MONITORING AND CONTROLLING THE SMART ELECTRIC POWER GRID.

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The power grid is getting old…

- Today's electric power grid is a legacy of a long evolution that has many structural vestiges of the monopoly period

- As a result much power is wasted
  - With new "green" power sources, some utilities literally purchase power and throw it away
  - A great deal of what we generate is lost in transmission
  - And much of what gets delivered ends up being used to light empty rooms, keep water hot when nobody is home to use the shower, or gets turned into heat by computers that has to be removed using air conditioning

- Statistics
  - **66%** of the energy produced for electricity is lost, 10% of that in transmission.
  - **71%** of the energy produced for transportation is wasted.
  - **20%** of the energy produced to run American industry is lost, and
  - **20%** of the energy that we use in our commercial and residential buildings is wasted.

Smart-Grid Vision

- Within the home, office or building: a smart-meter dispatches power-hungry tasks at times convenient to the grid
  - Home A/C, freezer
  - Hot water heater, dish or clothes washer
  - Recharging an electric vehicle

- The meter knows a lot about you and privacy is a concern here. "Privacy preservation" highly desired

The smart grid would also control:

- High-power inverters for DC / AC linkages
- High-tension long-haul interconnects for sharing excess power needed to maintain load balance
- Power storage units (pumped water, inertial storage systems, even batteries)
- Microgenerators that phase in when demand is high and prices justify doing so, out when not in use
- Grid use of excess power from home solar arrays

A little bit of history

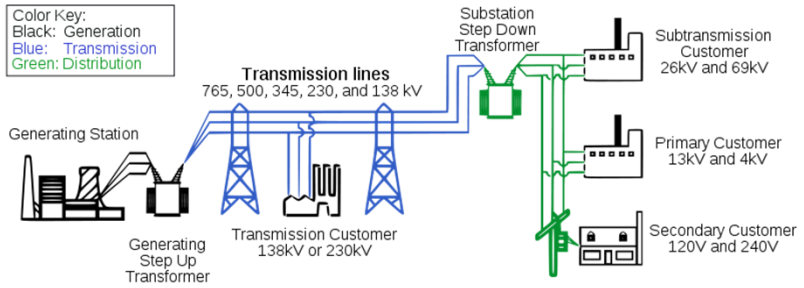
- Prior to the 1960's, most power in the United States was controlled by regional monopolies
  - They had sole control over the power generation, delivery and billing structure
  - There was no competition, so prices were regulated
  - Owning a utility was a guarantee of hefty revenue
- But the lack of competition also meant that there was little incentive for innovation
- Similar stories in many countries worldwide

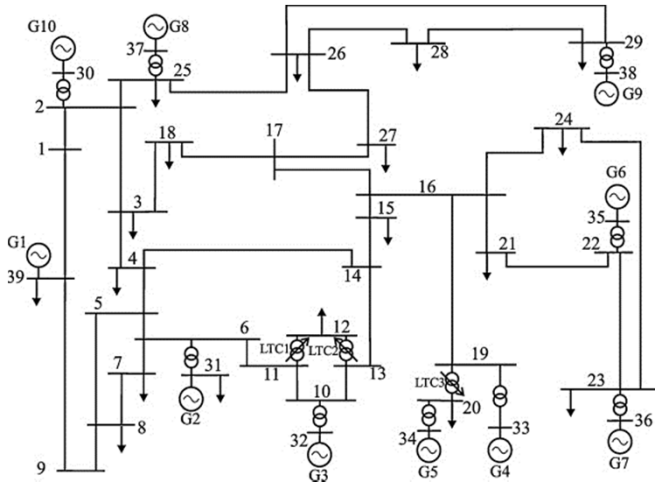
Restructuring: The US response

- A process of restructuring has slowly changed this:
  - Big regions broken into a collection of power producing companies, “independent service operator” (ISO), consumer-delivery companies
  - Emergence of 24-hour ahead of time power exchange markets where larger “parcels” of power can be bought and sold, permitting 24-hour lead time planning to ensure that the grid will meet its needs
  - ISO helps ensure competitiveness and stability
  - Increased use of long-distance high-tension lines to share “reactive power” between regions

How a small power grid operates

- Power flows "like water"
  - Path of least resistance
- Governed by Kirchoff's Law
- Power enters at every generator, exits at every load
- Hierarchical structure:
  - Primary "power busses"
  - Secondary smaller local feeds





10-Generator, 39-bus New England System

Operating a restructured grid

- Many entities, each with very limited visibility into the state of their neigbors
  - Two issues: **limited sharing of topological data** and **limited sharing of real-time status**, driven by competitive concerns, security worries, "evolution" of the system topology as lines break, are fixed, are changed
  - In practice, you "know your own grid" and know (a little) about tie-lines to your neighbors
- Various ad-hoc sharing and collaboration solutions are in place.... long list of blackouts in past decade testify to the issues with this approach!

State estimation

- This is the problem of collecting measurements of the power system
- Then fitting the measurements to a model generated from the systems bus architecture
- Like a least-squares optimization… complicated by:
  - Transients as devices come on/go offline
  - Imprecision of our models of the physical grid itself: The bus architecture is really a simplification of the actual system and fails to capture many aspects

Ways of doing state estimation

- Historical: SCADA
  - Track the line voltage and frequency
  - If frequency drifts, adjust generators
  - "State estimation" by fitting power equation to observed data, a computationally costly task

- New: "synchrophasor measurement unit" or PMU
  - Directly measures the phase angle of a power bus
  - Enables fast, hierarchical state estimation... *but only if the current topology is accurately known*

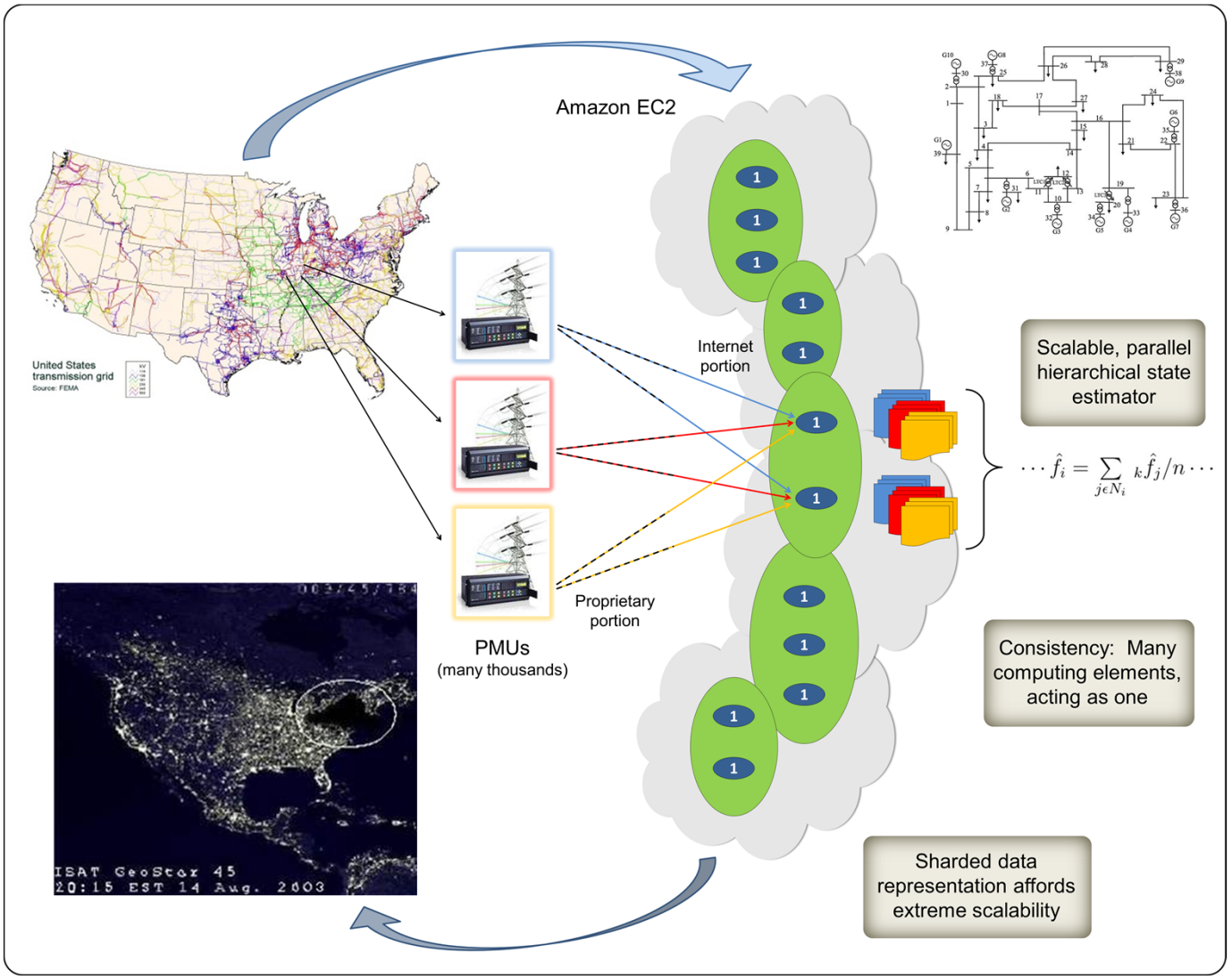
Adoption Limitations

- Renewables very hard to "plan" for, hence often offer power at times when it isn't convenient and can sag suddenly (visualize: cloud over solar field)
- Poor past experiences with machine-control solutions in the physical loop
- In a restructured grid, visibility into neighboring regions is of limited quality, topology data may be unavailable
- Commercial market place dominated by six big players, and they sell all the products. Extremely proprietary

Power grid under attack?

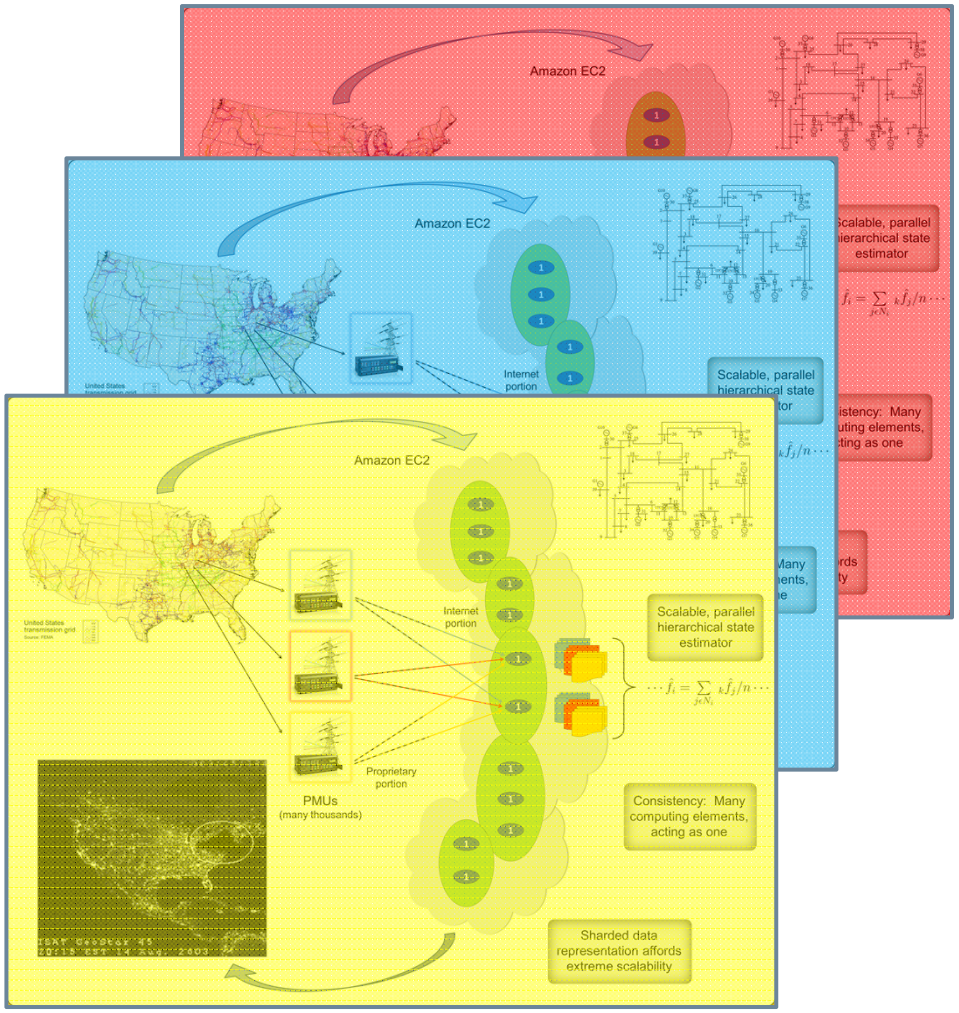
- Richard Clarke has argued (in his book CyberWar) that we are at grave risk of attack on the grid
  - He believes that the grid is already so connected to the Internet that it can be disrupted easily
  - Argues that some forms of attack would destroy huge amounts of hard to replace infrastructure: "logic bombs"
  - And he suggests that many countries may actually have prepositioned these logic bombs for use during times of political stress or war

GridCloud: Scalable, secure monitoring



As deployed: Mutually-distrusting domains

- Distinct owners: Peers plus hierarchy (ISO)
- Owner controls data flow: distinct security policies
- ISO integrates data… but as we get further from sources, quality of information is a potential concern



Key design features

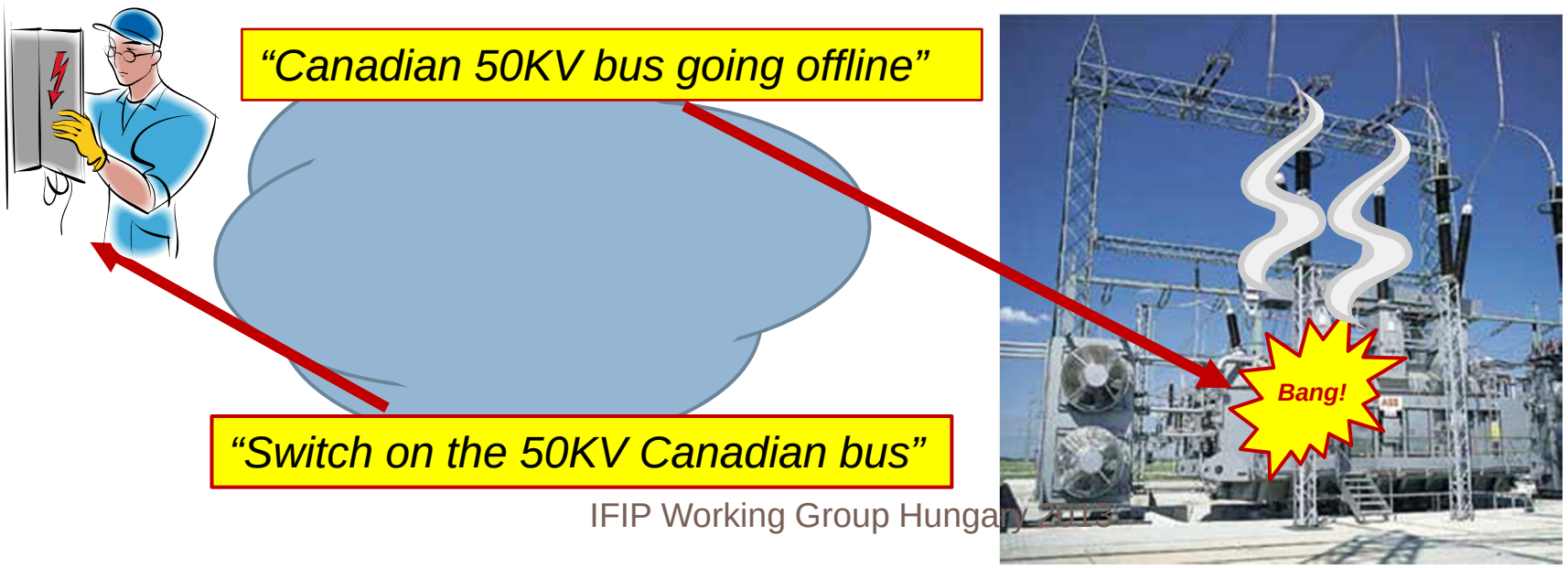
- Redundancy to overcome network or cloud scheduling delays, faults
- Open-flow network routing scheme integrated with a new security architecture we've developed
- On cloud, can host various applications: some ignore sharded data format but others could leverage it
- We use Isis2 to manage and control the system
  - Free open source group communication system
  - Includes a new scalable distributed "data analysis" tool

What will GridCloud applications do?

- Consume monitoring data, output "advice" (later, perhaps do direct control for some technologies)
- These applications fall into categories
  - Use of machine-learning to develop optimized plans for dispatch of power
  - Tools for helping operators manage and control their smart grid networks
  - Contingency reaction solutions for dealing with various kinds of environmental (or other) disruptions
  - "What-if?" technologies to assist the owner in evolving their system with new technology capabilities

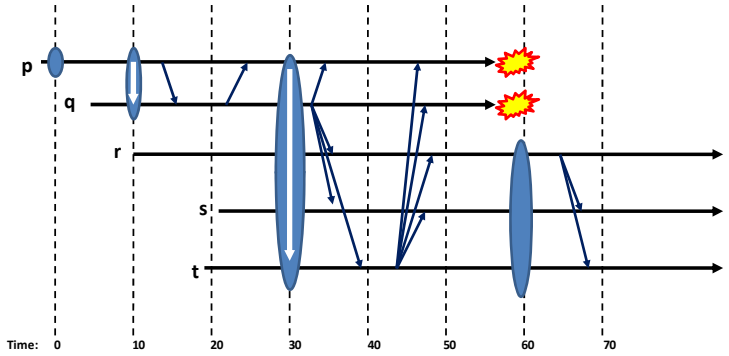
Dangers of Inconsistency

- Inconsistency causes bugs
  - Cloud control system speaks with "two voices"
  - In physical infrastructure settings, consequences can be very costly

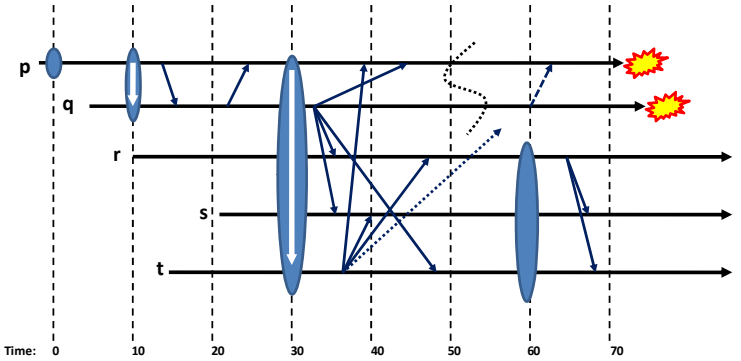


GridCloud Consistency: Based on Isis^2

Non-replicated reference execution



Synchronous execution



Virtually synchronous execution

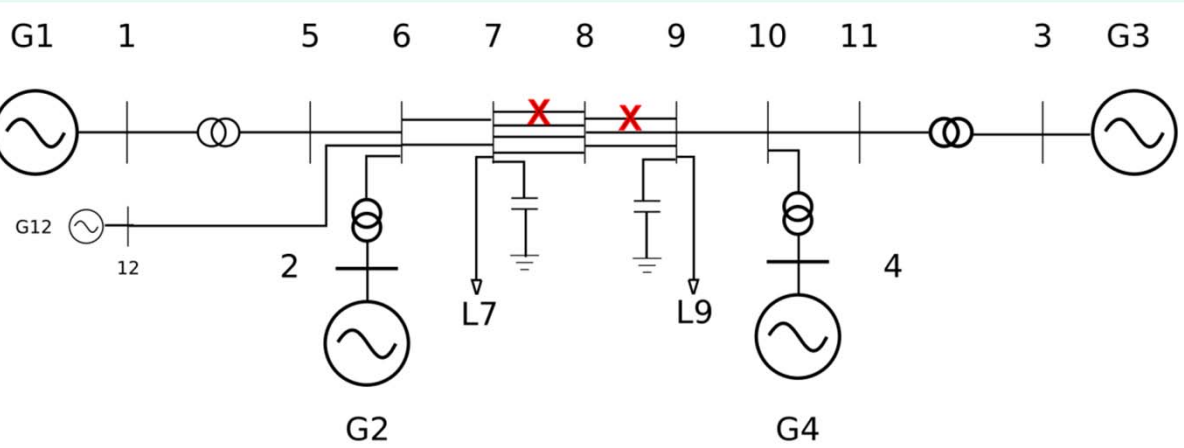
- ***Virtually synchronous runs* are indistinguishable from synchronous runs**
- *We are using Isis^2 to create a control and management system for GridCloud*

Security

- Mutually suspicious organizations that nonetheless must collaborate safely while repelling attackers
  - Human issue: design acceptable information sharing policies at a relatively "fine grained" level
  - API issue: Need suitable ways to express these policies so that operators will understand them
  - Technical issue: GridCloud managed network would need to correctly implement the desired behaviors
- Given complexity of the setting, these goals represent significant challenges

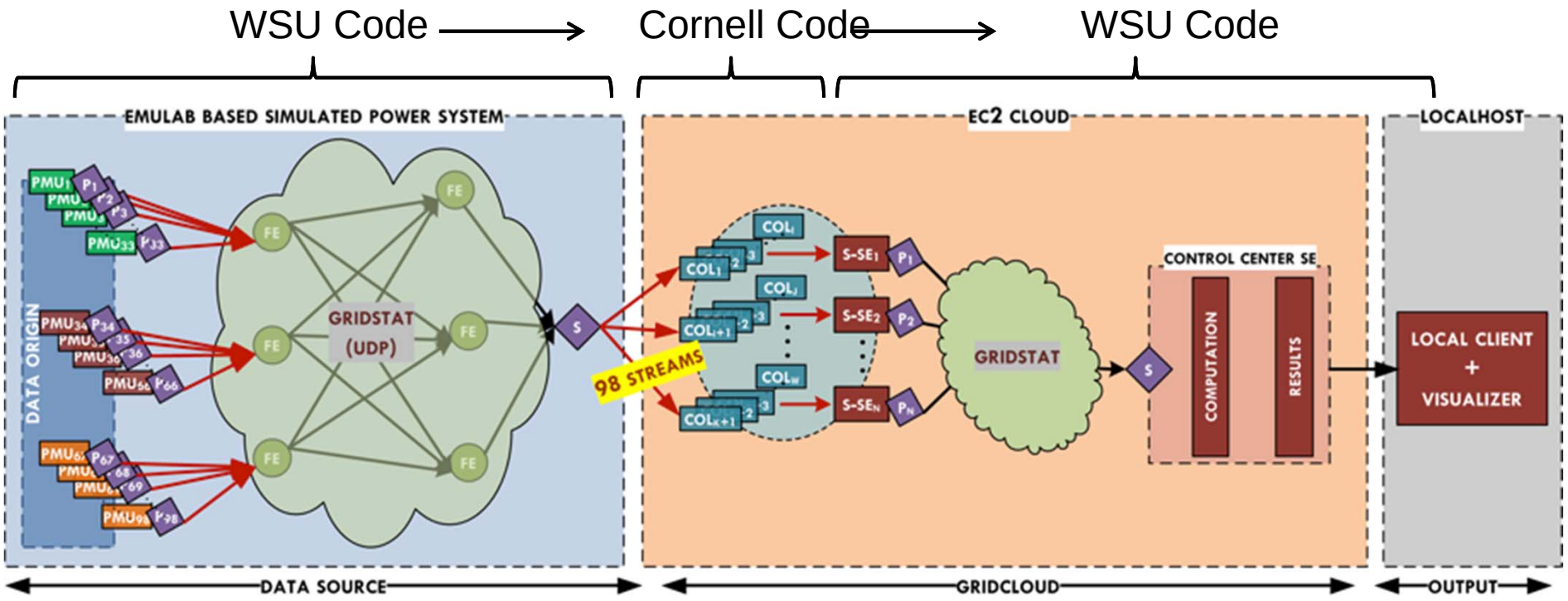
Experiments with our prototype

- 2 Area System Simulation – Standard IEEE test system
- Two Induced Contingencies
  - @ 1min mark – line 7-8 disconnected
    - Reconnected after 5 seconds
  - @ 5min mark – lines 7-8 & 8-9 disconnected
    - Not reconnected

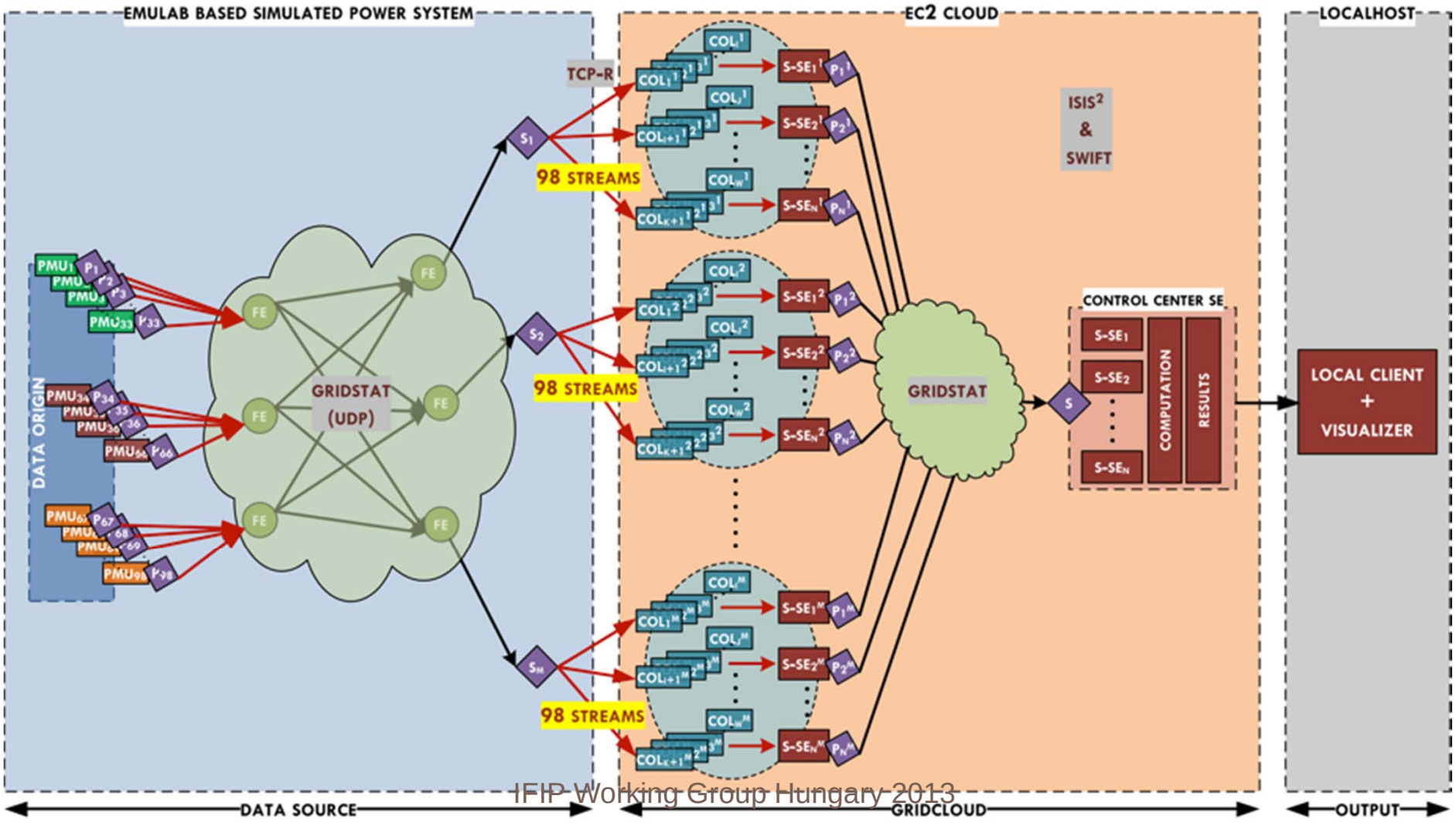


Early experience with GridCloud

- Starting point: An existing state estimation system

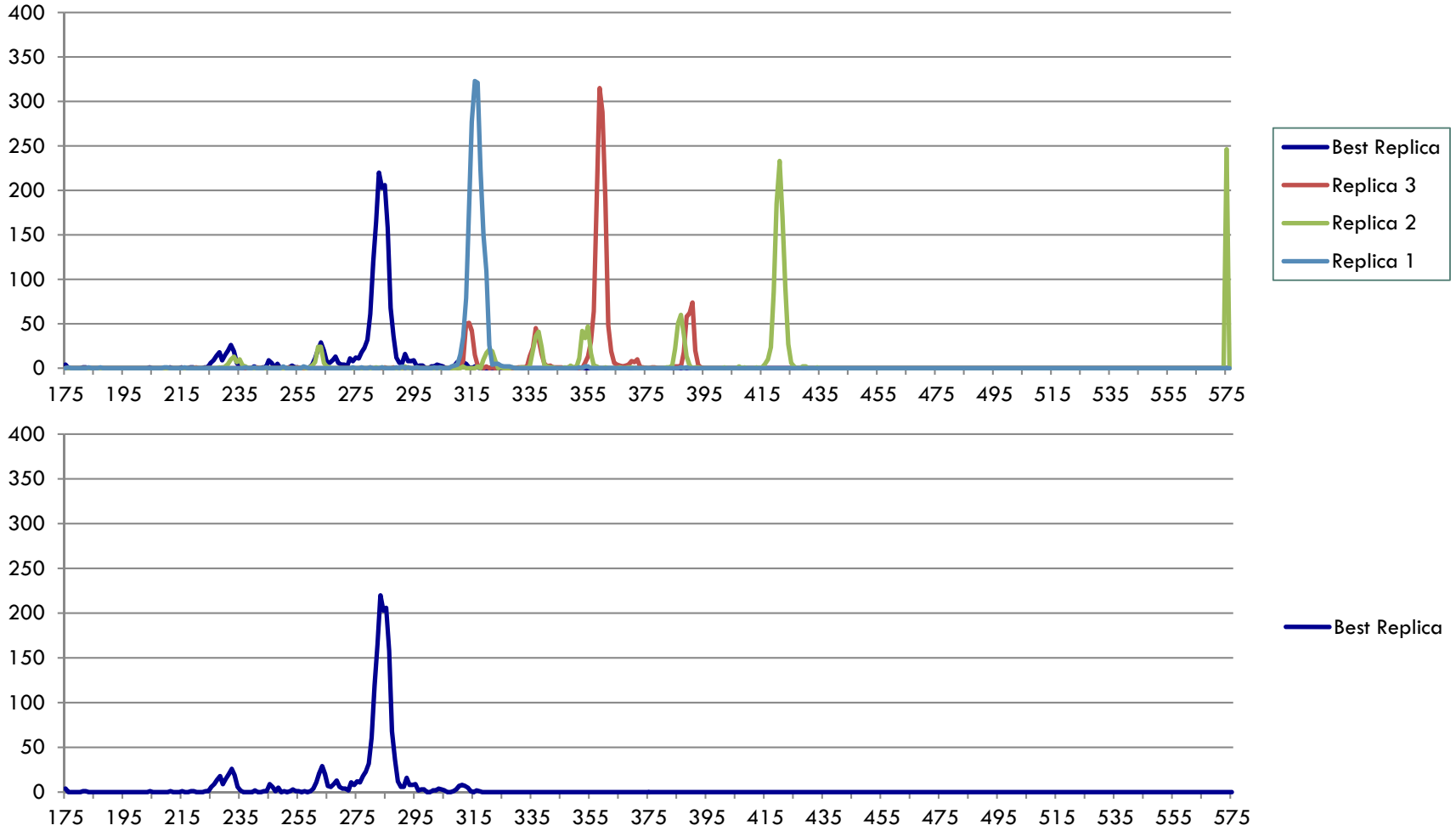


Modified version leverages redundancy



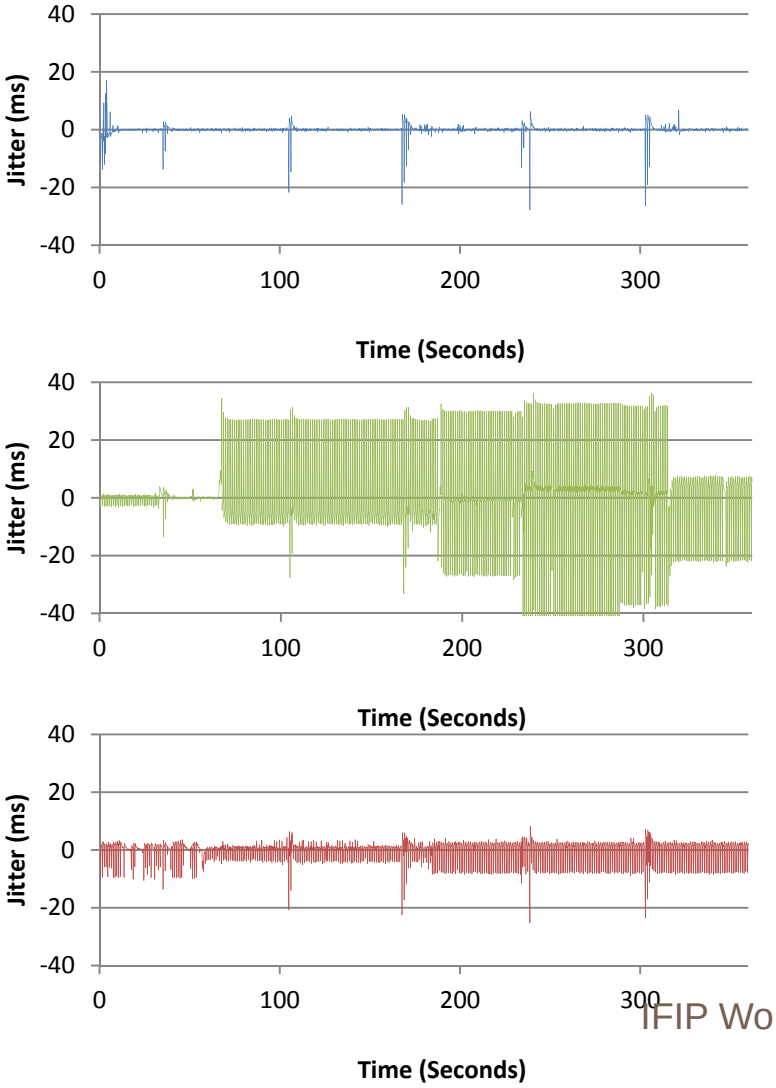
Latency Distribution

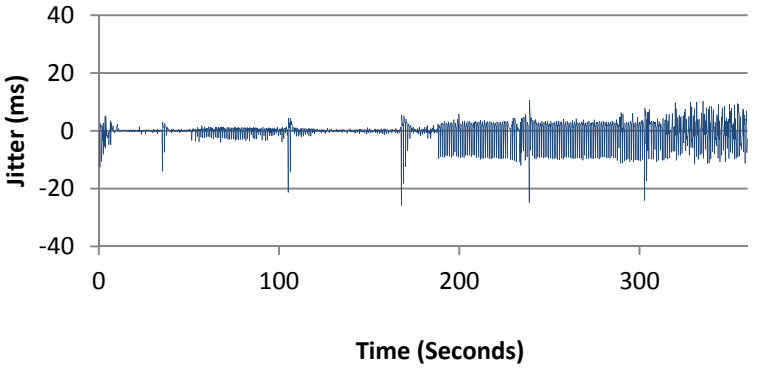
Graphs: Number of times a particular latency occurs



Jitter

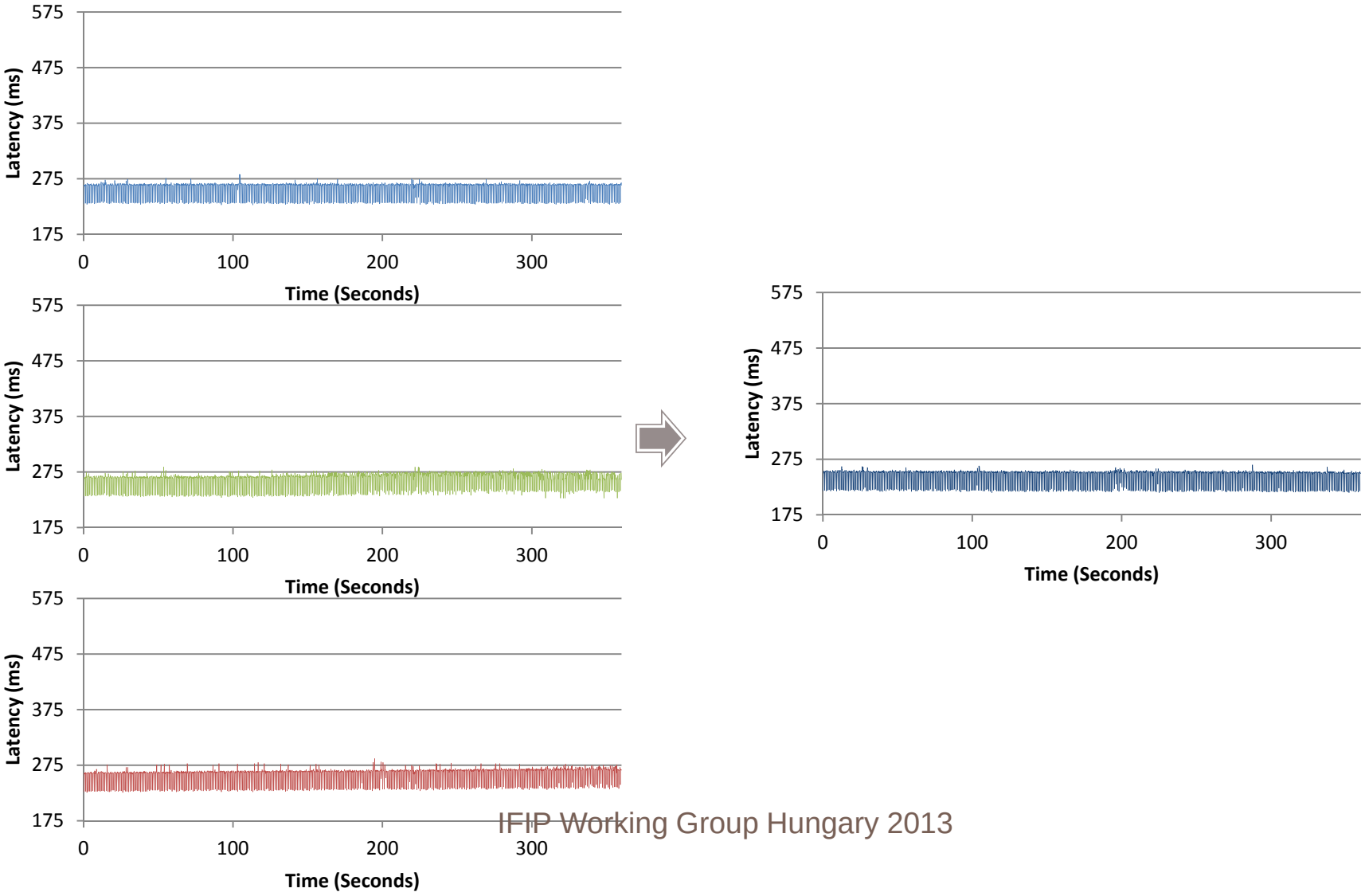
Graphs: Jitter of previous latency graphs





Replica Latency Reduction

Graphs: Latency – Length of time until all necessary data is available

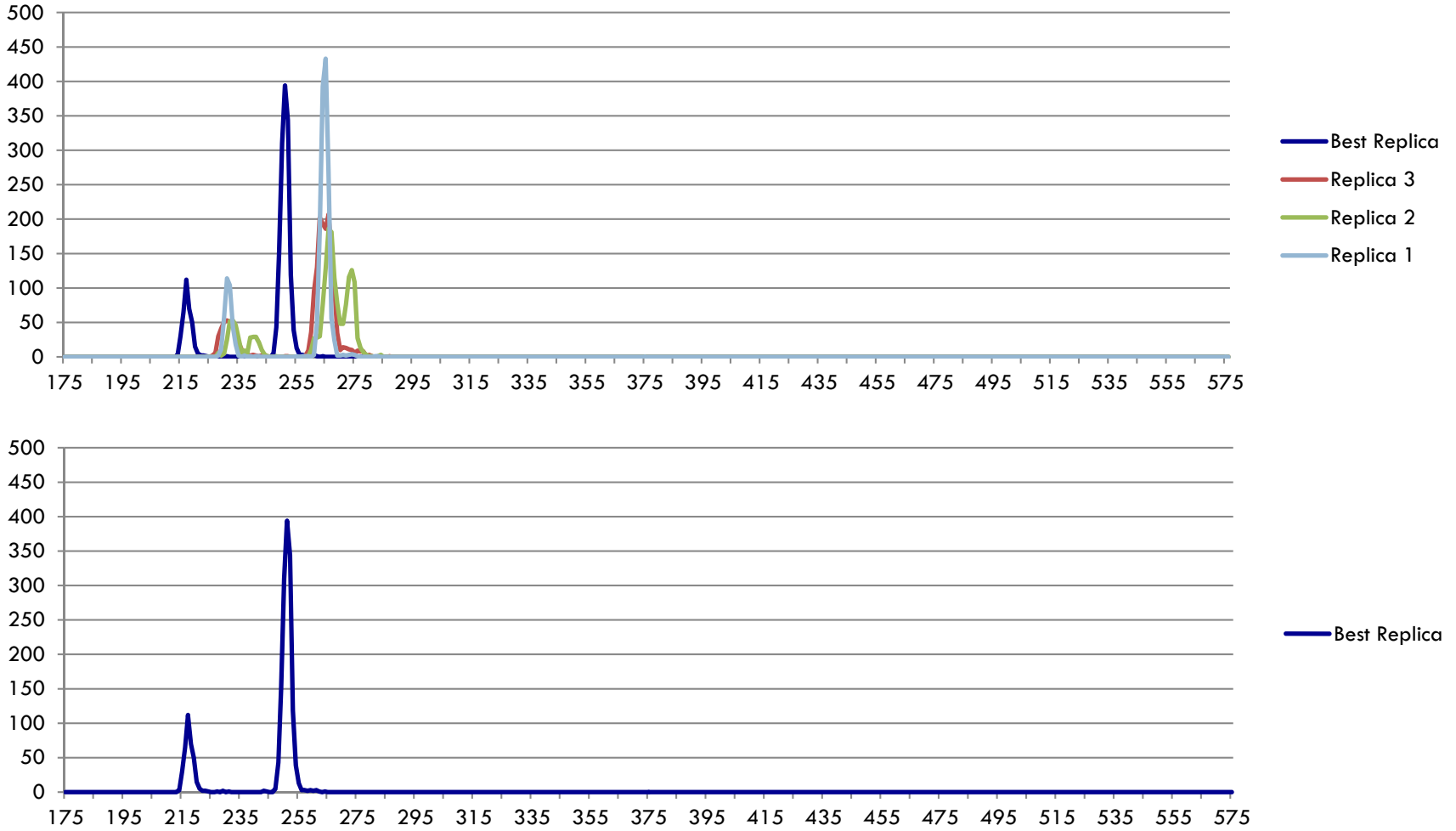


Improvement Summary

- Vastly reduced latency and jitter
  - All replica latency reduced from typical [235 , 350] to [215 , 250]
  - All replica jitter reduced from typical [-10 ,10] to [-5 , 5]
- Consistency from replica to replica has improved
- Consistency between “all replicas” to a particular replica has improved
- Consistency over time for each run has improved

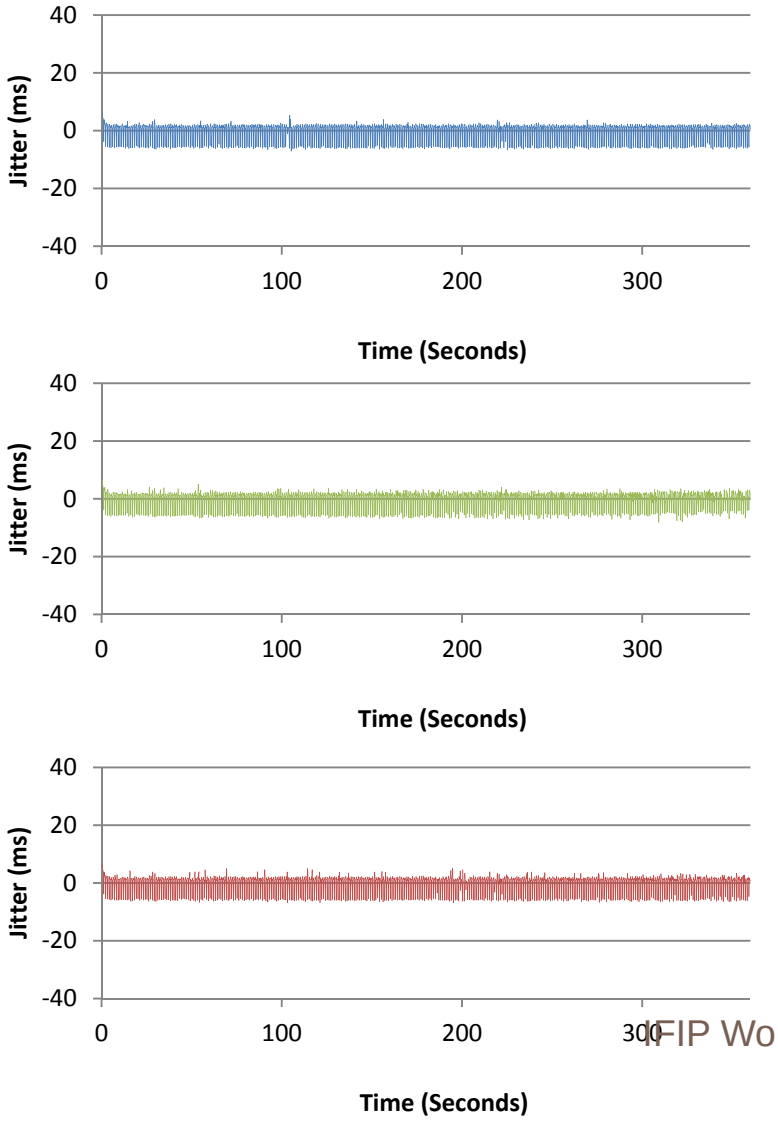
Today: Latency Distribution

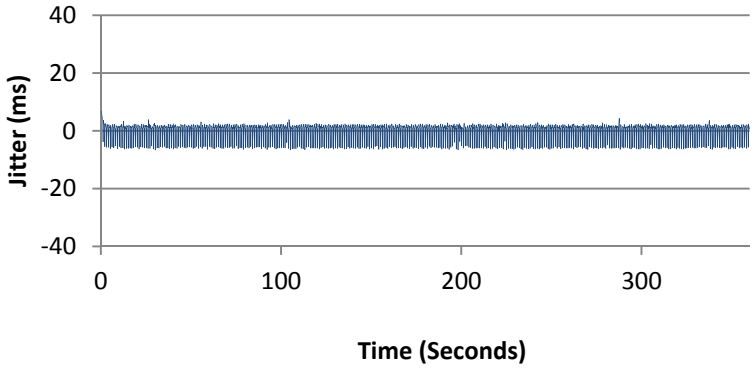
Graphs: Number of times a particular latency occurs



Today: Jitter

Graphs: Jitter of previous latency graphs



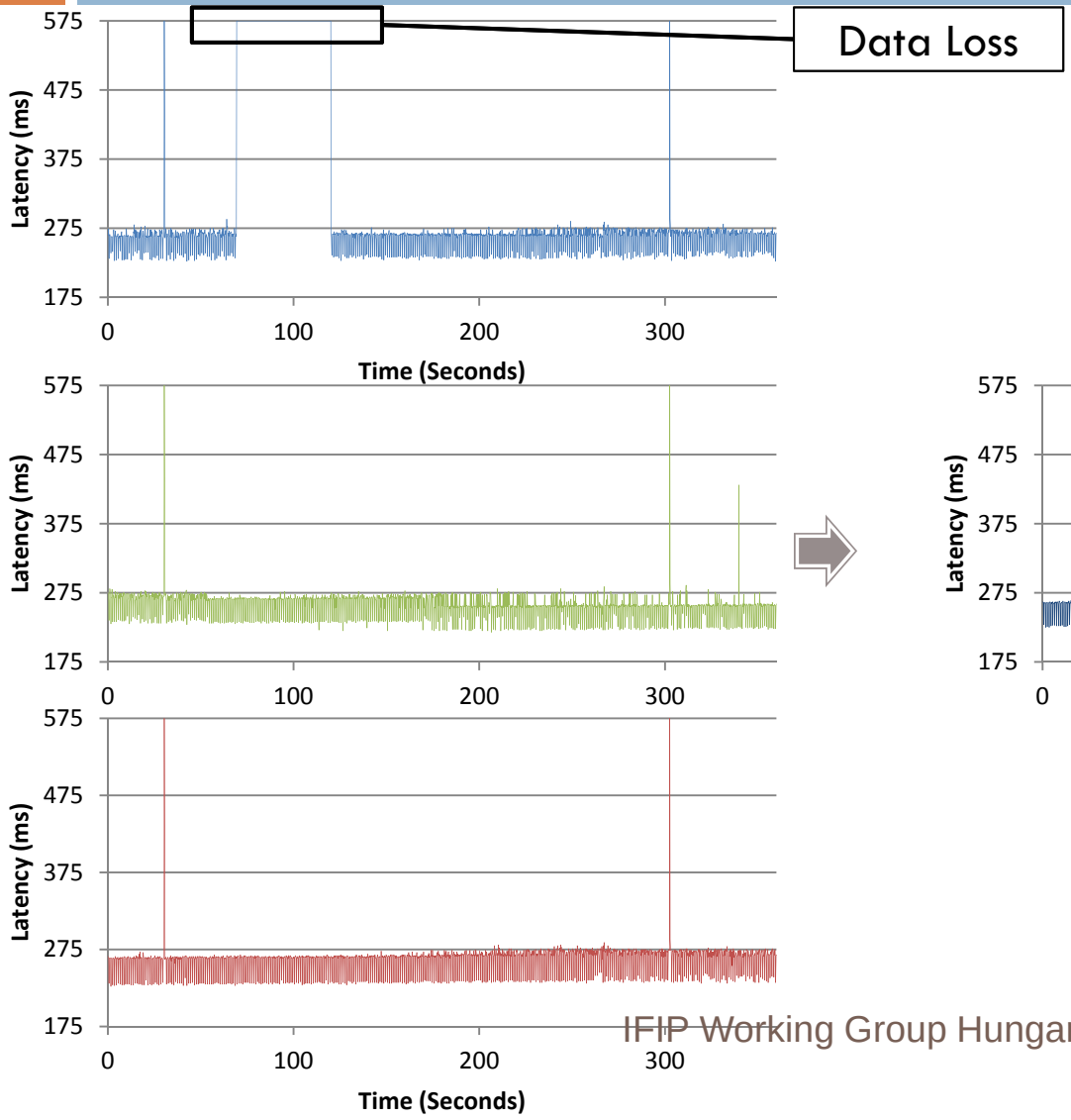


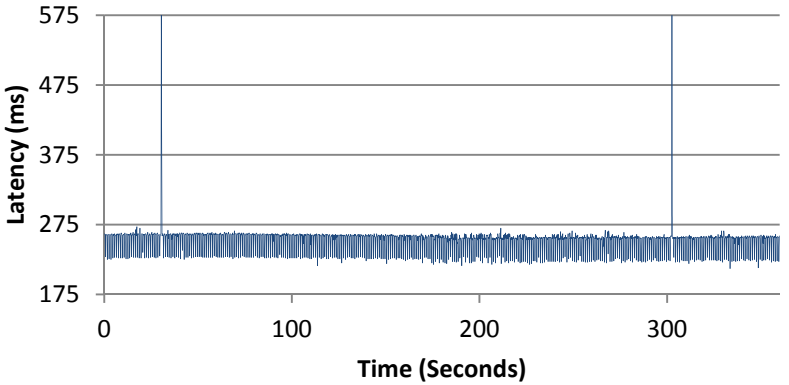
Case Study: Failure of 1/6th of Collector Nodes

- We fail Replica1-Node2 of the collectors for 1 minute
- This results in 62 out of 294 PMU streams being unavailable for 1 minute

Failure Case: Replica Latency Reduction

Graphs: Latency – Length of time until all necessary data is available





Failure Case: Latency Distribution

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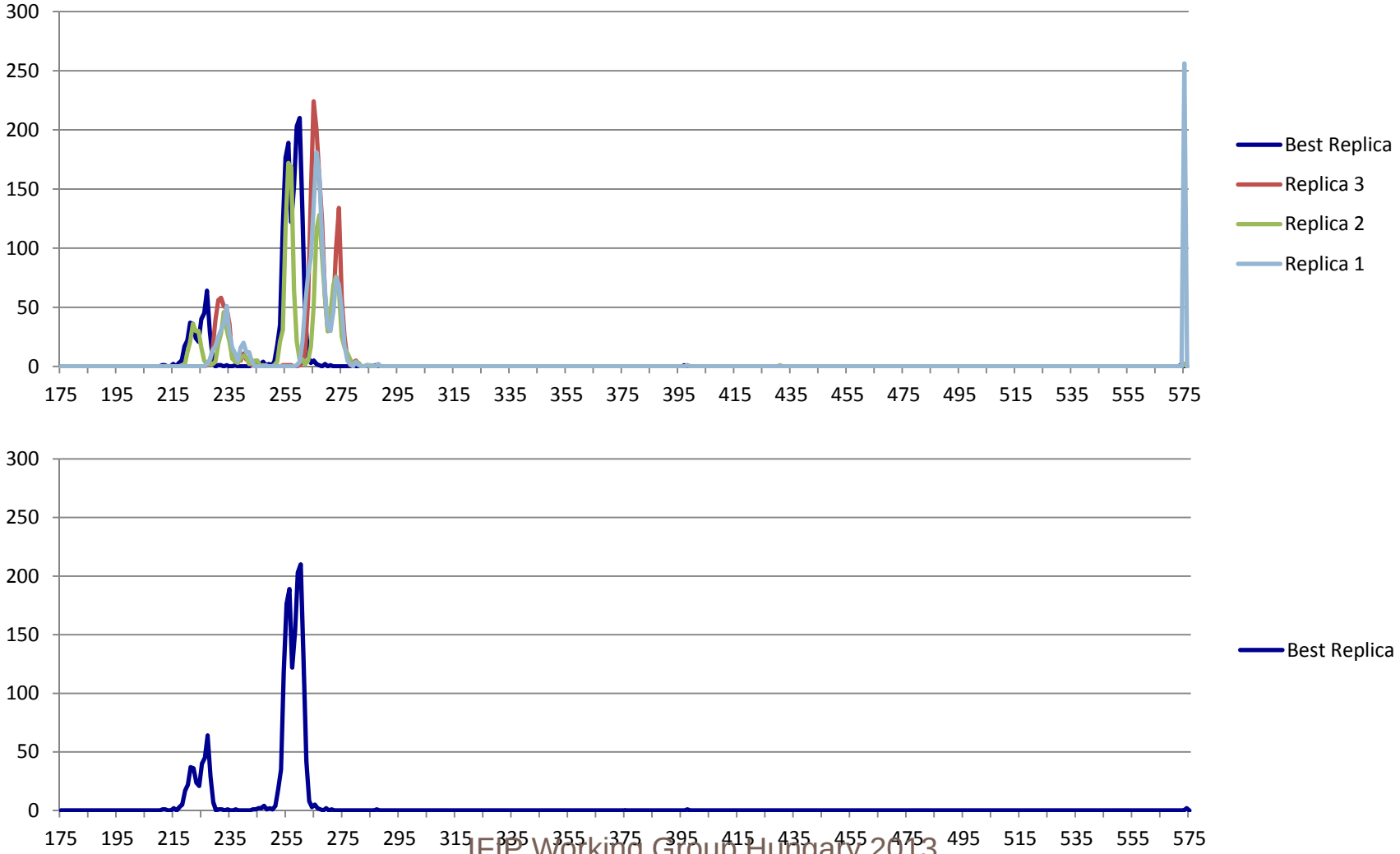

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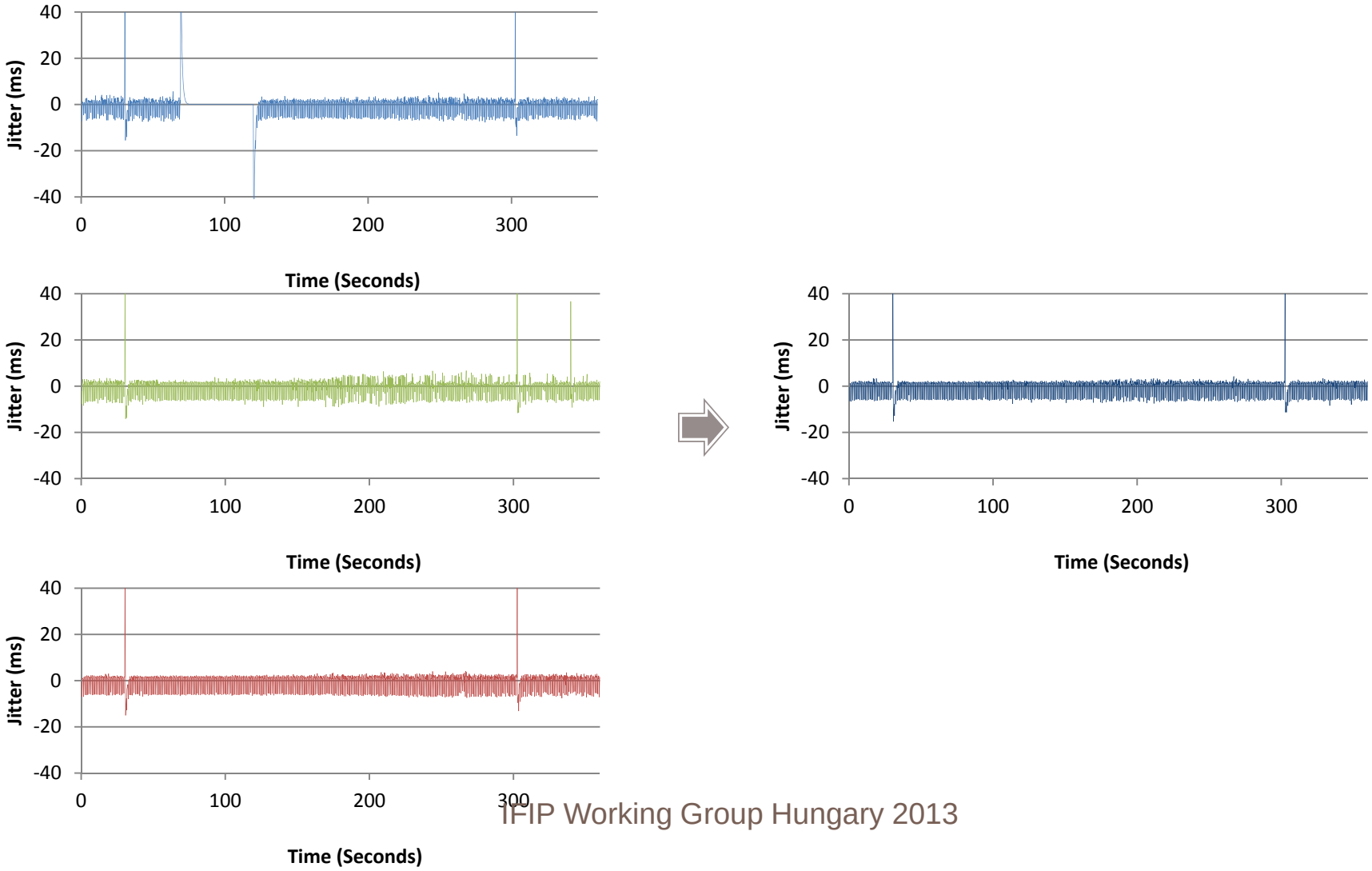
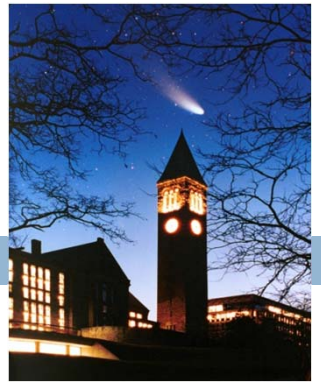


A long road ahead…

- Future monitoring need could involve tens or hundreds of thousands of PMUs operated by multiple mutually distrusting organizations
- Security requirements will force us into a world with multiple side-by-side "micro-clouds" that share data only in controlled ways
- Any serious system will host many "smart" applications and need to automate dispatch, scheduling, configuration management

GridCloud envisions a kind of "GooglePlex" for the Smart Grid



- A complex mix of technical, security and even social challenges
  - Research can demonstrate feasibility but actual uptake will depend on economics and political factors
  - Prototype uses Isis^2 in many ways (isis2.codeplex.com)

- We're trying to hide the technologies we use, such as Isis^2, from users. Analogy: conductor of an orchestra
  - Nonetheless, the style of power grid computing changes
  - Even our open source model is new for this community