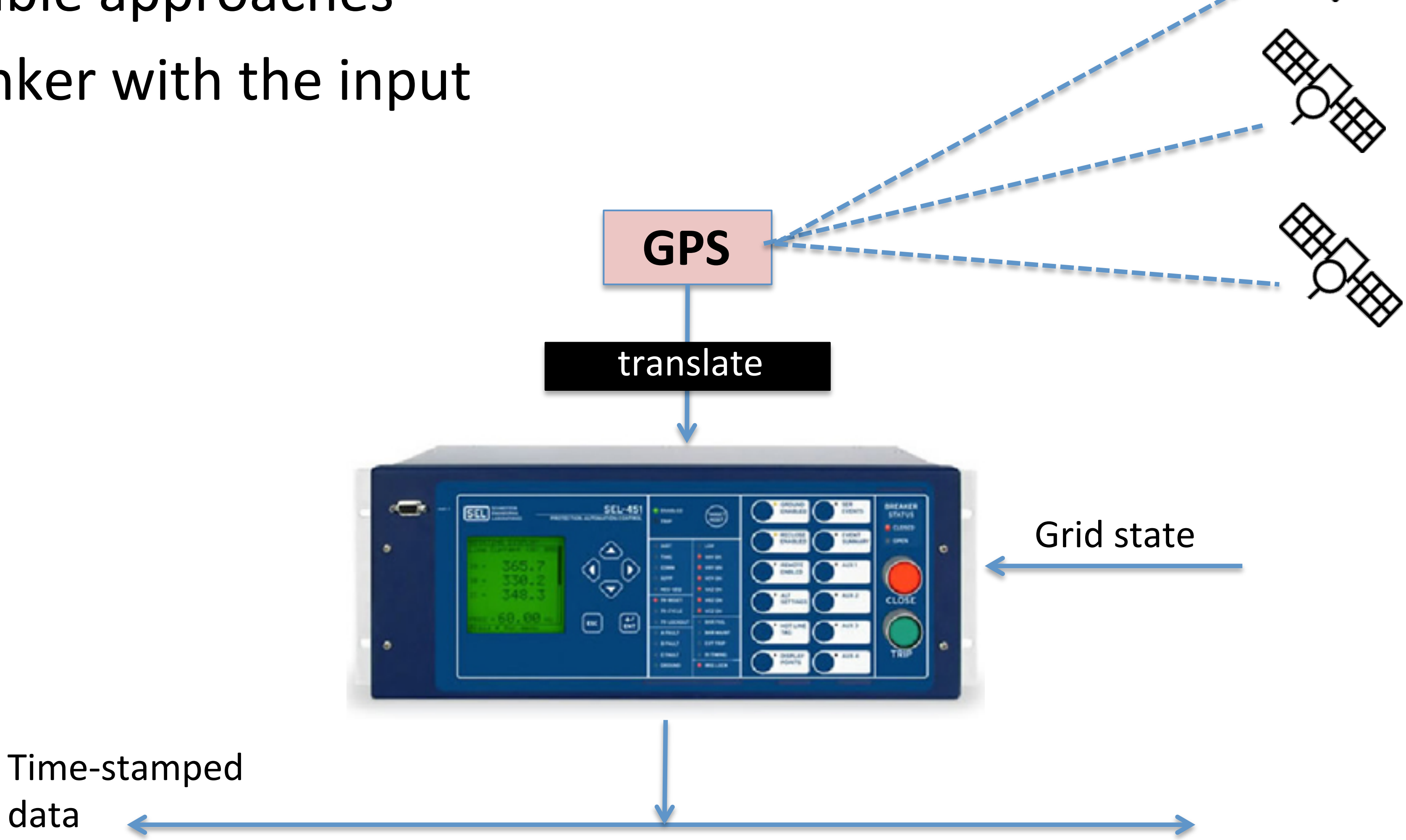
- But some important special cases
  - PMU



# Device Execution and Virtual Time

## Possible approaches

- Tinker with the input

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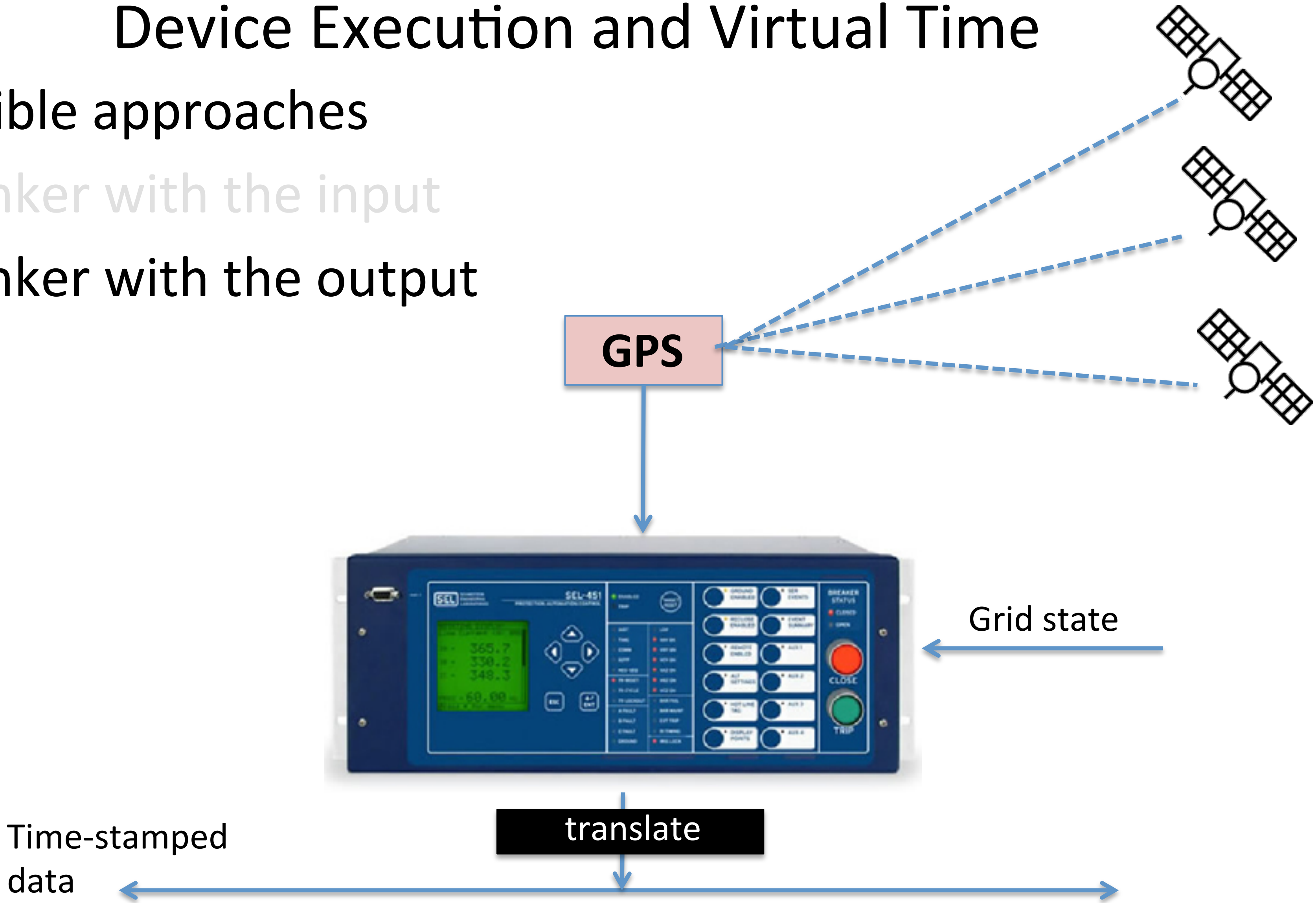
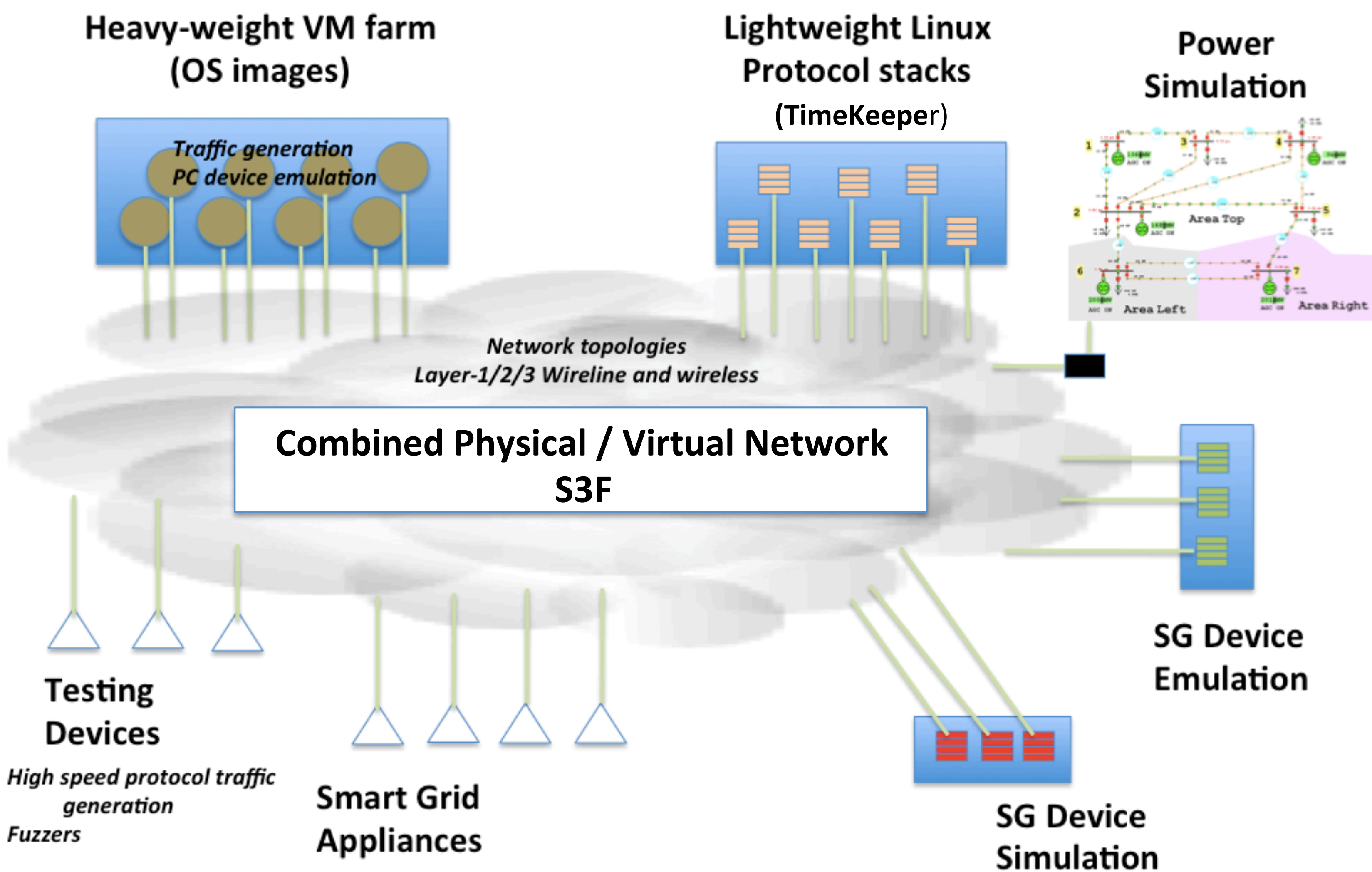
Possible approaches

- Tinker with the input
- Tinker with the output



# Assembling Pieces of the Puzzle

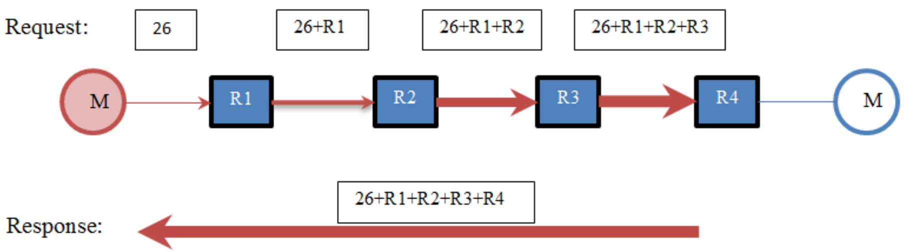


# Examples

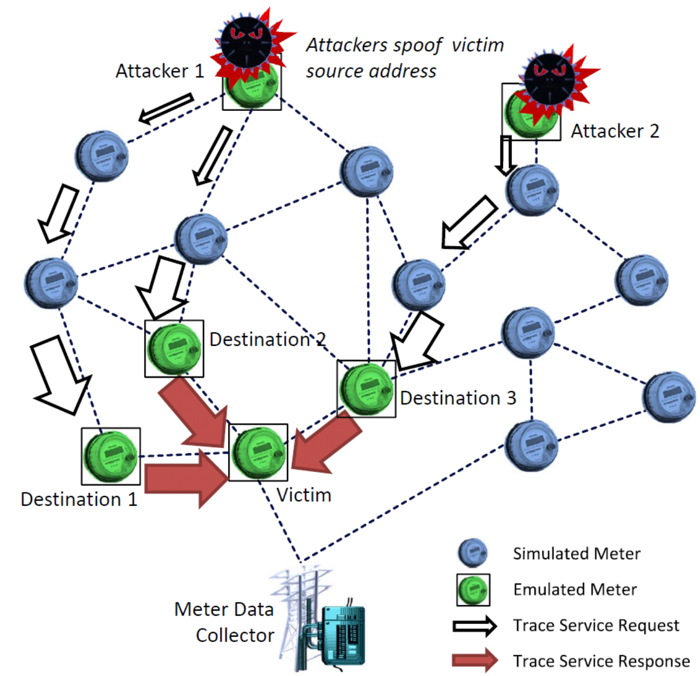
# Example Use of a Smart Grid Testbed

## DDoS Attack Using C12.22 Trace Service in AMI

C12.22 Trace Service




- Amplification
  - Increased volume of traffic
- Reflection
  - Spoofed source address

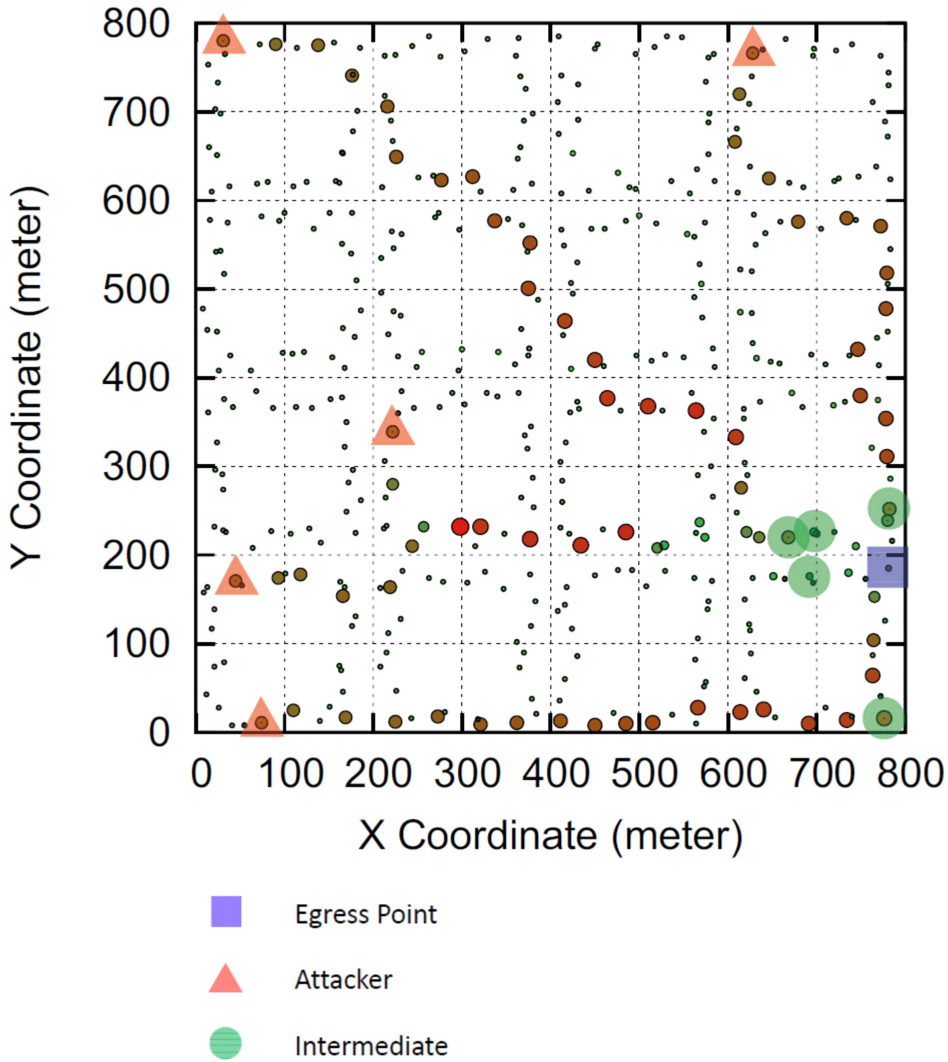



# Components used

- Meter emulation
- Meter simulation
- Access point simulation
- Zigbee wireless simulation

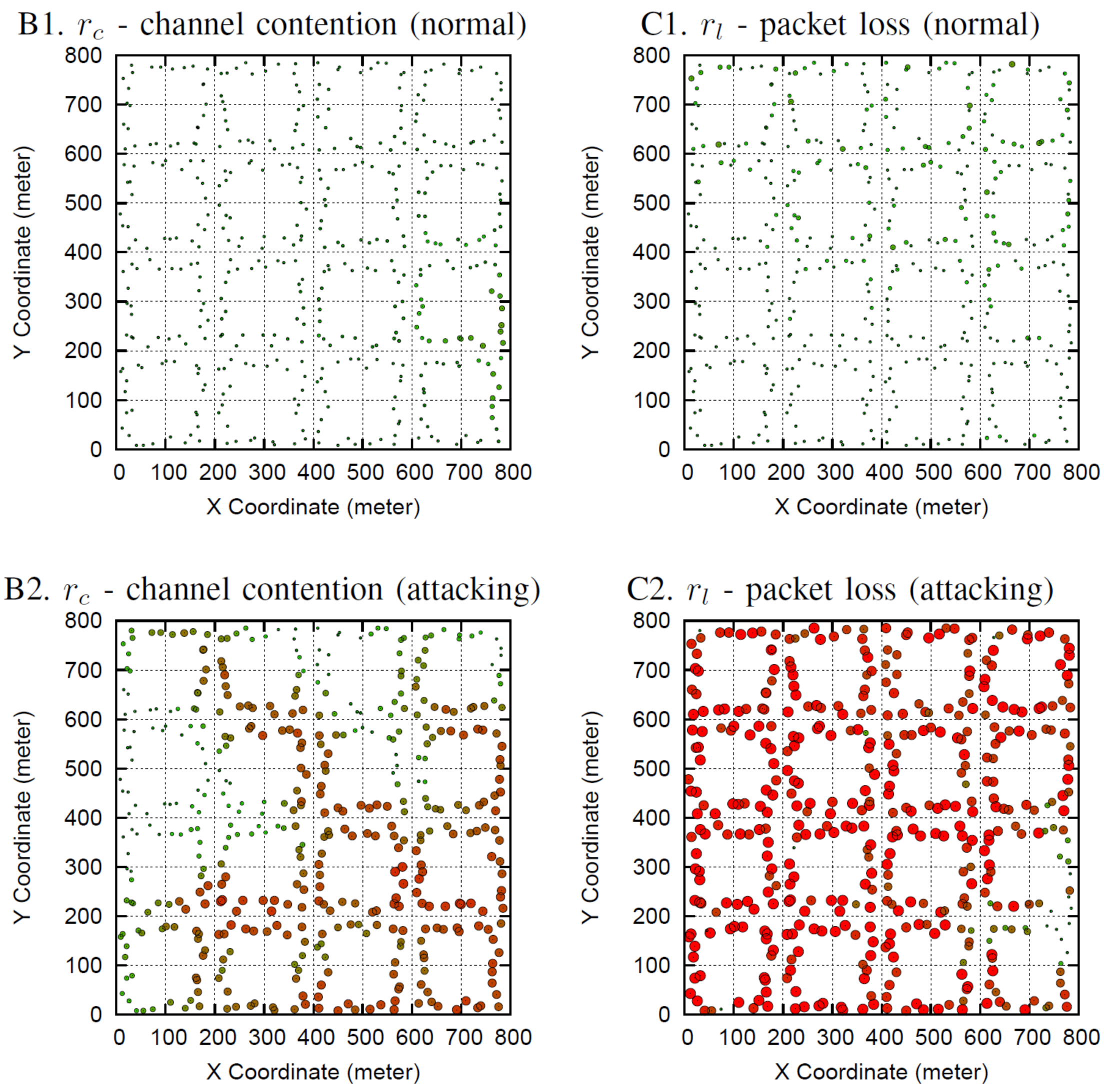
Might have included power simulation but wasn't needed

# Experiment




- 4x4 blocks, 448 meters
- 5 attackers
- Victim: the single egress point (meter gateway)
- ZigBee wireless network, 1 Mb/s bandwidth
- Normal traffic: 100-byte packet per 10 second
- Attacking traffic: 200 times faster, 15-30 hops

# Experimental Results



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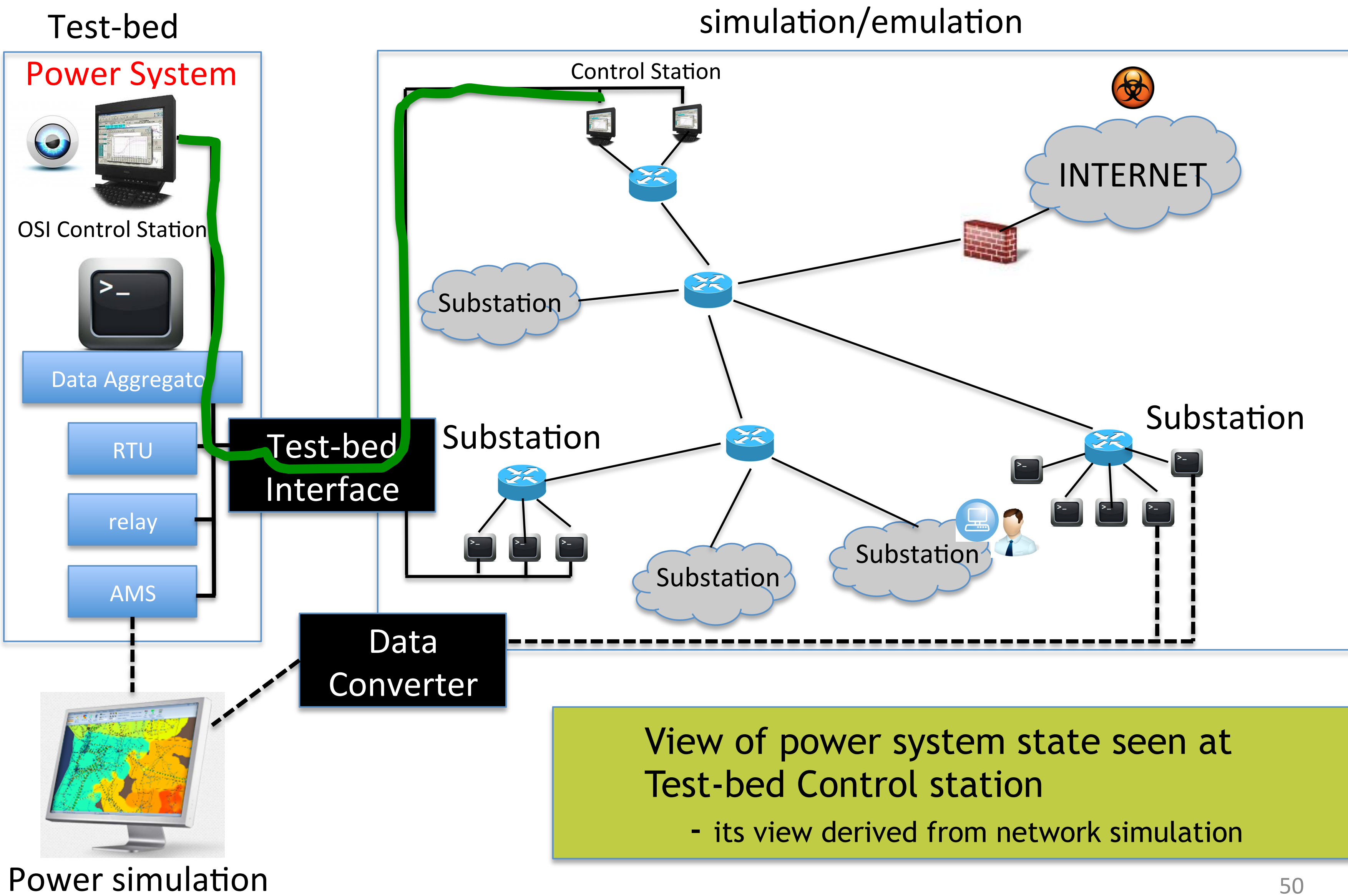


View of power system state seen at Test-bed Control station

- its view derived from network simulation

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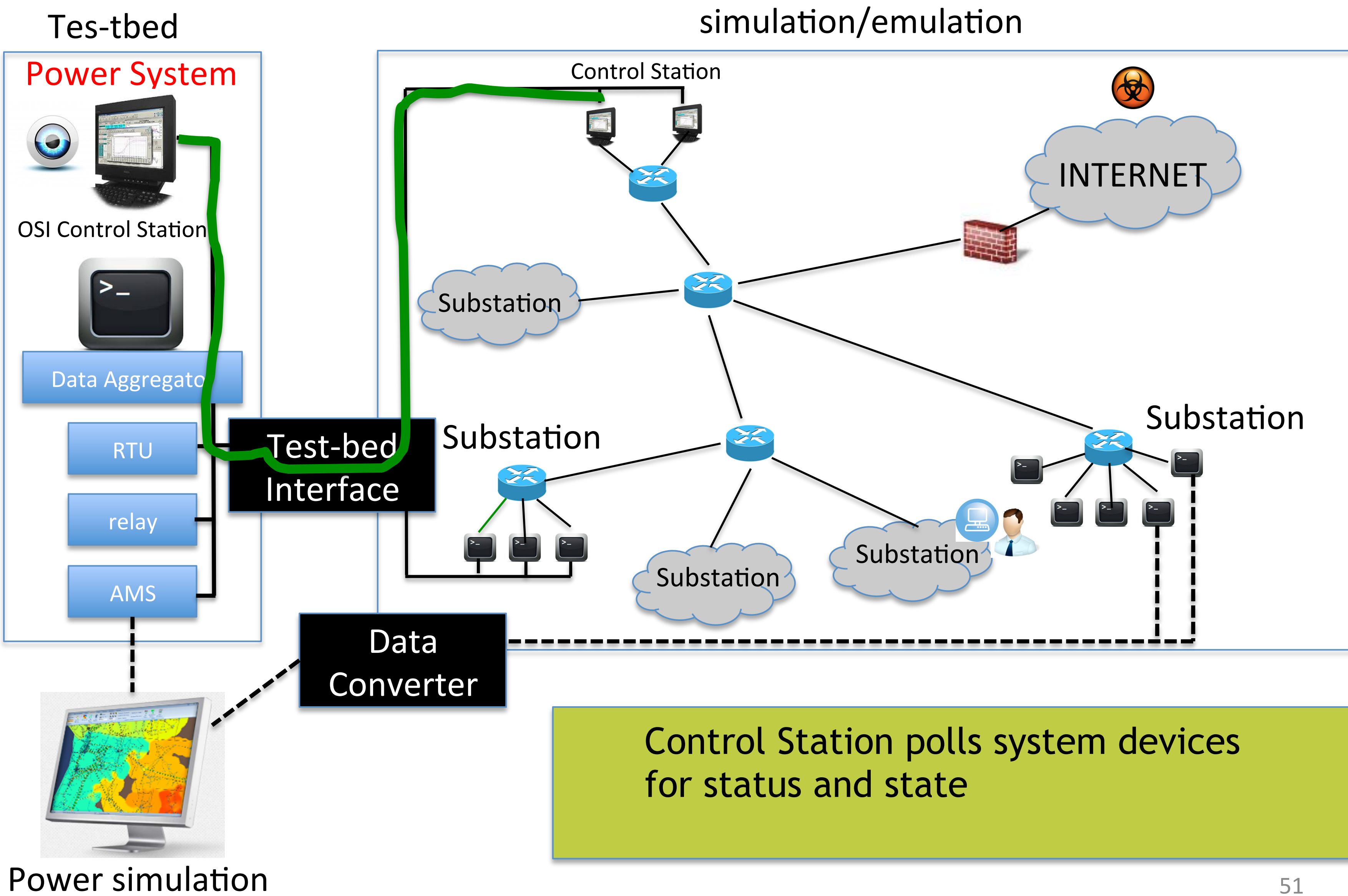


Control Station polls system devices for status and state

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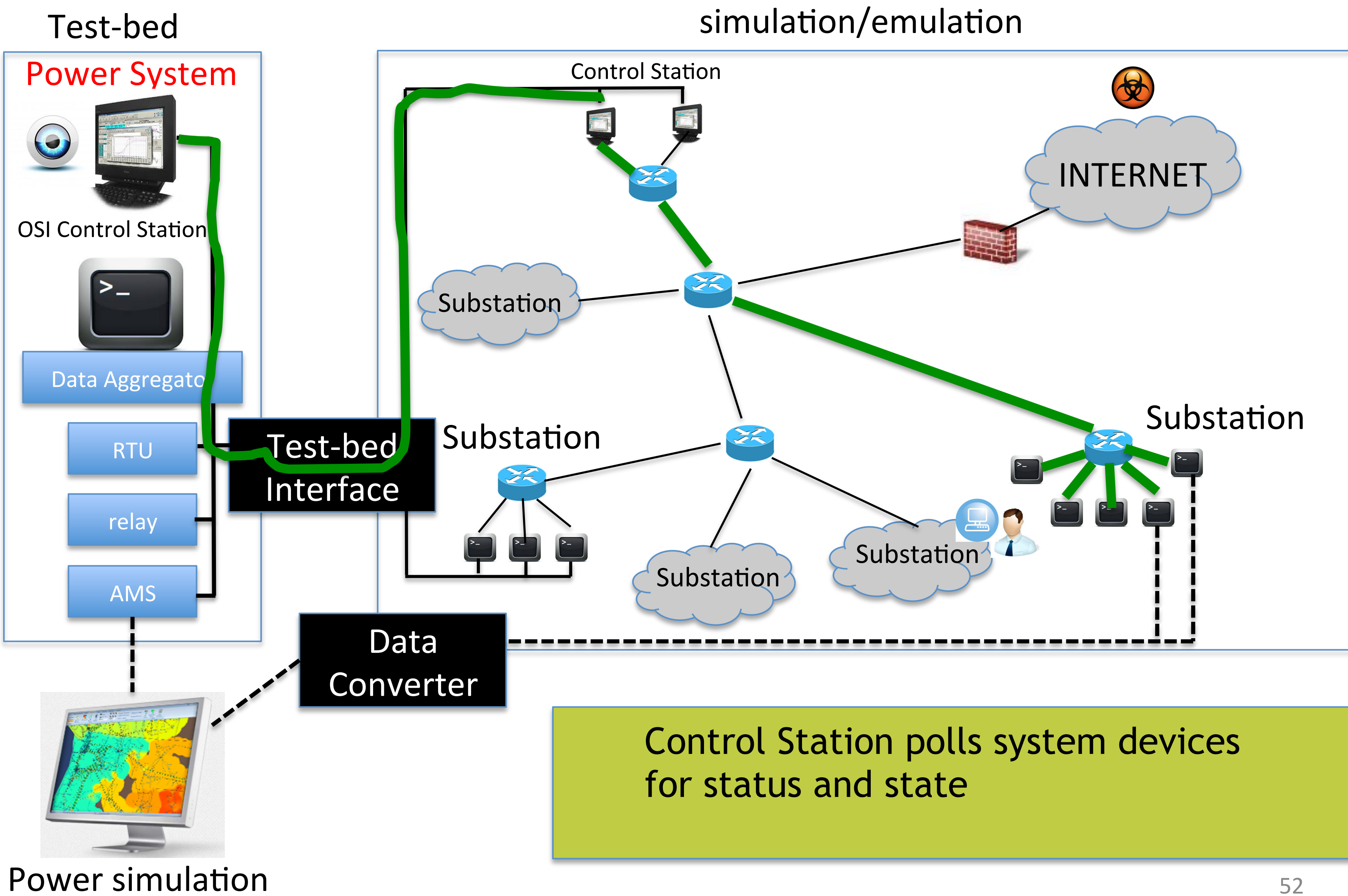


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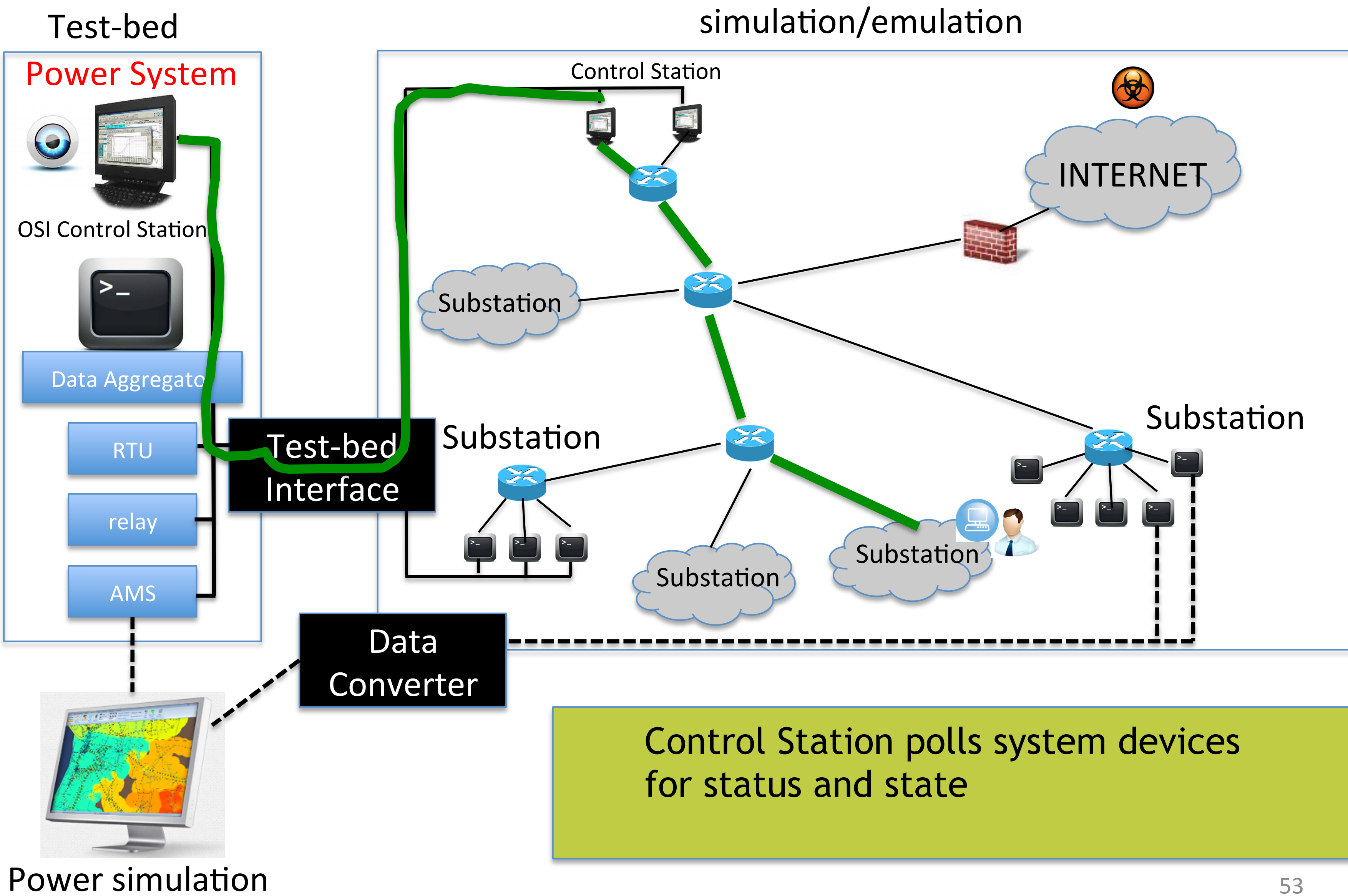


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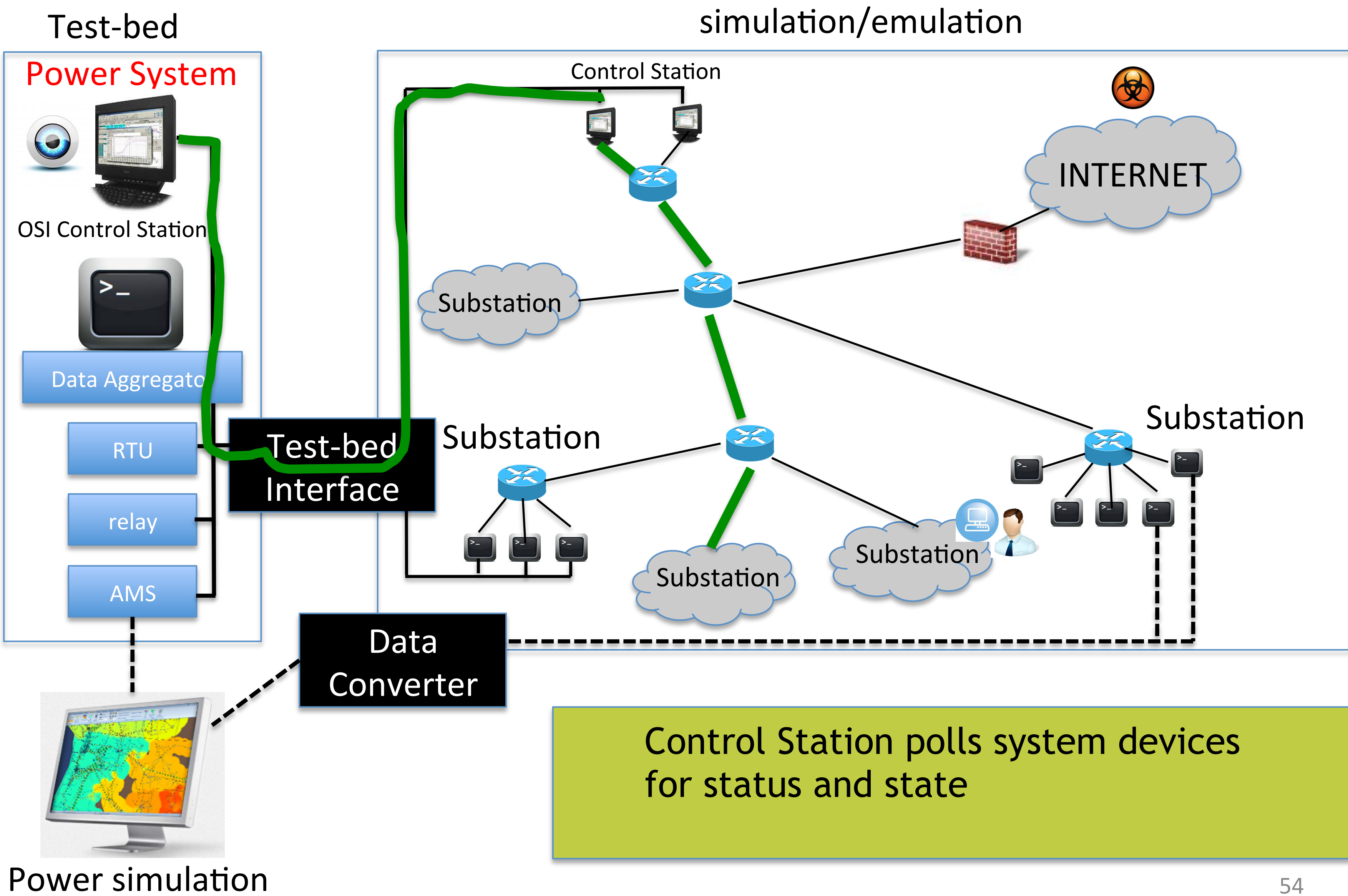


Control Station polls system devices for status and state

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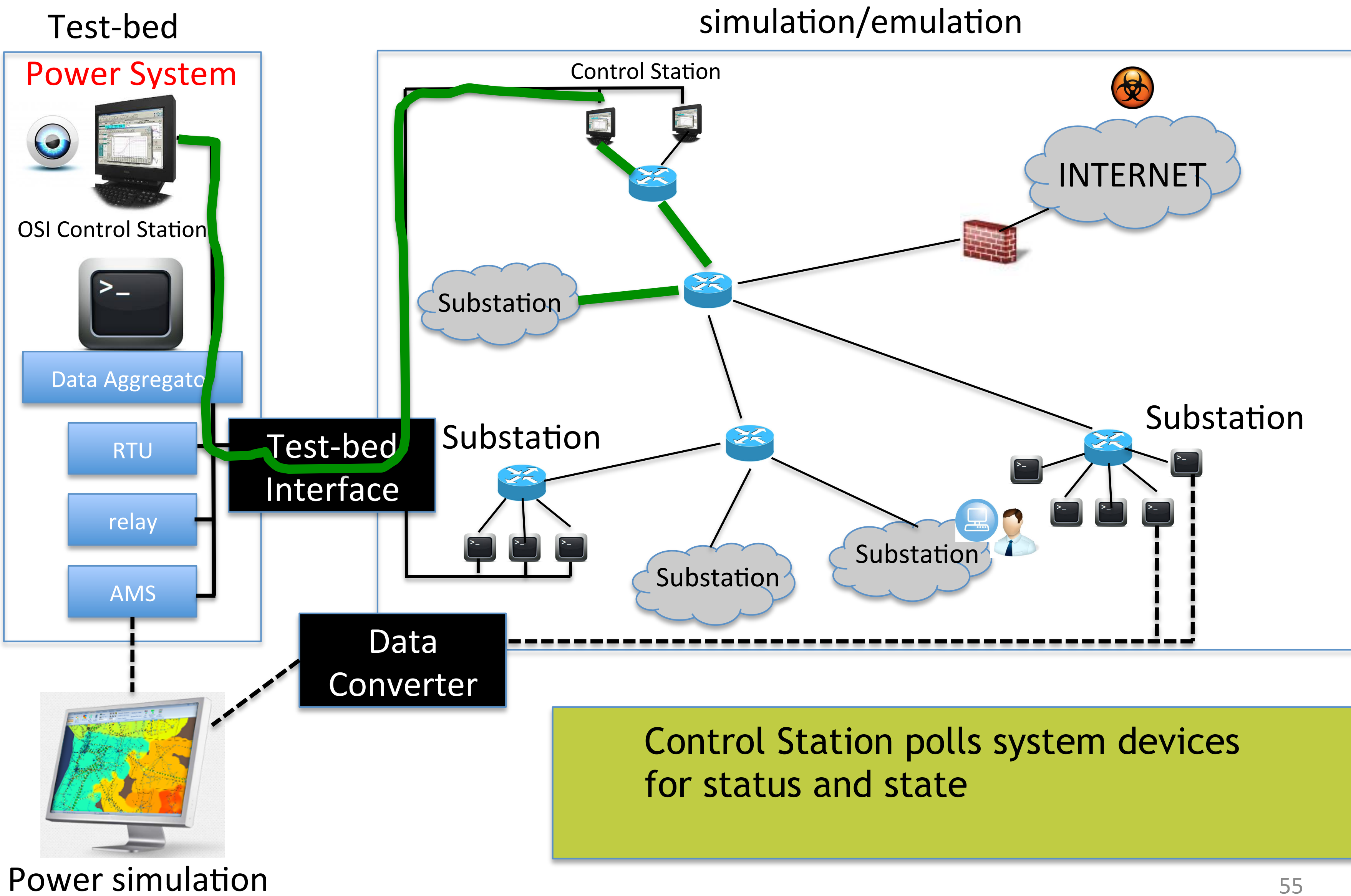


Control Station polls system devices for status and state

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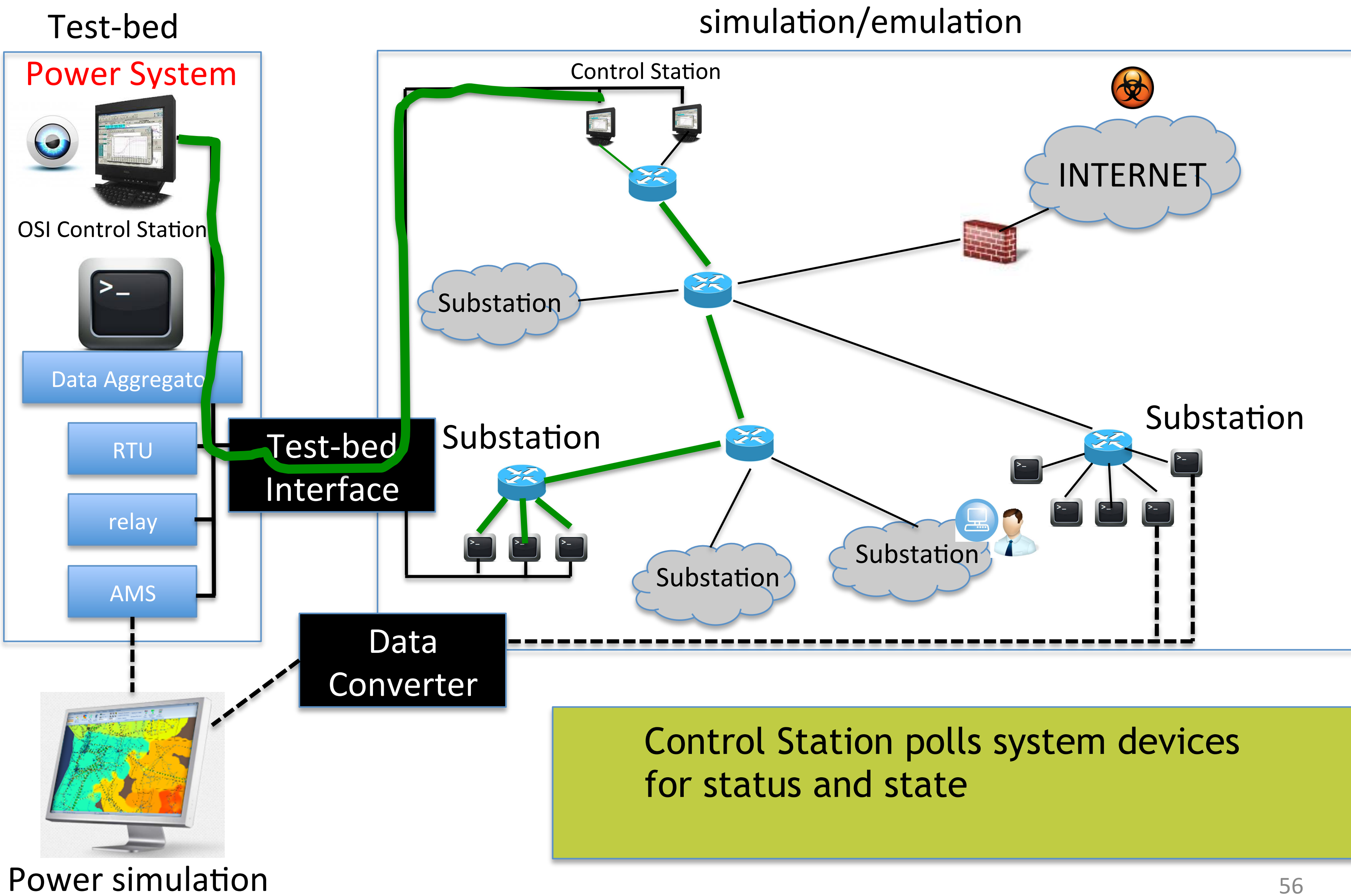
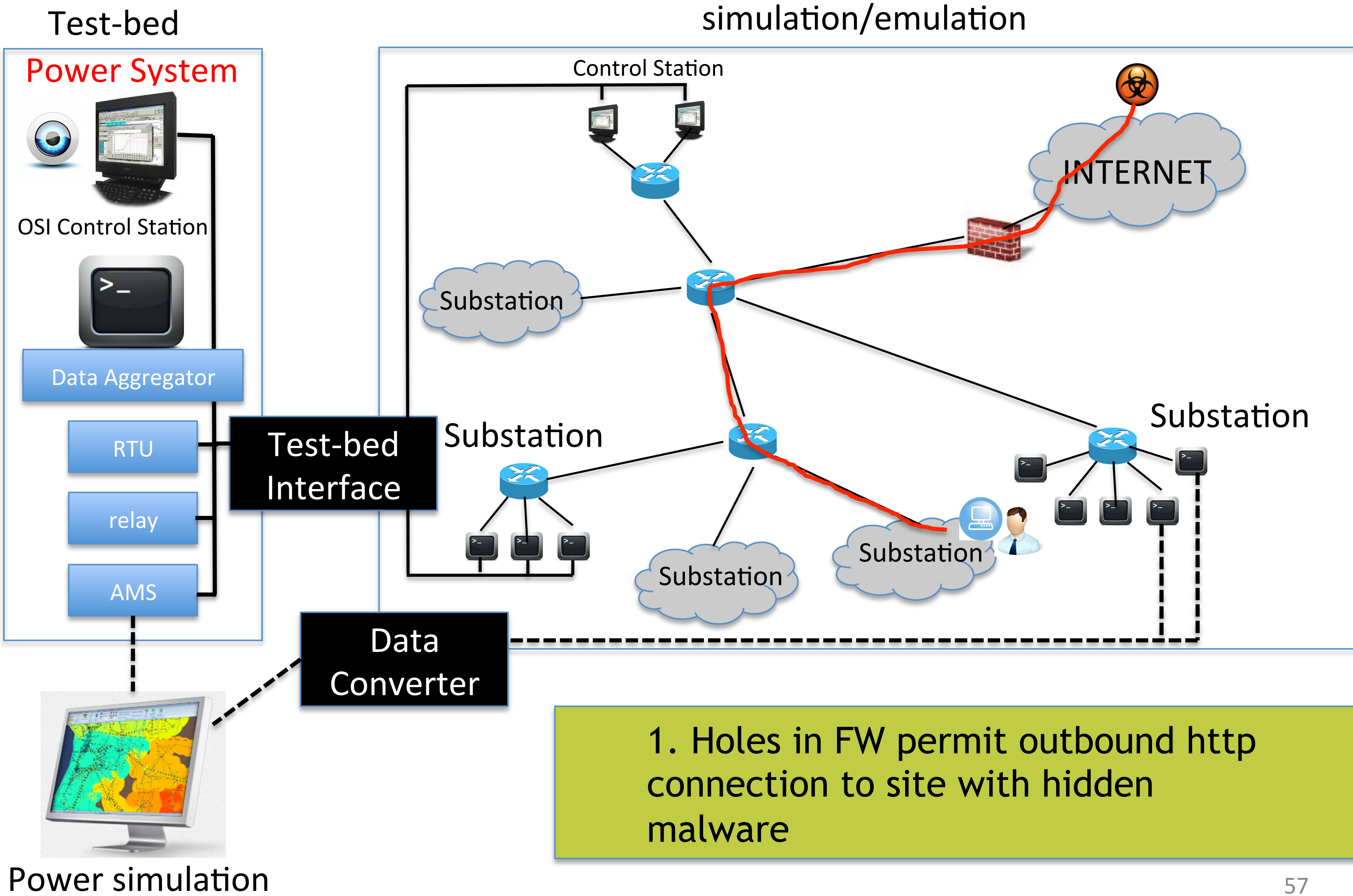


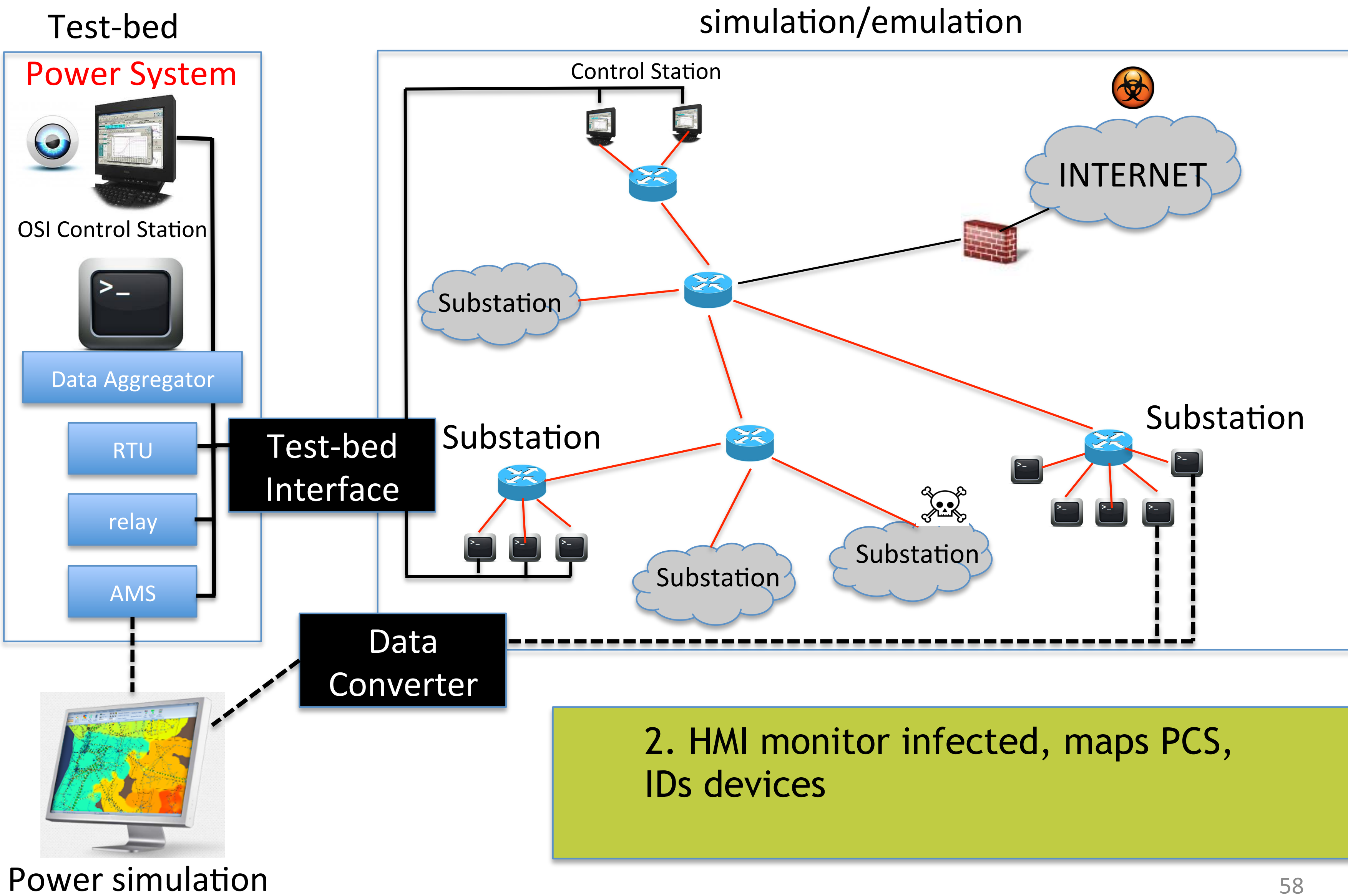

Control Station polls system devices for status and state

# Example : Attack on Situational Awareness



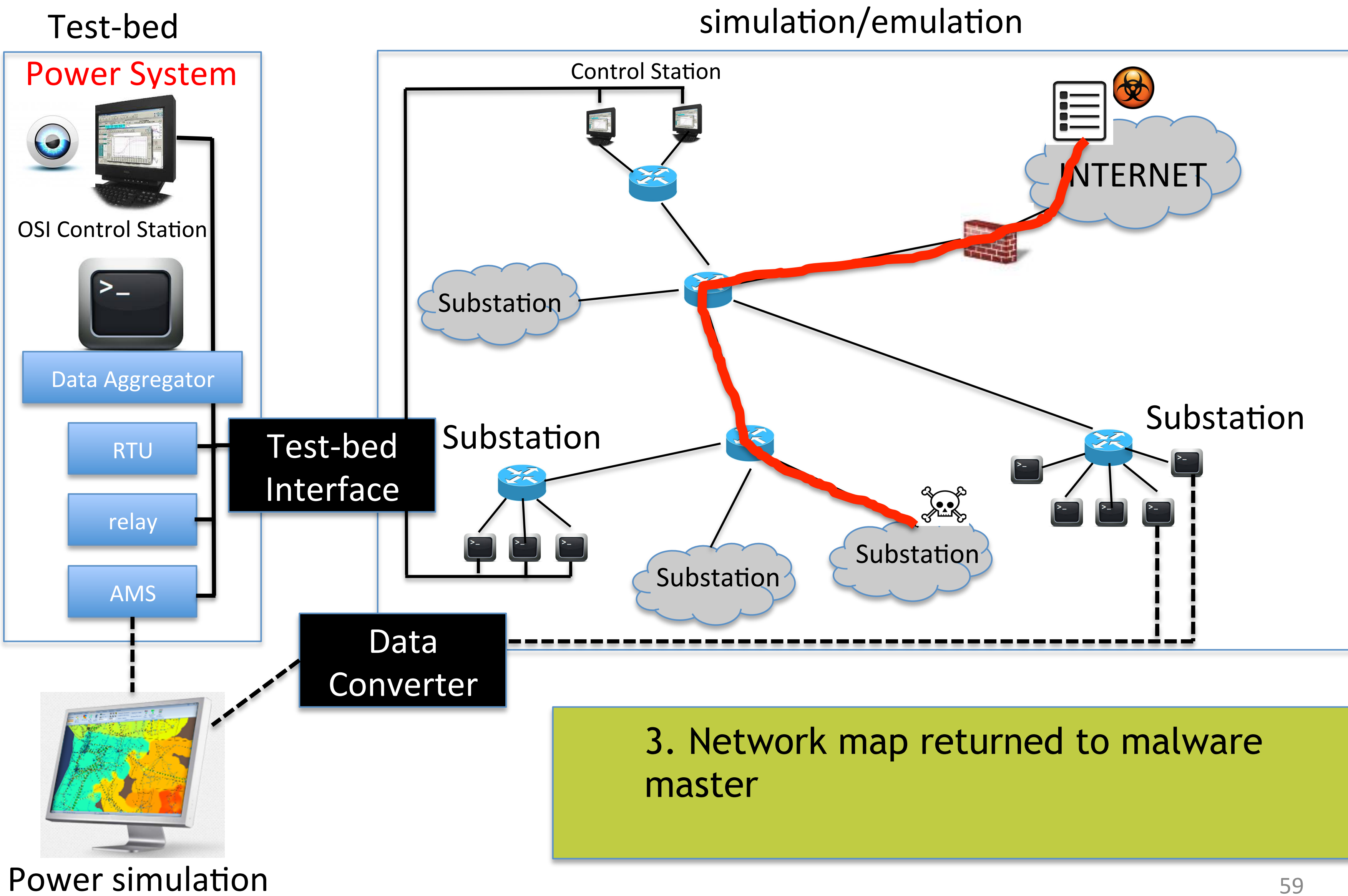

1. Holes in FW permit outbound http connection to site with hidden malware

# Example : Attack on Situational Awareness



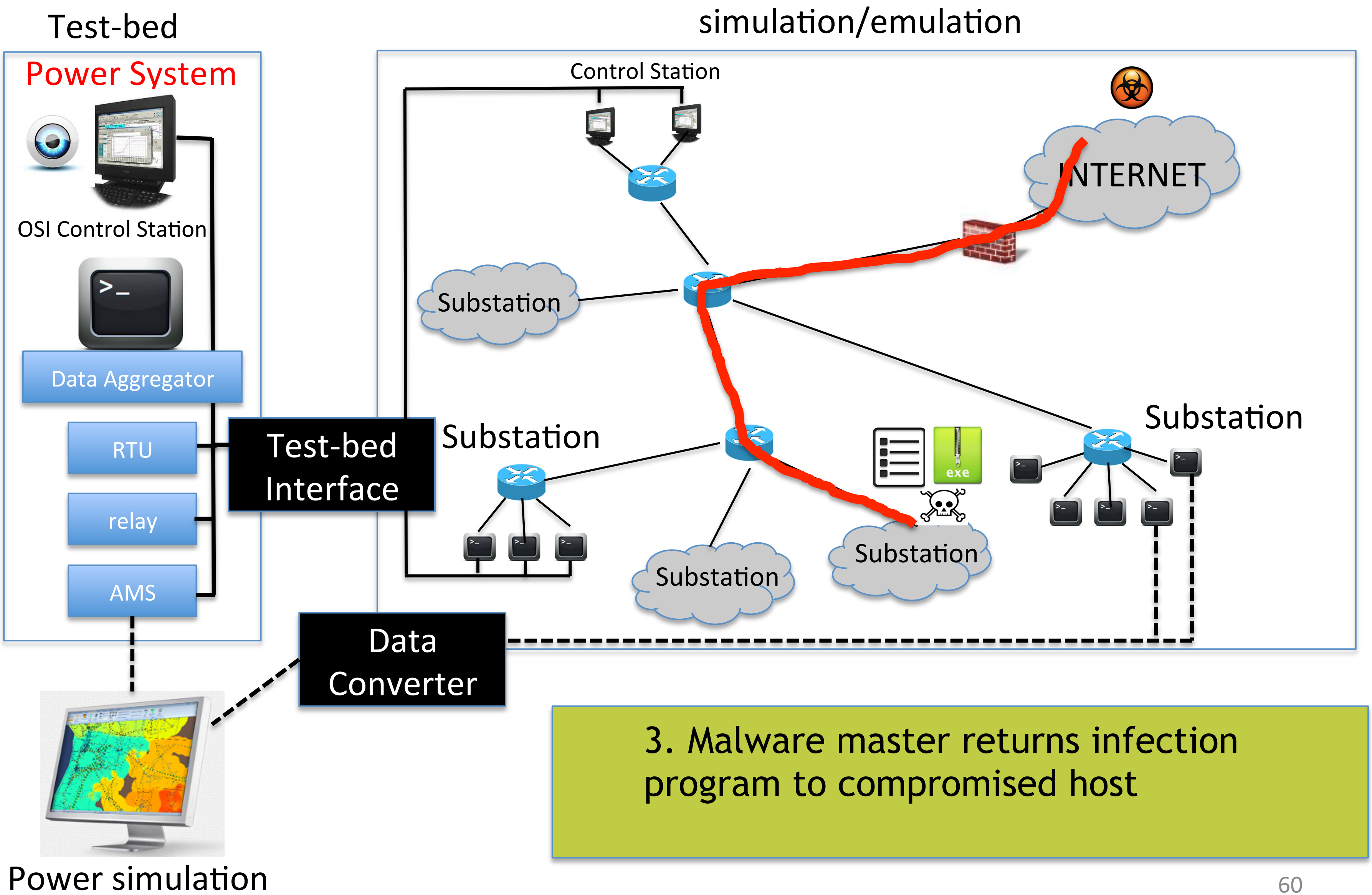

2. HMI monitor infected, maps PCS, IDs devices

# Example : Attack on Situational Awareness



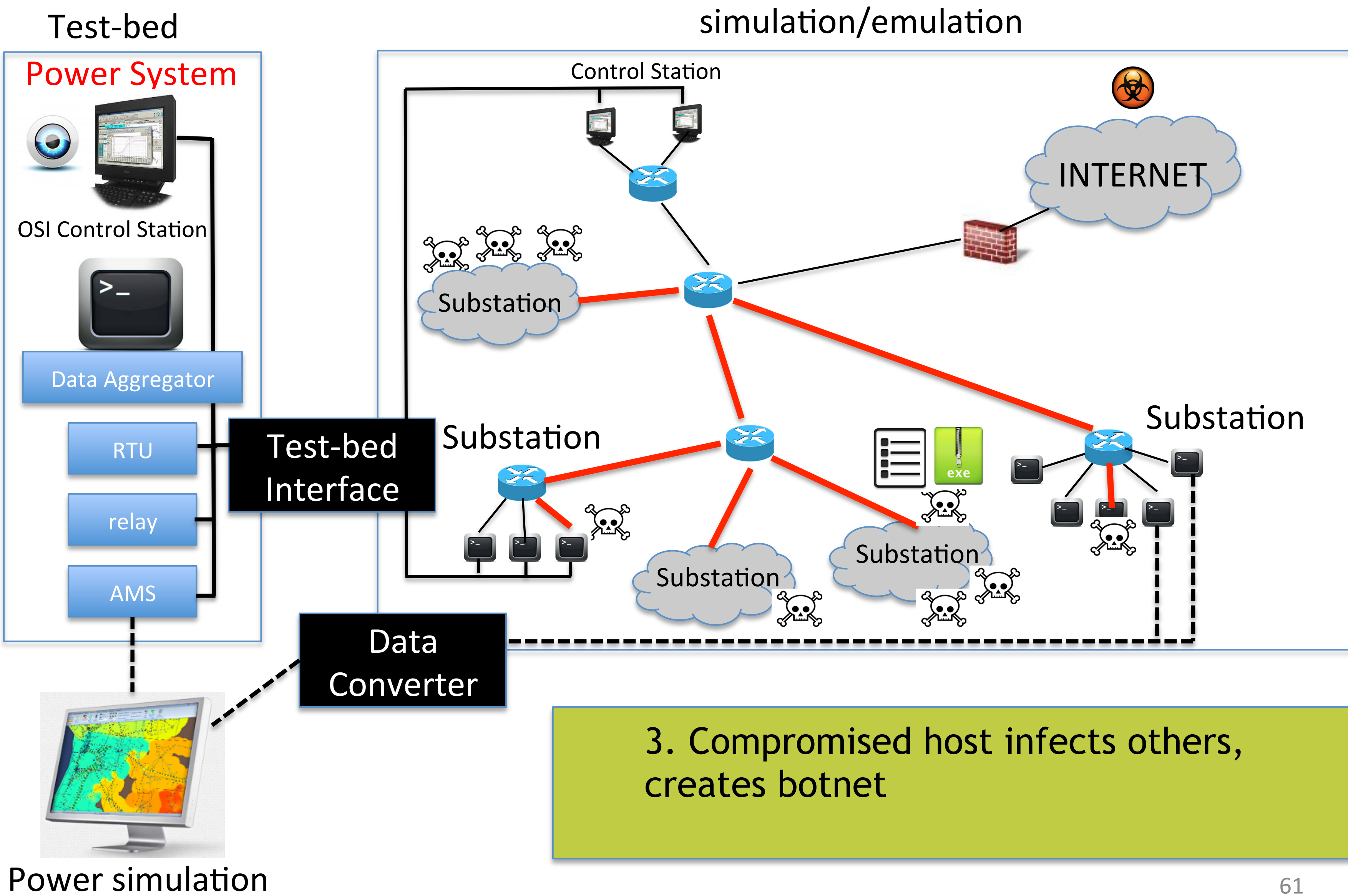

3. Network map returned to malware master

# Example : Attack on Situational Awareness



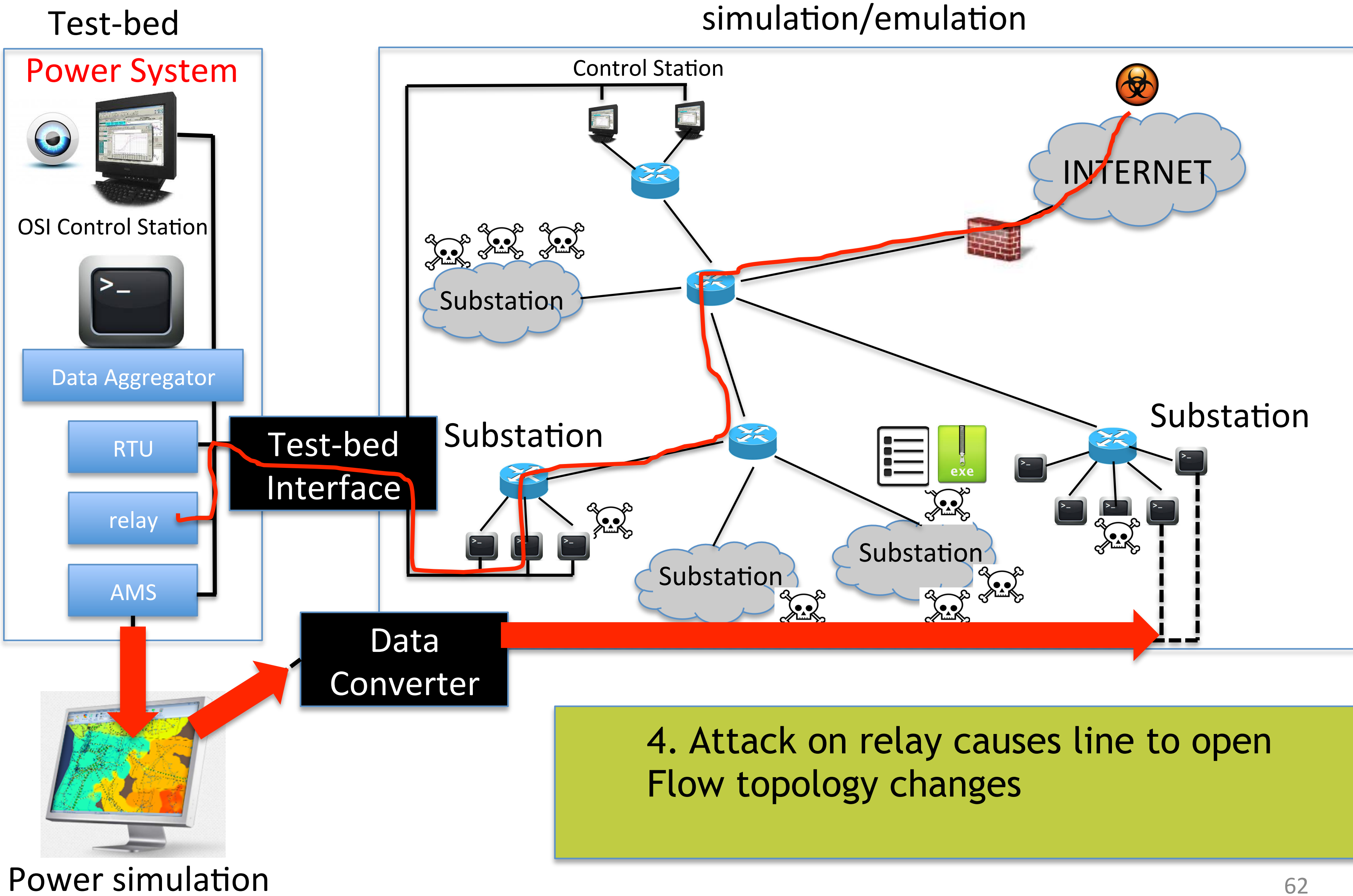

3. Malware master returns infection program to compromised host

# Example : Attack on Situational Awareness



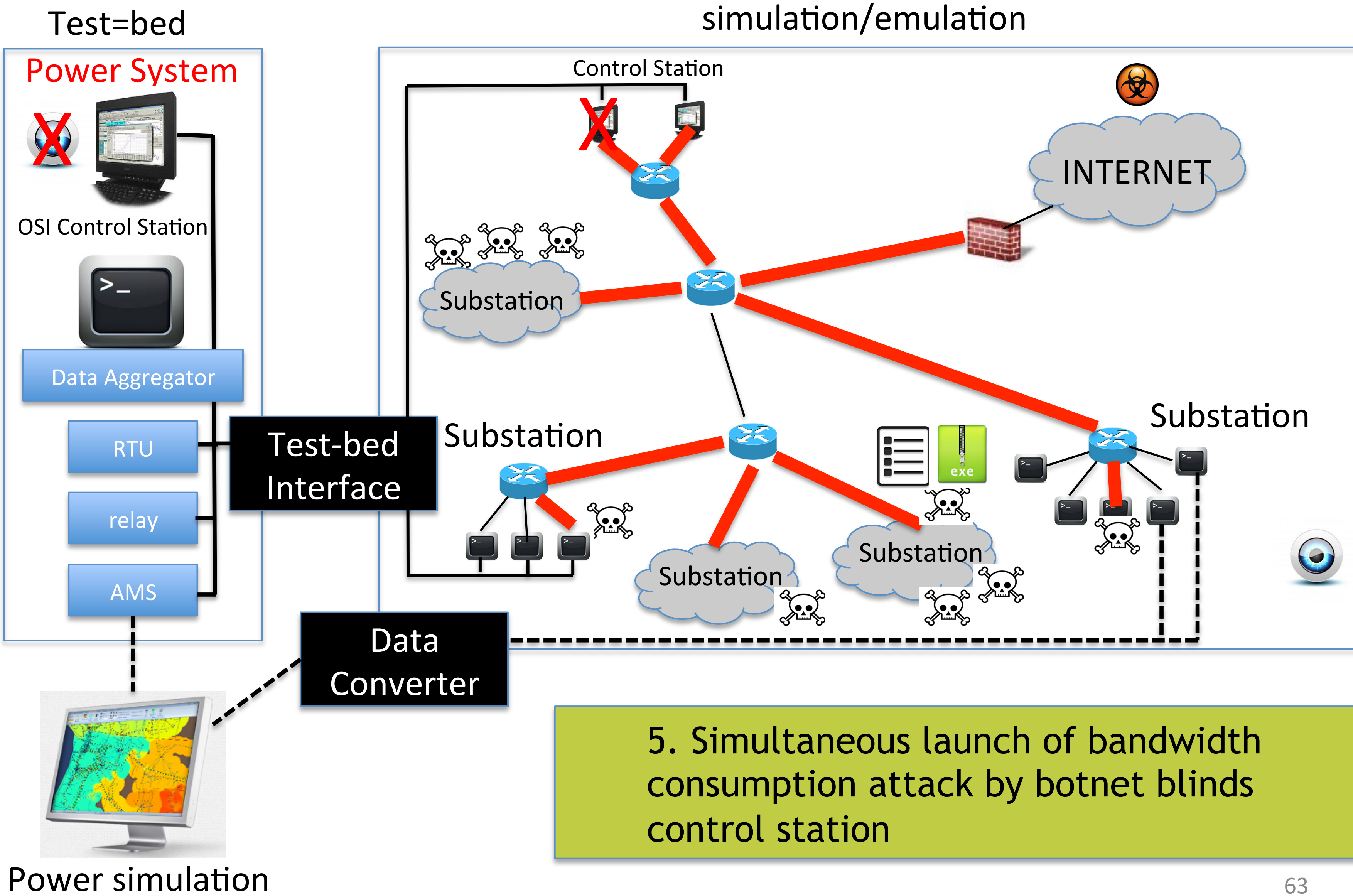

3. Compromised host infects others, creates botnet

# Example : Attack on Situational Awareness




4. Attack on relay causes line to open
Flow topology changes

# Example : Attack on Situational Awareness




5. Simultaneous launch of bandwidth consumption attack by botnet blinds control station

# Conclusion

Virtual time consistency in Smart Grid test-beds

- Allows greater flexibility in what can be studied

Integration of device/communication simulation + emulation well underway

Integration of power flow simulation with device/communication simulation has been accomplished

- Flow simulator needs special hooks

Integration of devices with virtual time is a Work in Progress