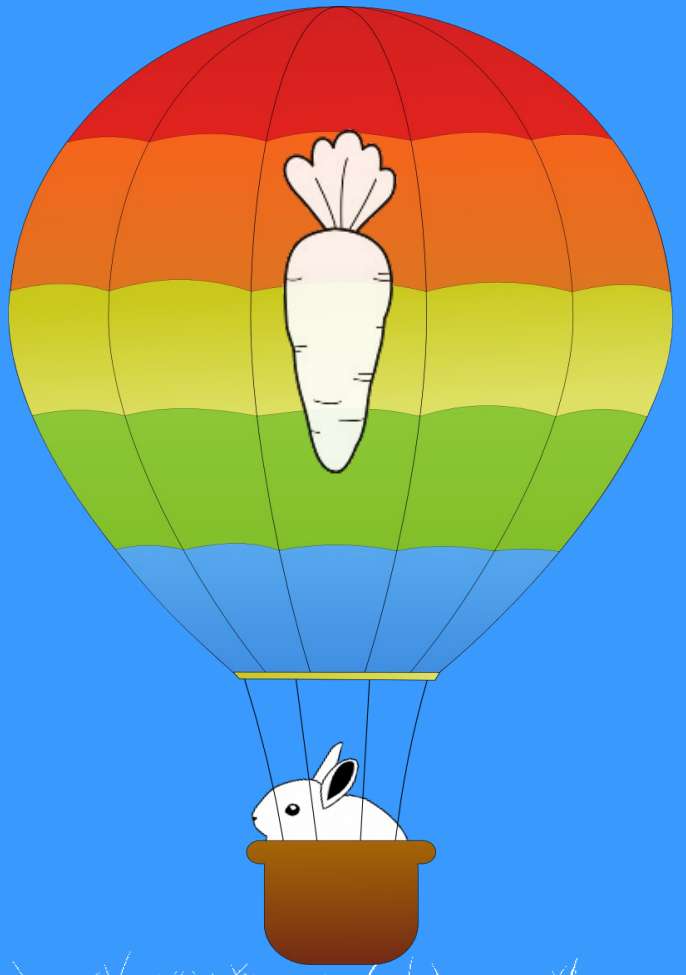
DESIGN, IMPLEMENTATION, AND EVALUATION OF NAPALI: A NOVEL DISTRIBUTED SENSOR NETWORK FOR IMPROVED POWER QUALITY MONITORING.

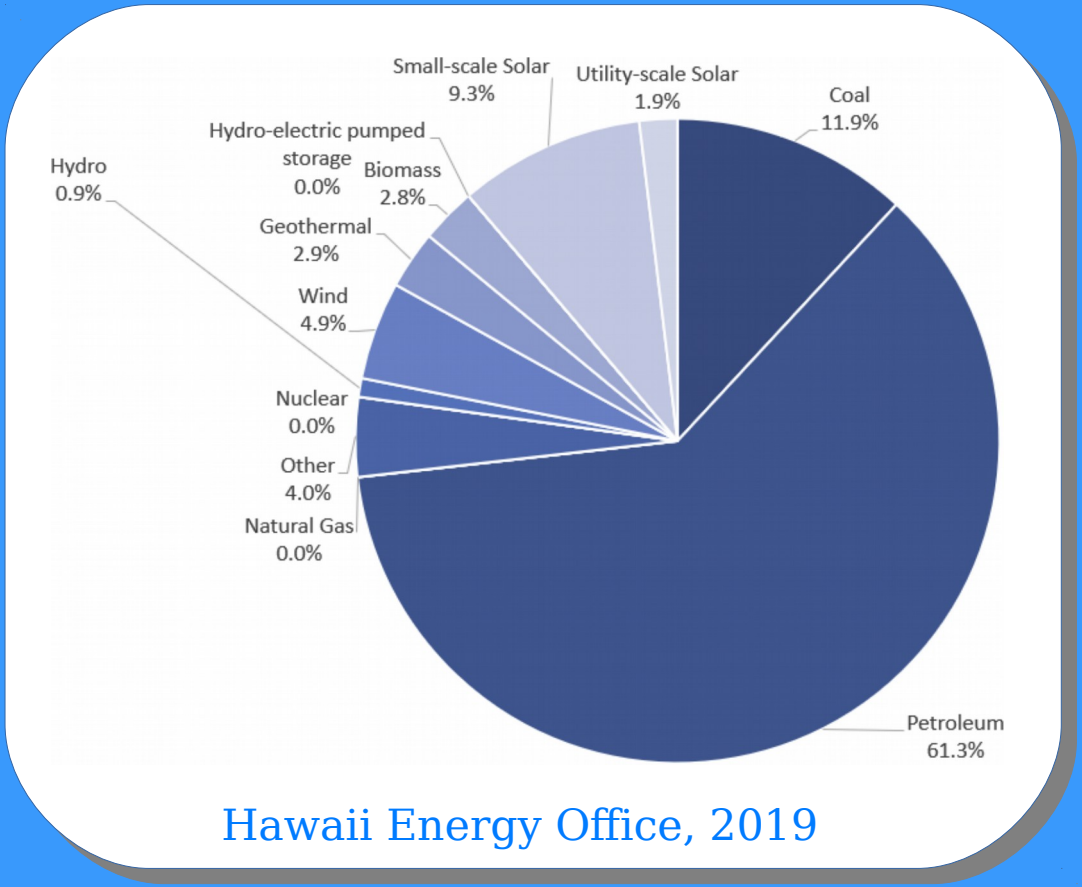
Dr Sergey Negrashov
March 10, 2020,

Outline

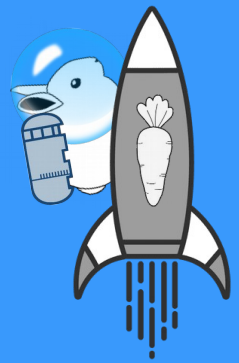
- Power Quality
- Napali
- OPQ Network
- Evaluation
- Applications
- Future Work



Climate Change

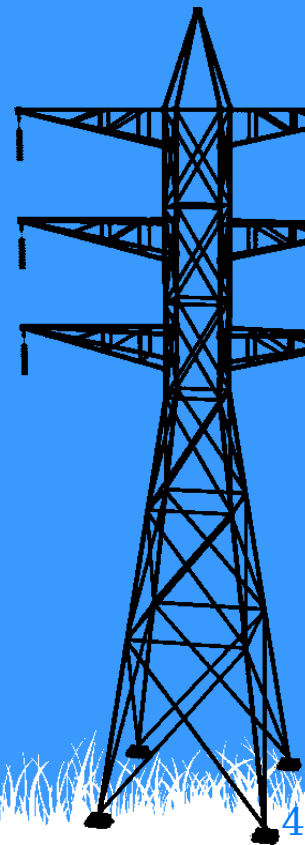


Hawaii Energy Office, 2019

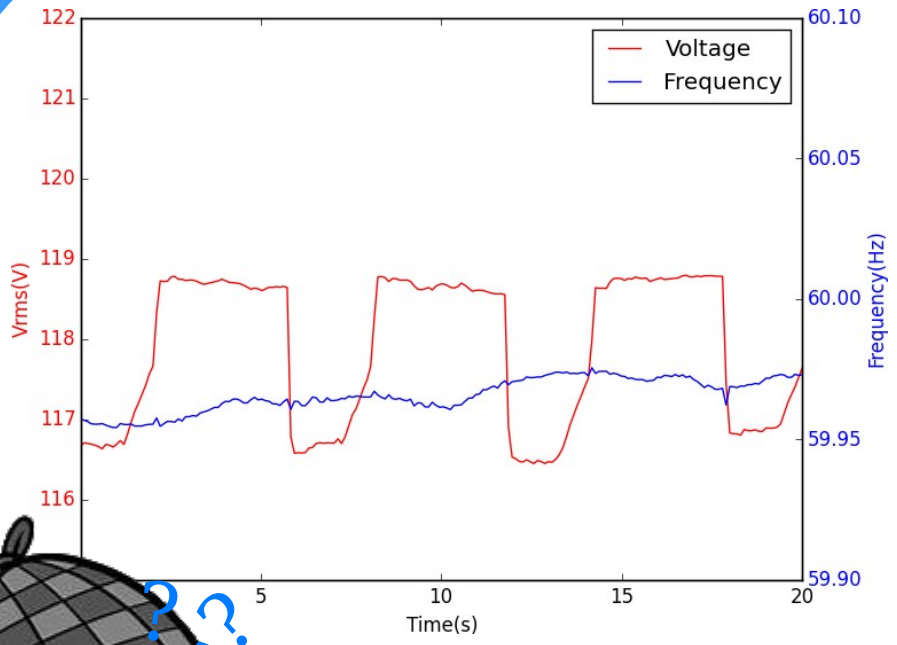


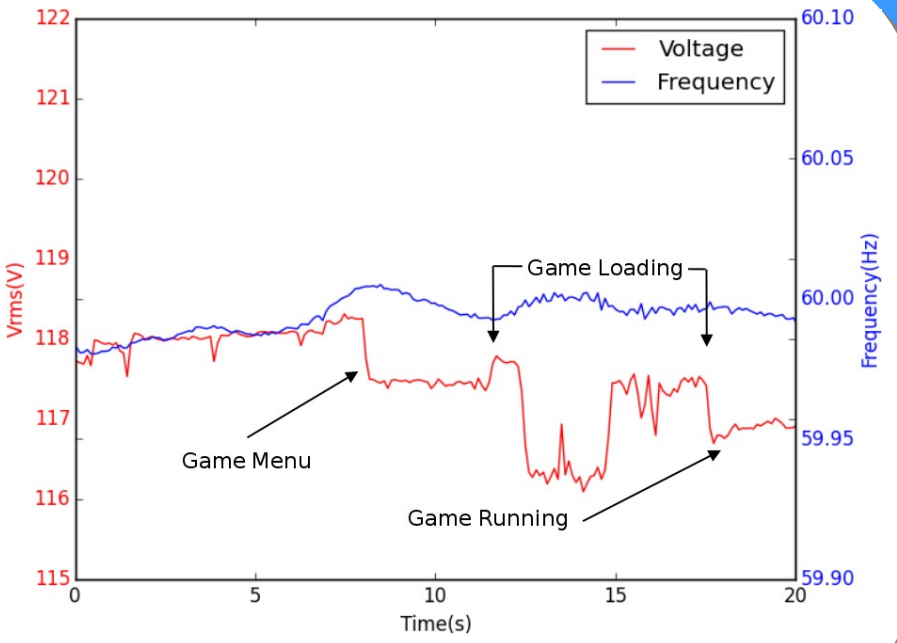
Problem of Power Quality

1. Amplitude
2. Fundamental Frequency
3. Harmonic Distortion
4. Transient
5. Phase Angle
6. Reactive Power

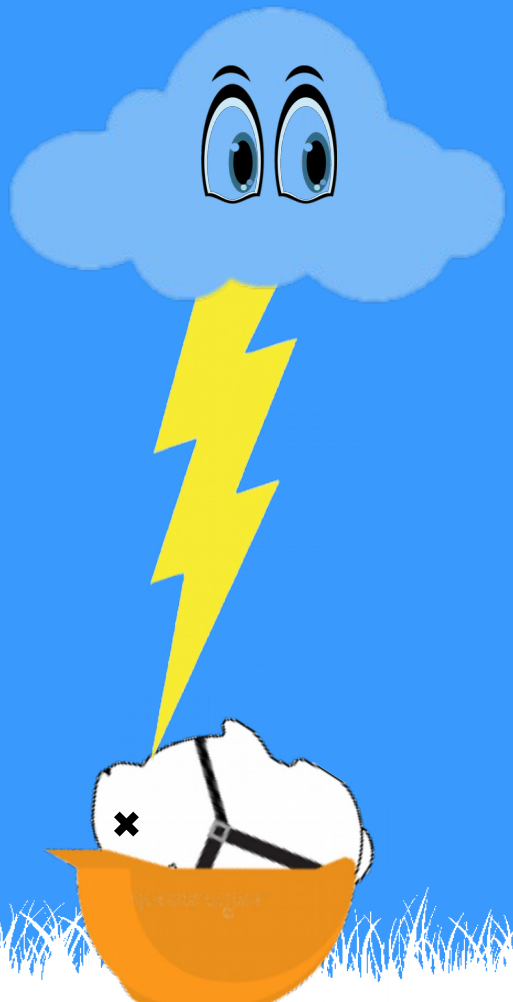


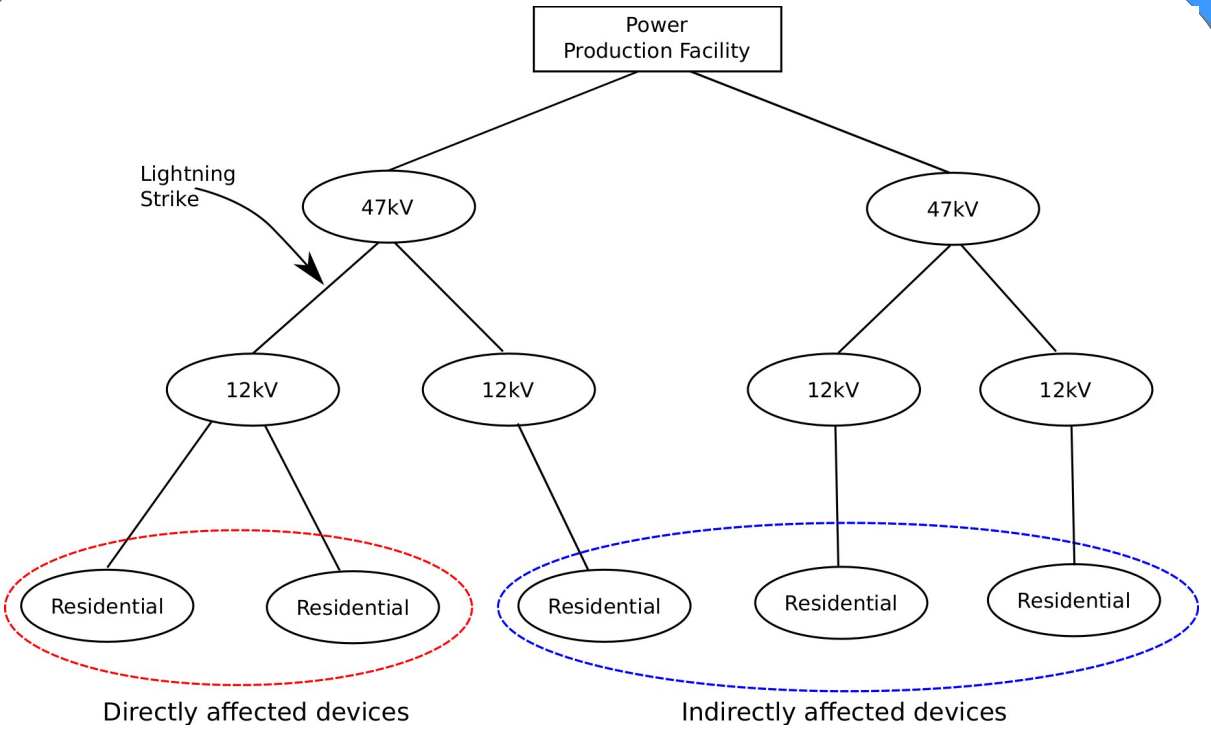
Where does the disturbance originate?





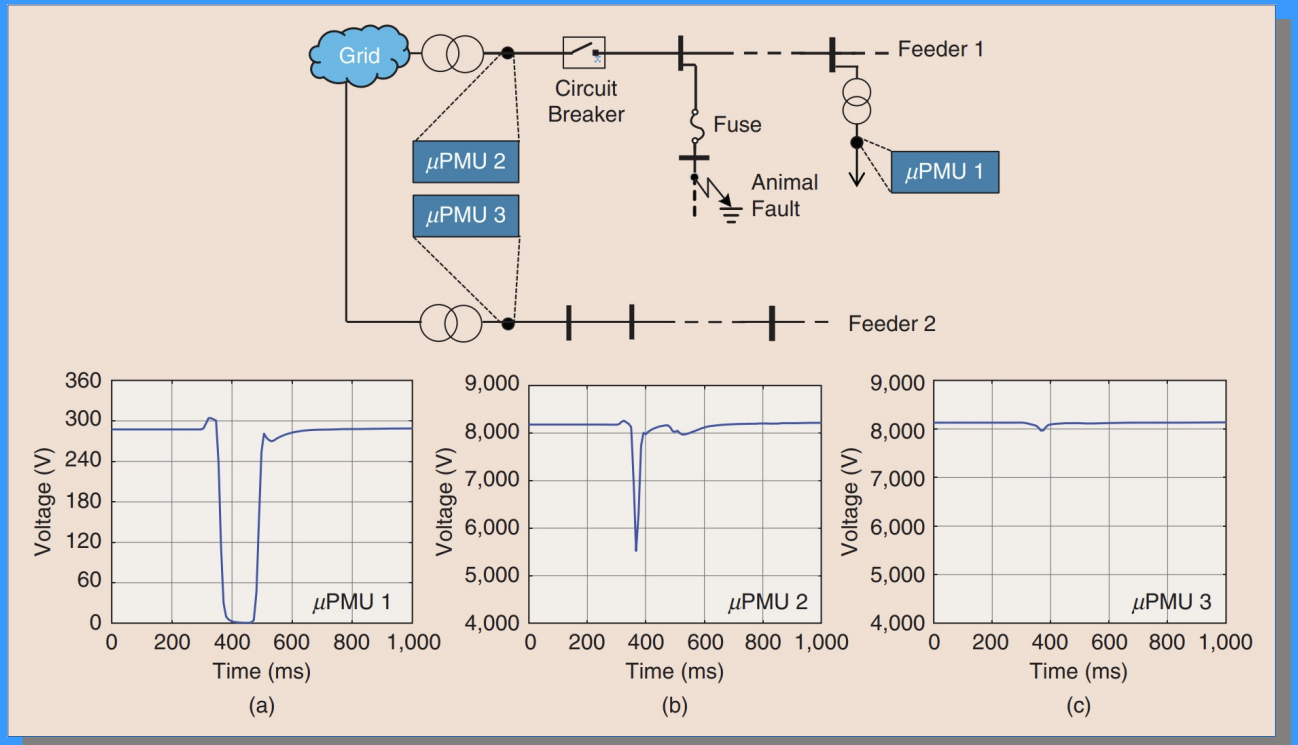
Event Propagation





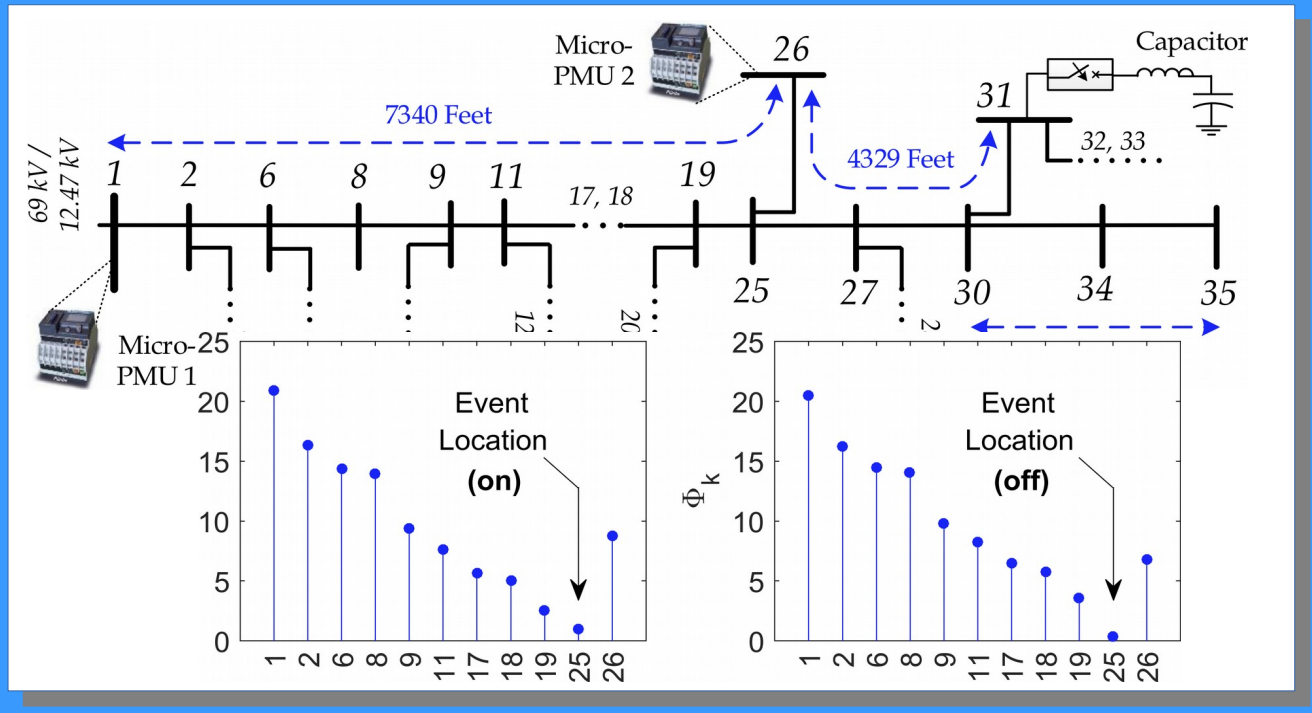
K Kahle. Power converters and power quality.
CERN, 2016

Manual Detection Methods



"Distribution synchrophasors: Pairing big data with analytics to create actionable information."
IEEE Power and Energy Magazine (2018)

PQ Event Localization



"Locating the source of events in power distribution systems using micro-PMU data."
IEEE Transactions on Power Systems (2018)

Event Detection

Animal

Detection

Bunny

Classification

Fancy Bunny

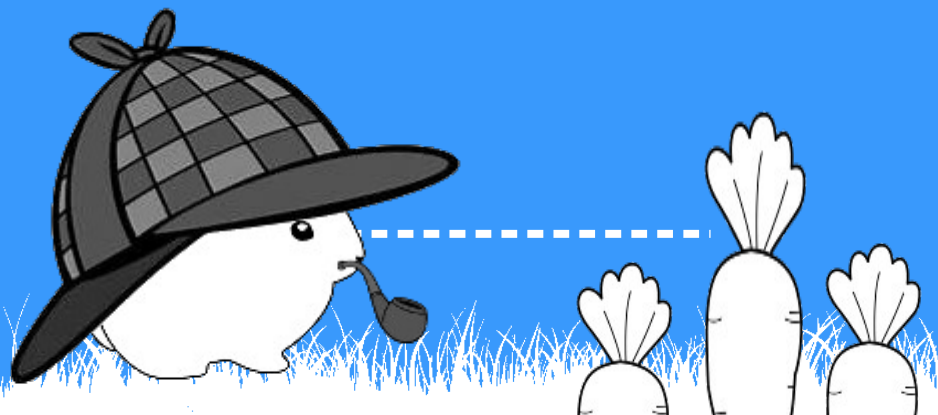
Event Detection Pipeline

Threshold Based Detection

Metric Extraction

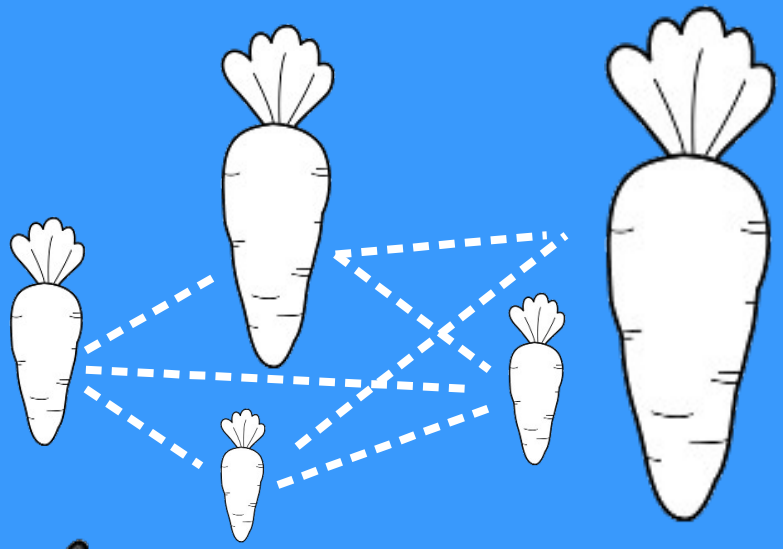
Threshold

Event Storage



Distributed Event Detection

Traditional Methods



Naive Detection
Send Everything

Self-Triggering
Detect Locally

Distributed Event Detection

Industry bleeding edge

Naive Detection

Send Everything

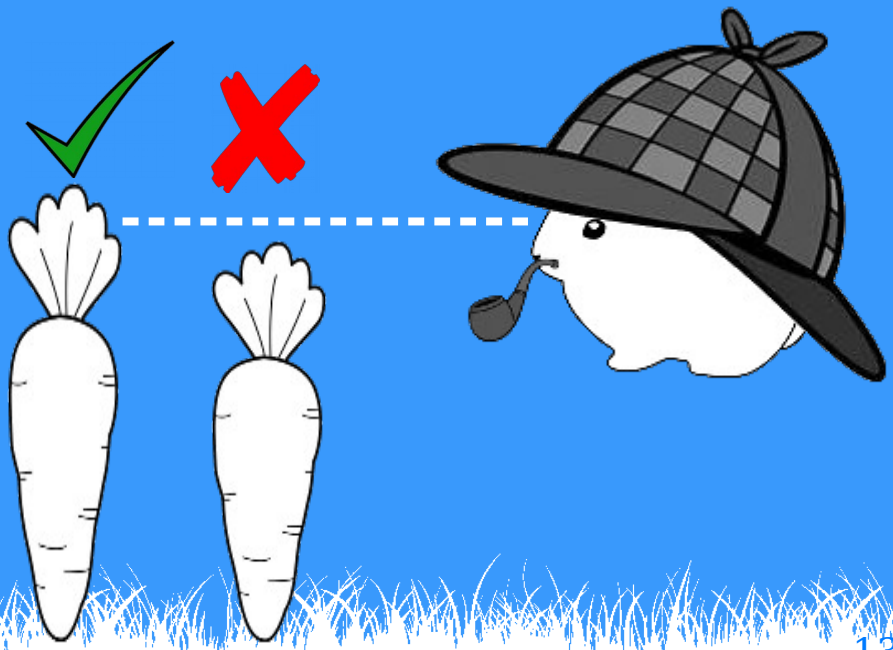
Self-Triggering

Detect Locally

Issues with Current Methods

Naive Detection
- Bandwidth
- Memory

Self-Triggered
- Detection Efficiency



Future of PQ Monitoring

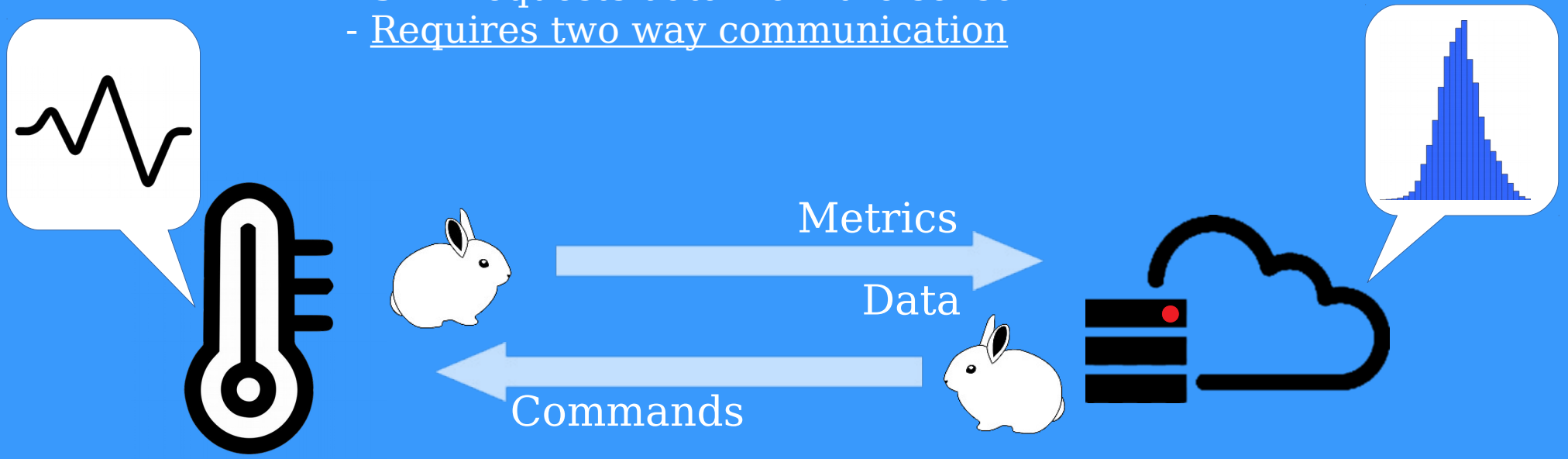
The main challenge is to go beyond manual methods based on the intuition and heuristics of human experts...

... it is crucial to develop the machine intelligence needed to automate and scale up the analytics on billions of µPMU measurements and terabytes of data on a daily basis and in real time.

"Distribution synchrophasors: Pairing big data with analytics to create actionable information."
IEEE Power and Energy Magazine (2018)

Napali

- Sensor forward metrics to the sink
- Sensor stores raw data locally
- Sink builds a statistical model of the sensor
- Sink requests data from the sensor
- Requires two way communication



Napali

- Sink maintains a coarse view of the entire system.
- Sink filters out local events.
- Sink determines which devices participate in event detection

Claim #1

Napali provides a novel architecture that is both a feasible solution to the problem of distributed power quality monitoring and provides significant benefits over the two standard alternative architectures.

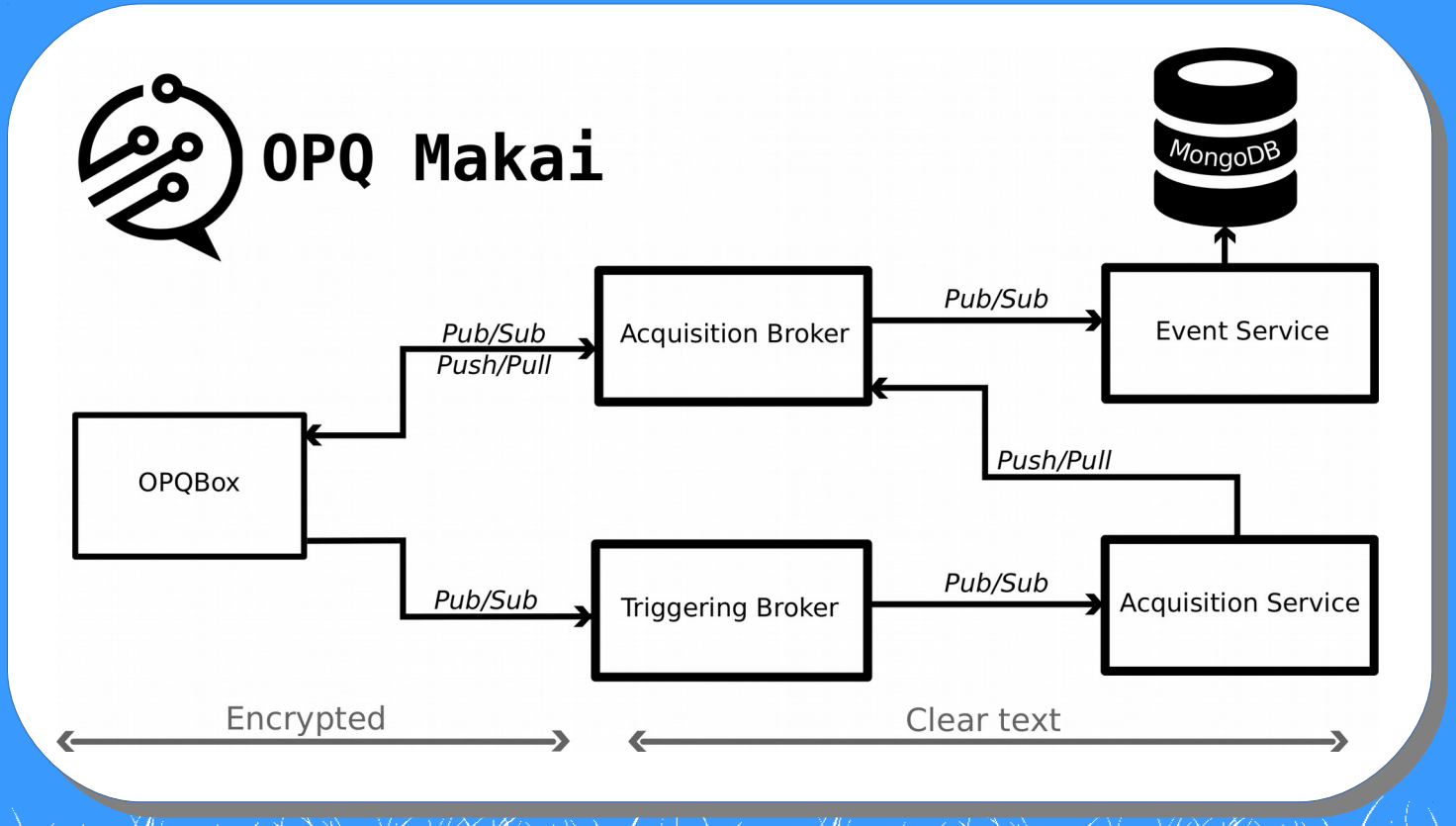
Claim #2

Napali architecture can, in principle, provide benefits for other domains beyond power quality.

Subclaims of the Thesis

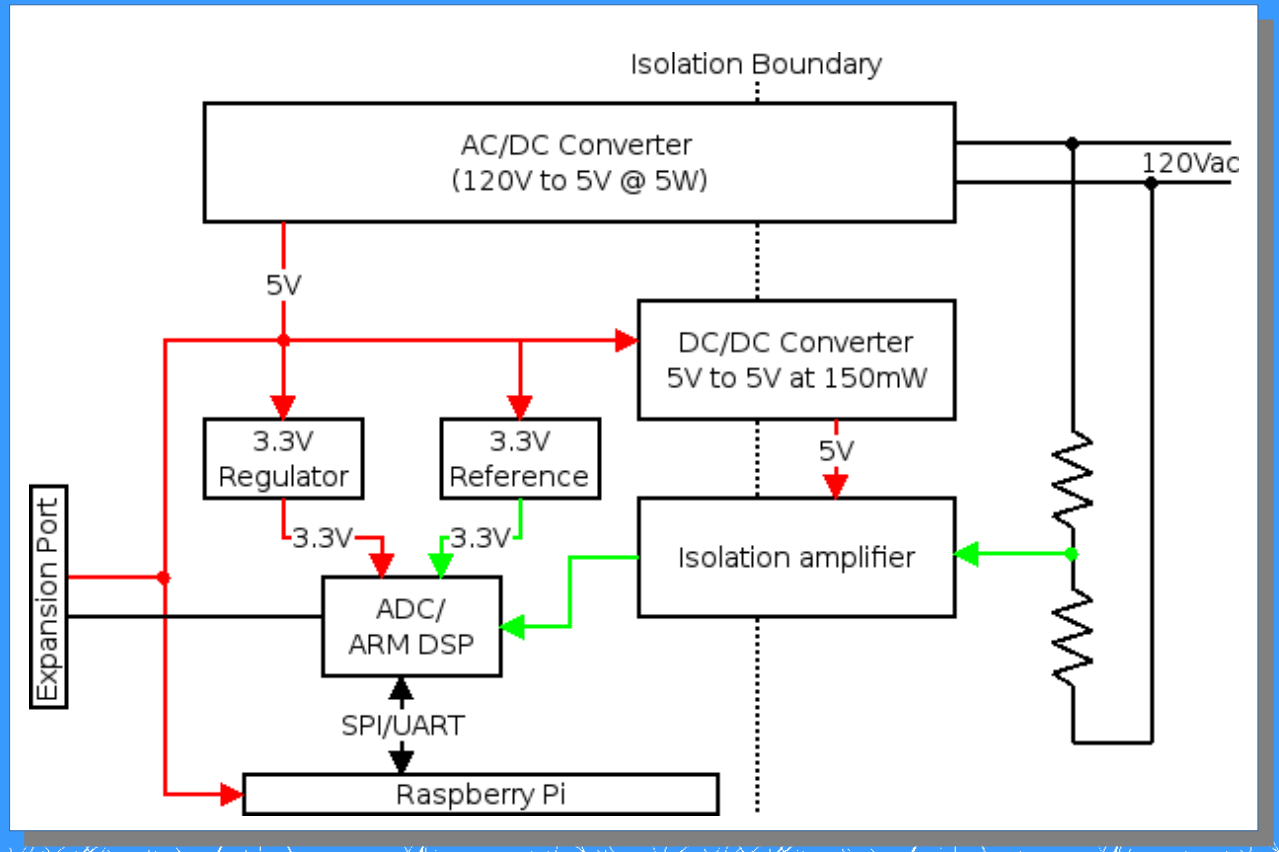
1. Napali minimizes bandwidth
2. Napali mitigates device latency effects
3. Napali minimizes sink processing requirements
4. Sub-threshold data acquisition is a viable event detection strategy
5. Temporal locality triggering results in a low false negative detection

Open Power Quality
Gridwide event detection



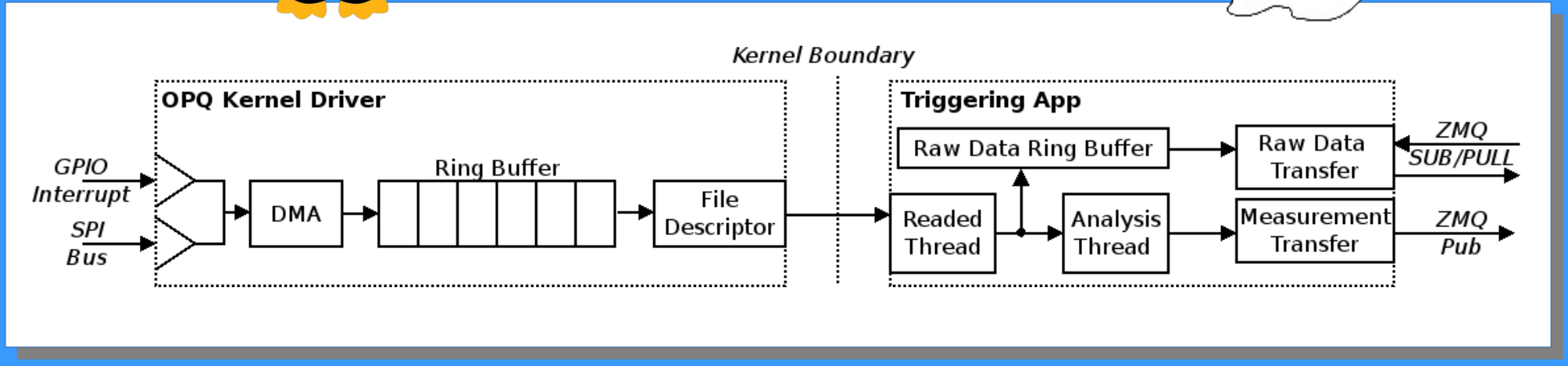
OPQ Box

Hardware



OPQ Box

Software



OPQ Box

Metrics

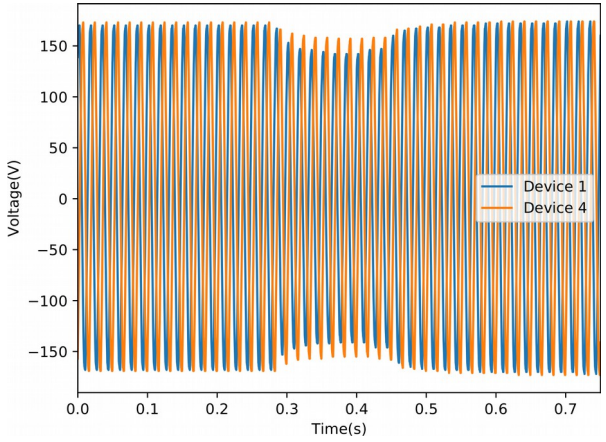
Metrics:
- V_{rms}
- Fundamental Frequency
- THD
- Transient

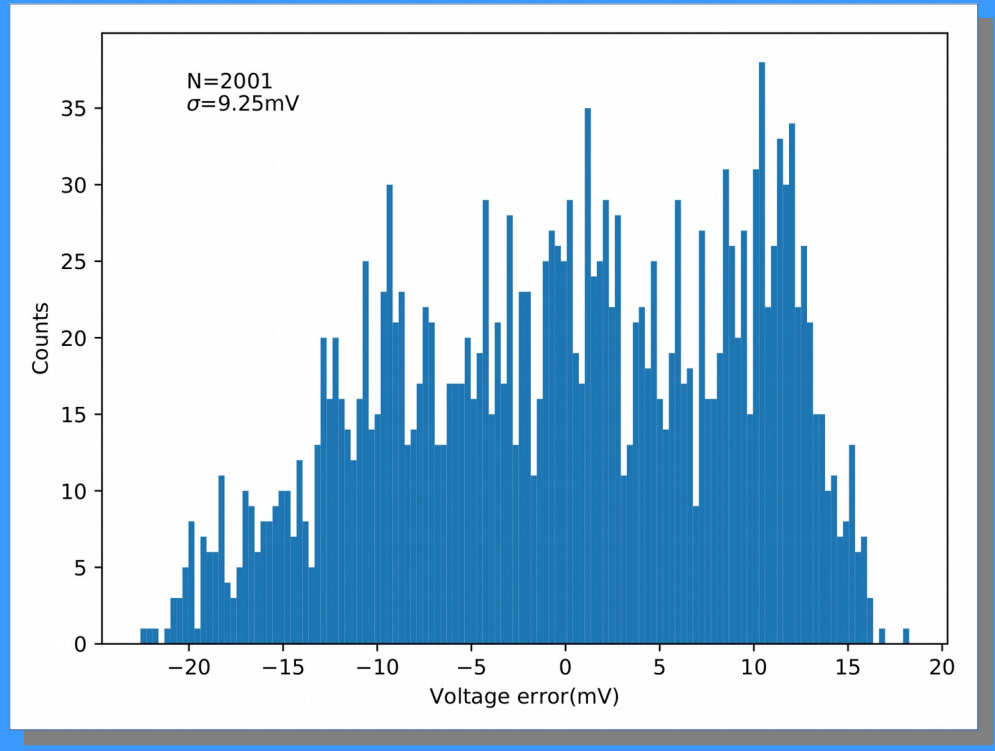
Transmission Rate:
- 1s (Mean/Min/Max)

RDRB:
- 1 Hour

In-vitro Validation

Amplitude(V_{rms})

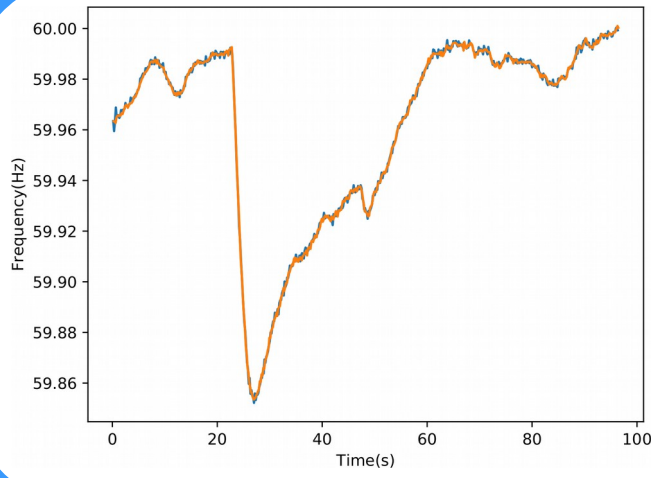


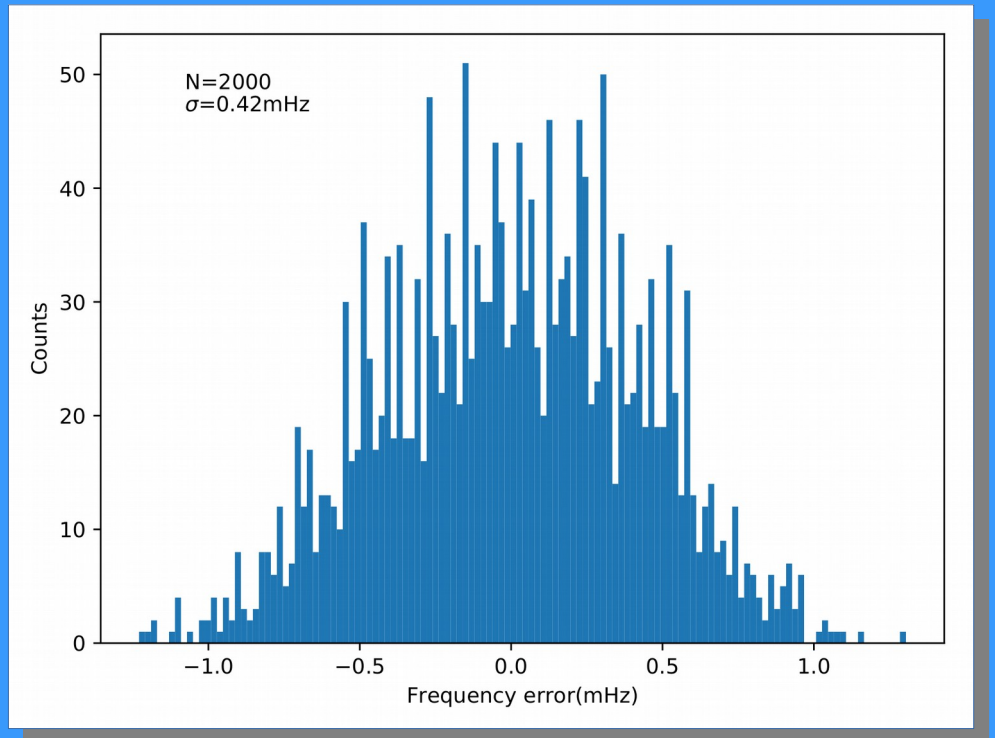


Validation against sdg1025

In-vitro Validation

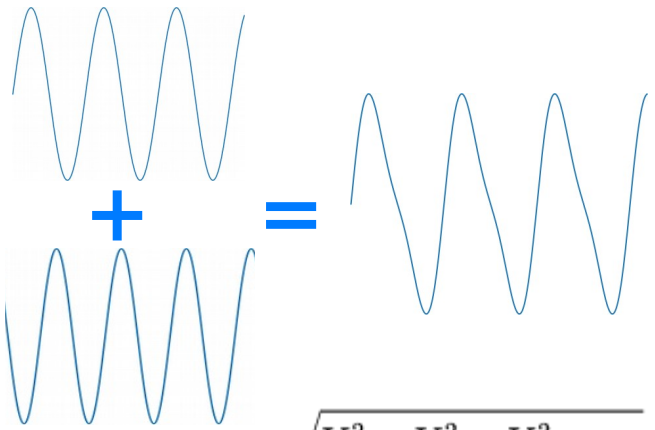
Frequency $f_{fundamental}$



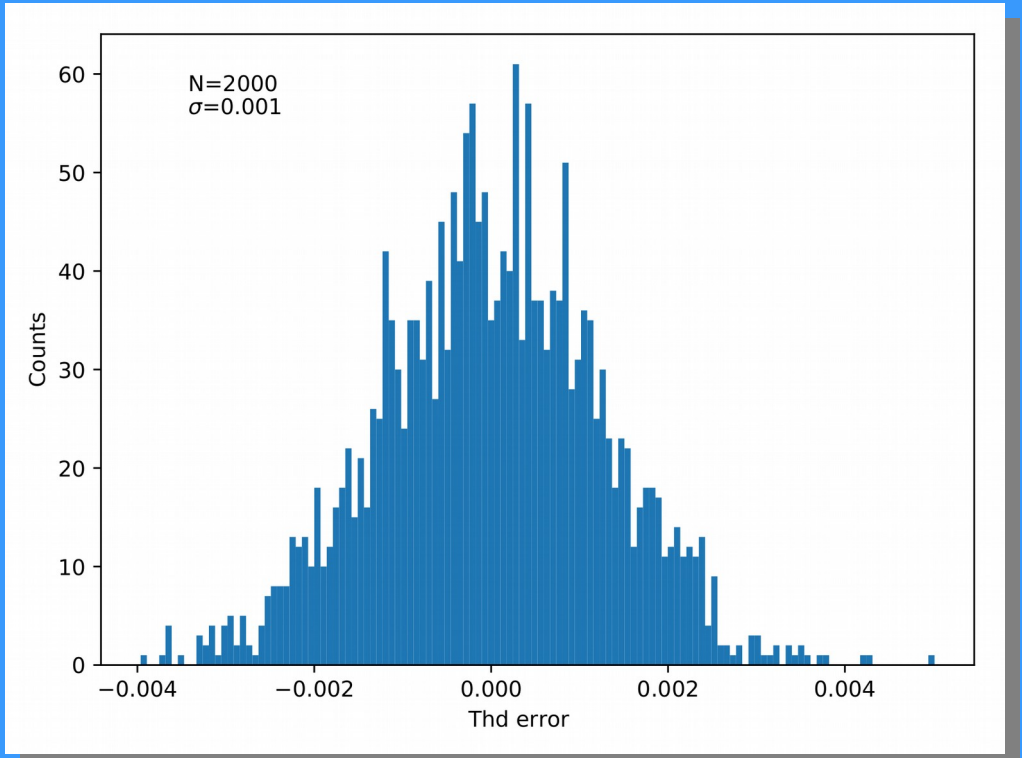


Validation against sdg1025

In-vitro Validation
Total Harmonic Distortion



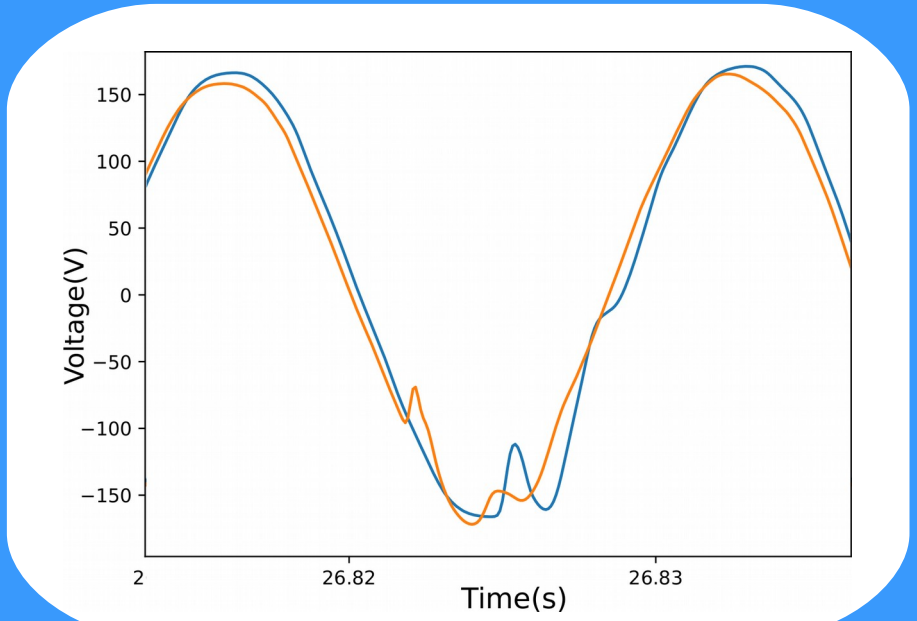
$$\mathrm{THD_F} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$

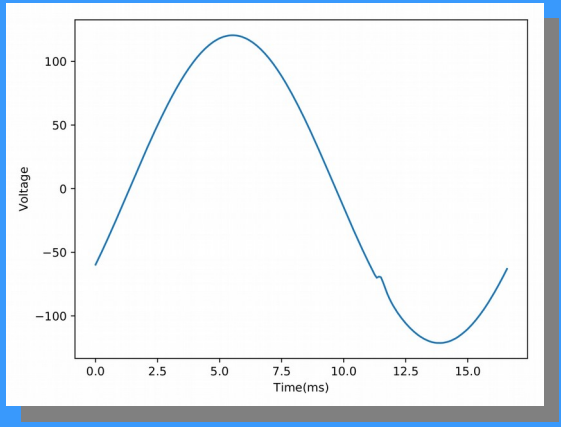


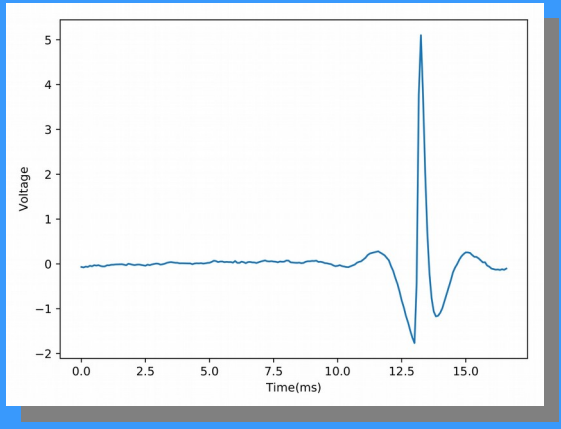
Validation against sdg1025

In-vitro Validation

Transients

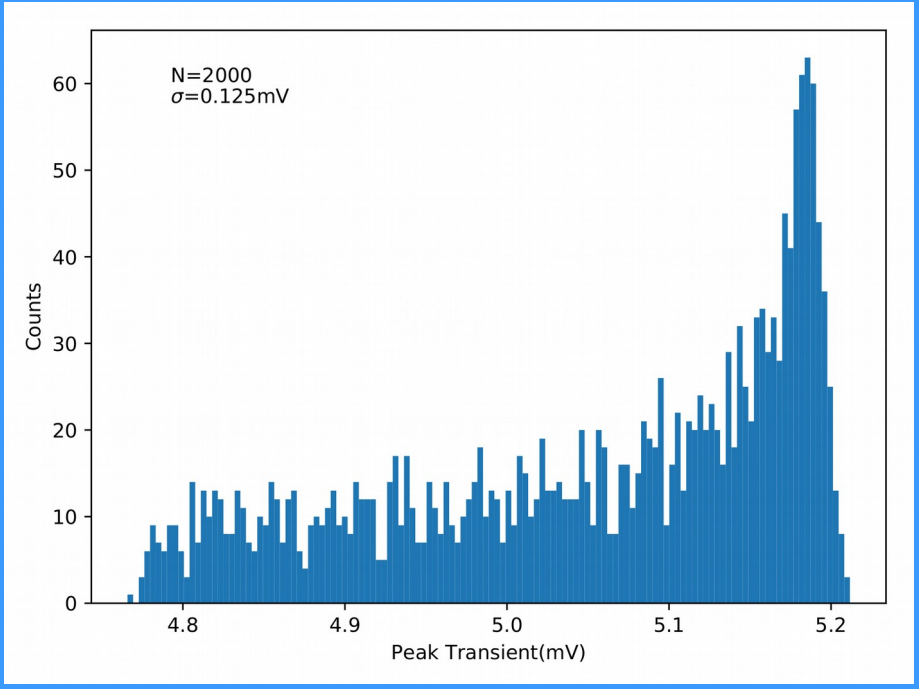






In-vitro Validation

Transients



Validation against sdg1025

Napali Device Model

For each device:
- mean
- std

Leaky mean:

$$\mu_{n+1} = (1-\alpha) * \mu_n + \alpha * m$$

$$\mu^2_{n+1} = (1-\alpha) * \mu^2_n + \alpha * m^2$$

$$\sigma^2_n = \mu^2_n - (\mu_n)^2$$

$$\sigma_n = \sqrt{\sigma^2_n}$$

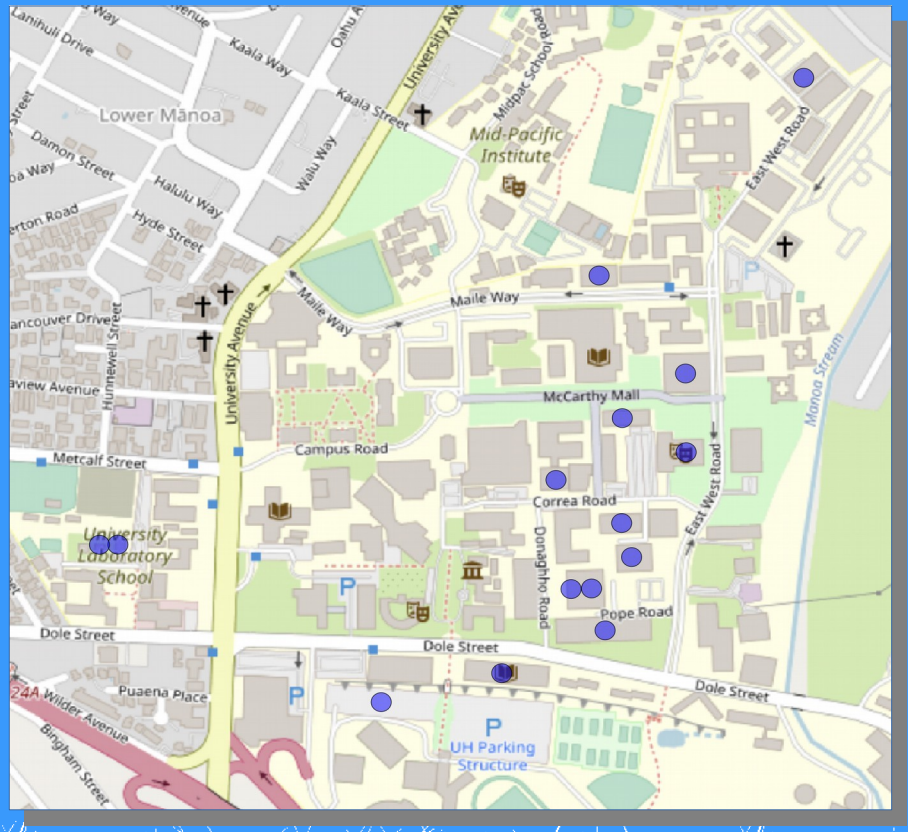
Event chronology:
1. Any device passes threshold.
2. Record any device > 3*std.
3. Wait until all devices are below threshold.
4. If device count is > 1 request data from
    - Devices which passed threshold.
    - Devices with a metric > 3*std.
5. If device count == 1:
    - No request is made.
6. Return to monitoring.

UH Deployment

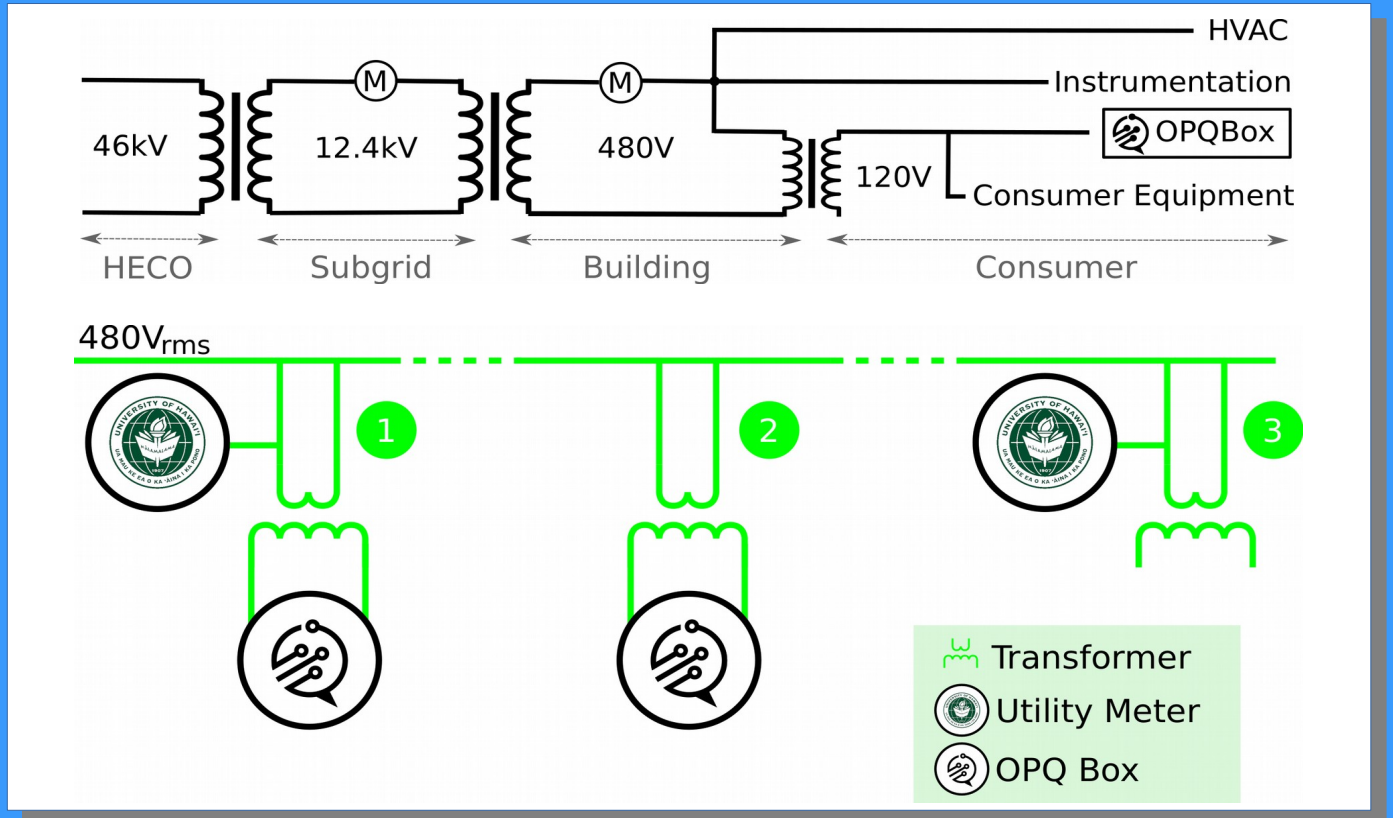
in-situ validation

- 15 Devices.
- 3 months of data.
- Still running.

Anyone want a PQ network?

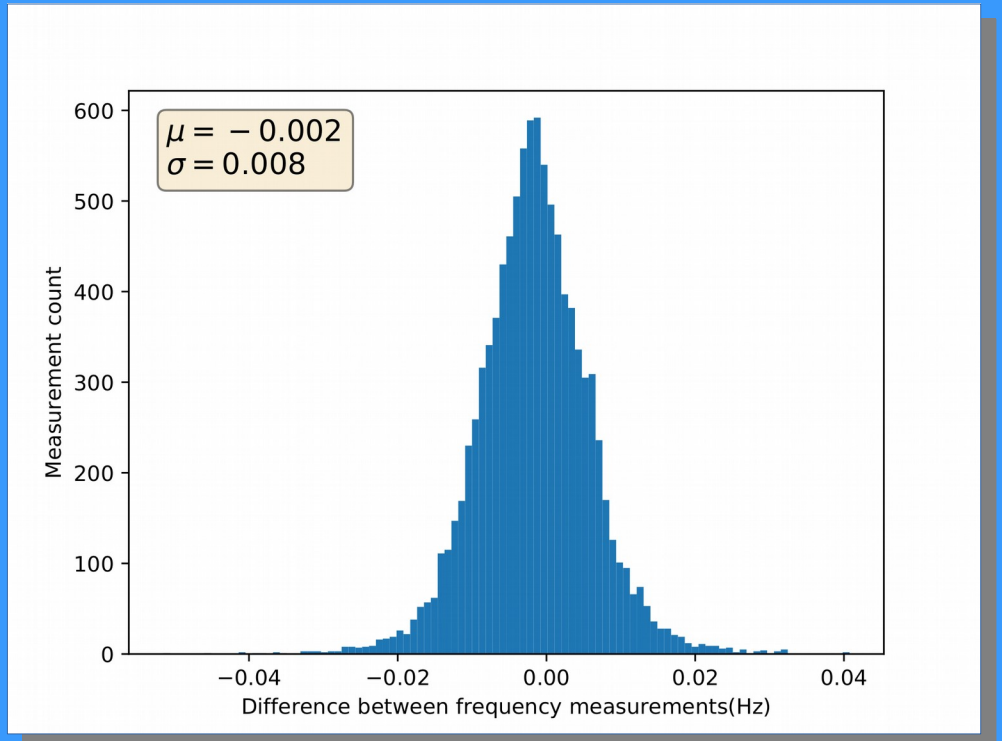


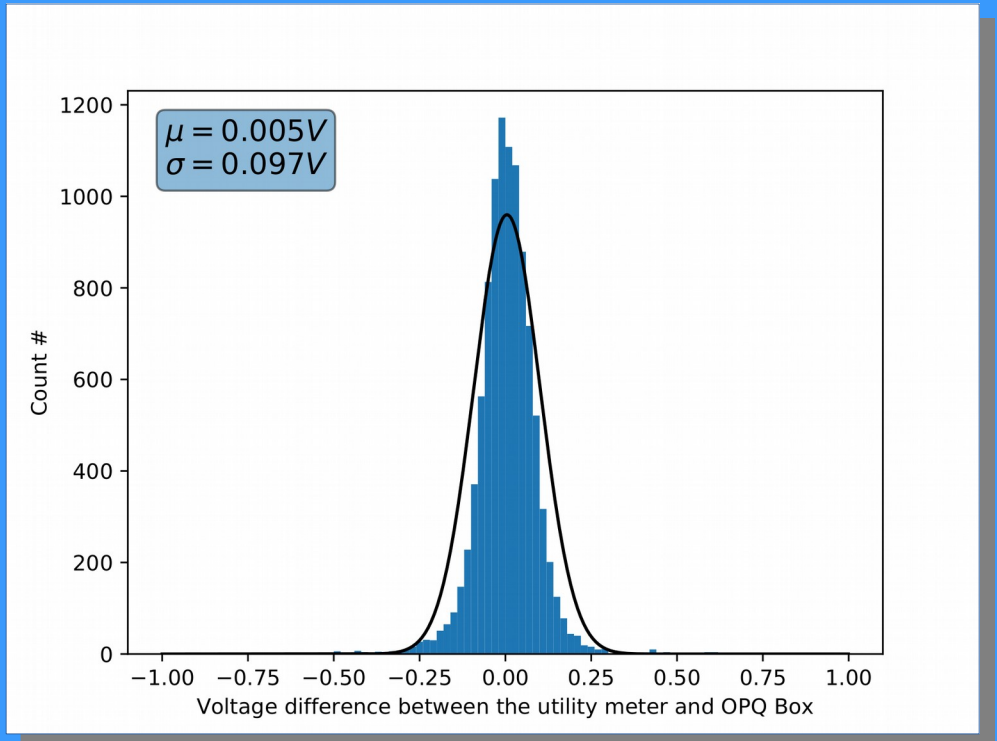
UH Deployment



In-vivo validation of OPQ Box

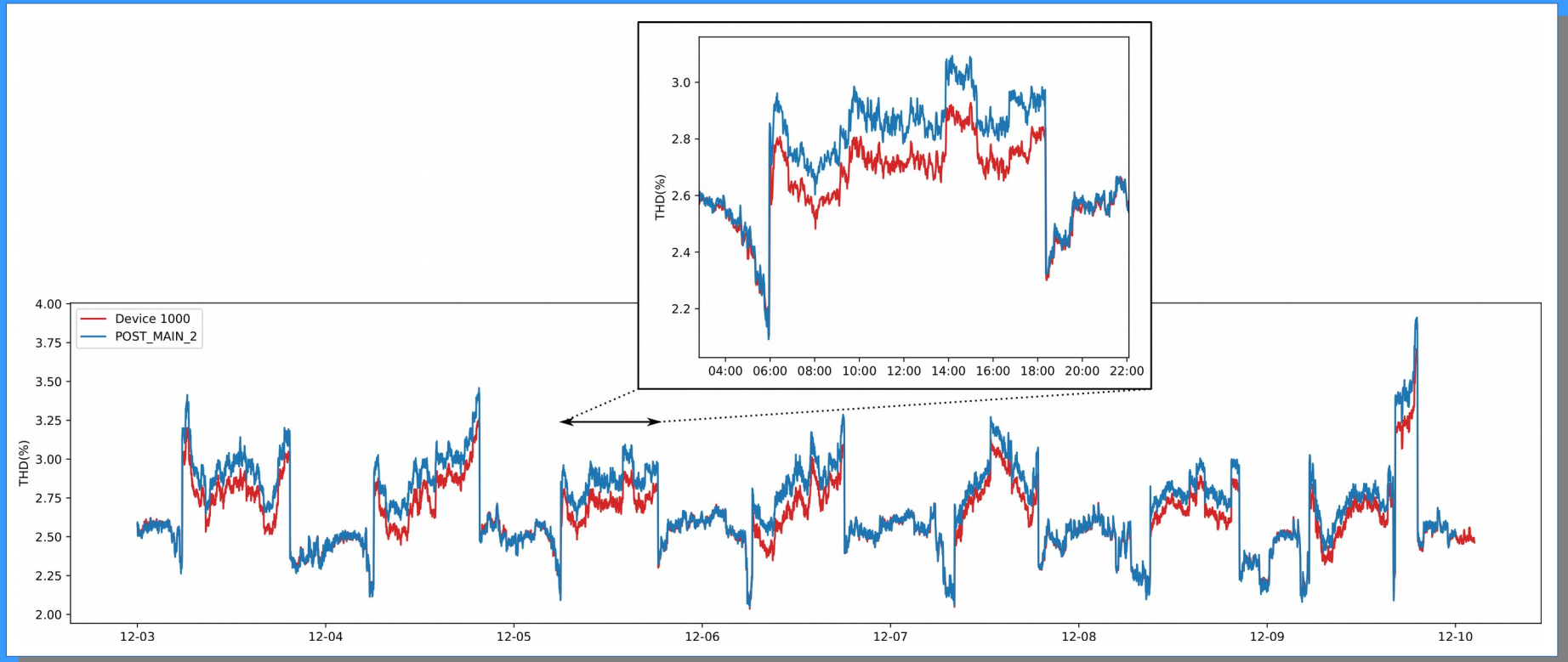
Comparison with UH meters(frequency and V_{rms})





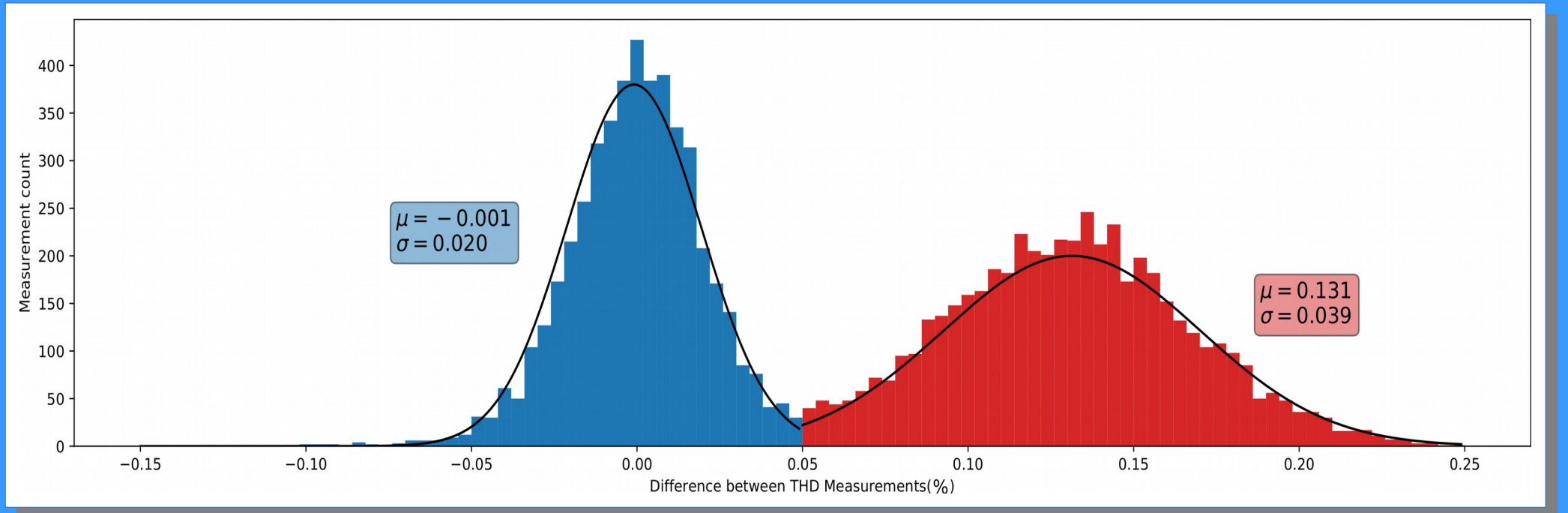
In-vivo validation of OPQ Box

Comparison with UH meters(THD)



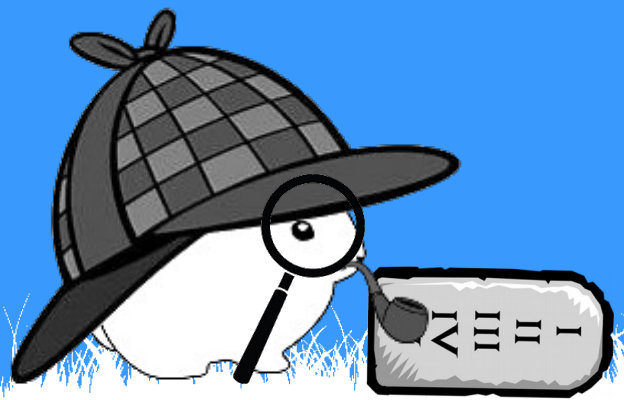
In-vivo validation of OPQ Box

Comparison with UH meters(THD)

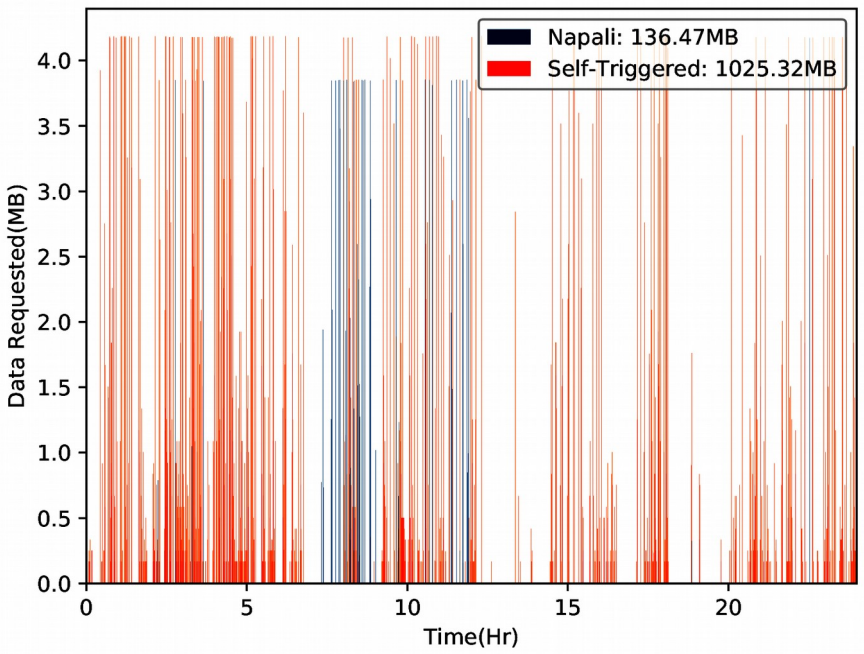


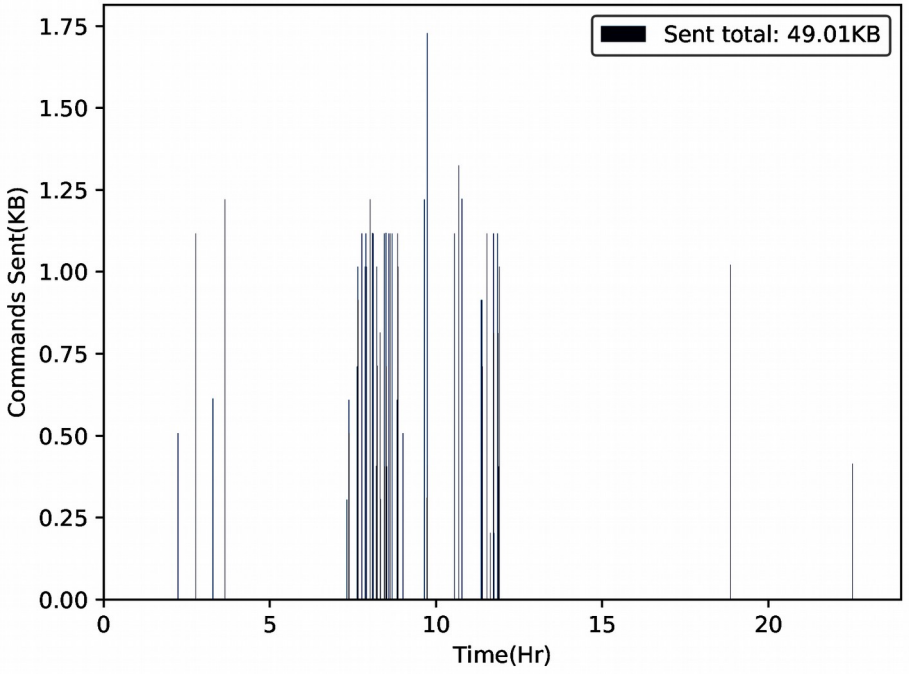
Testing Claims

1. Napali minimizes bandwidth usage
2. Napali mitigates device latency effects
3. Napali minimizes sink processing requirements
4. Sub-threshold data acquisition is a viable event detection strategy
5. Temporal locality triggering results in a low false negative detection

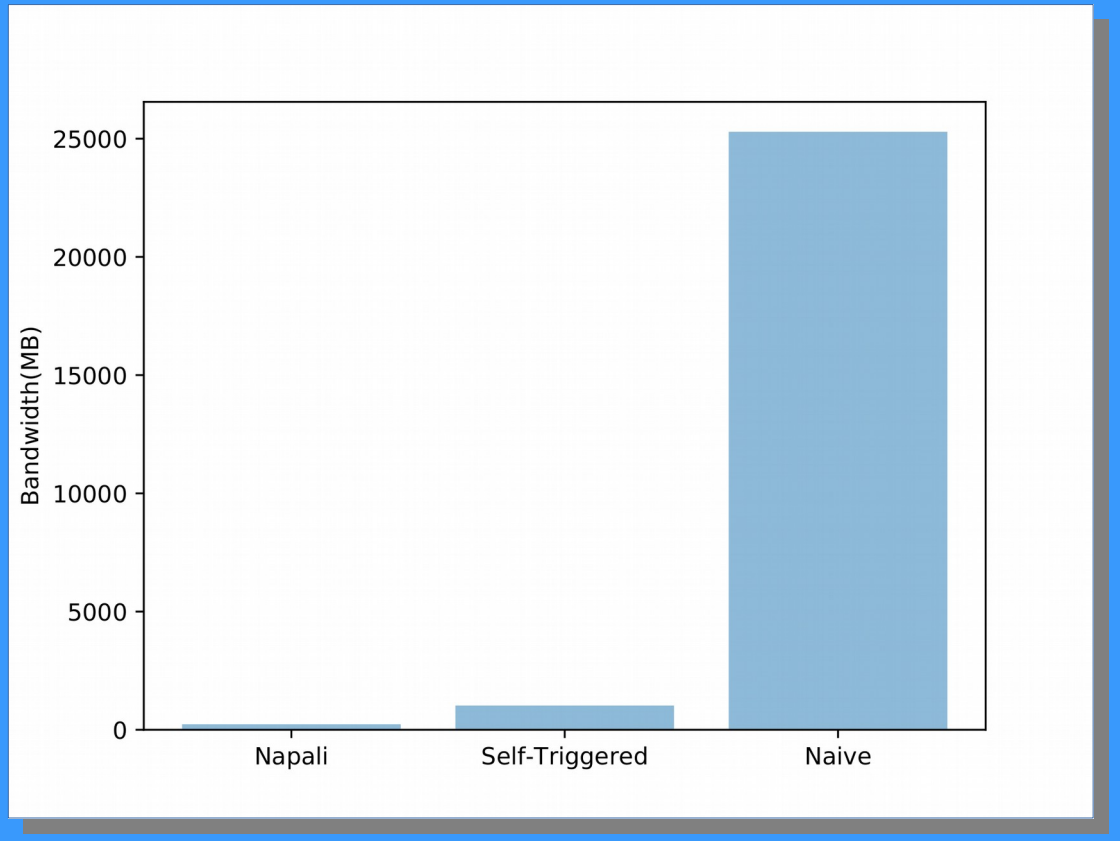


Claim: Napali Bandwidth Advantage



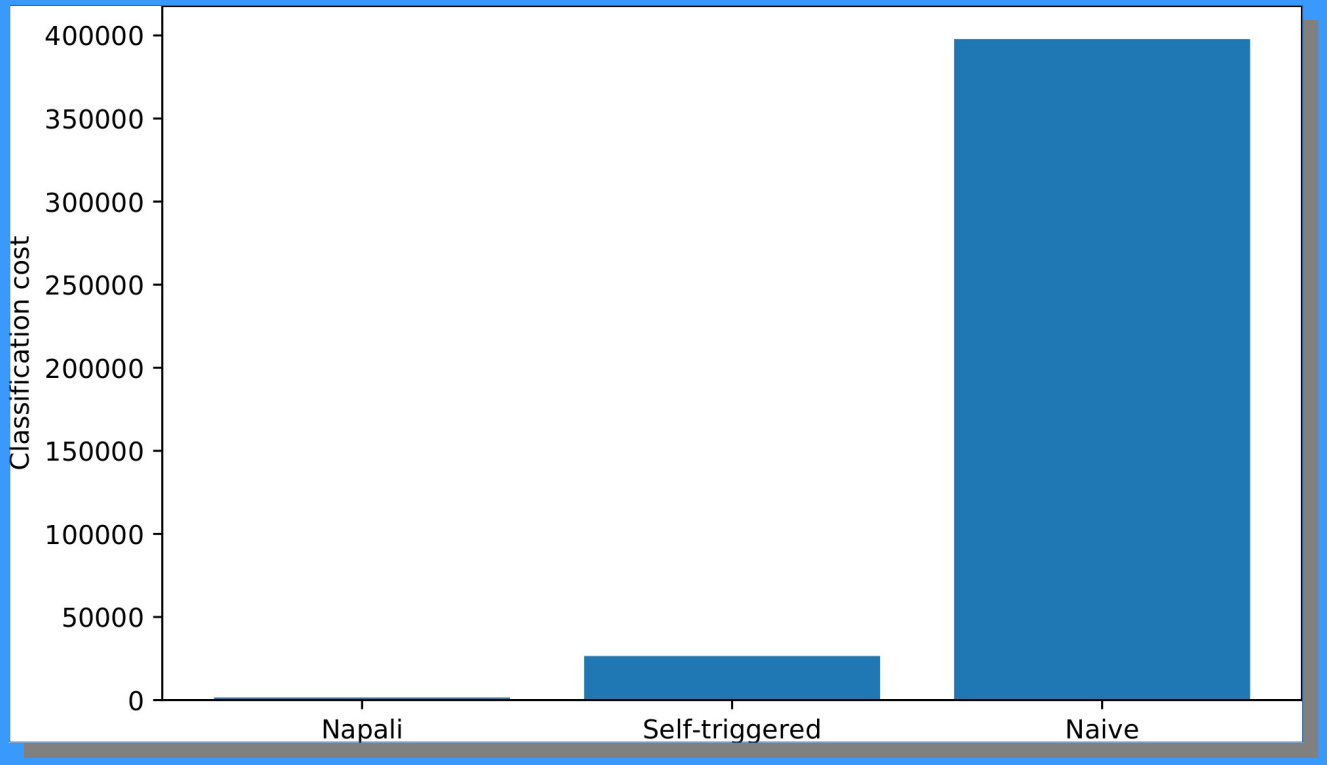


Claim: Napali Bandwidth Advantage



Claim: Computational Cost

classification cost

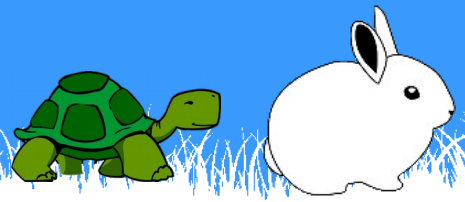


Claim: Latency

Late metrics over 24 hours

$$Buffer_{naive} = 2 * latency_{max} * (Datarate) * (\#ofdevice)$$

$$Buffer_{napali} = 2 * latency_{max} * (Metric\ rate) * (\#ofdevice)$$



Claim: Napali Sink Computational Cost Advantage

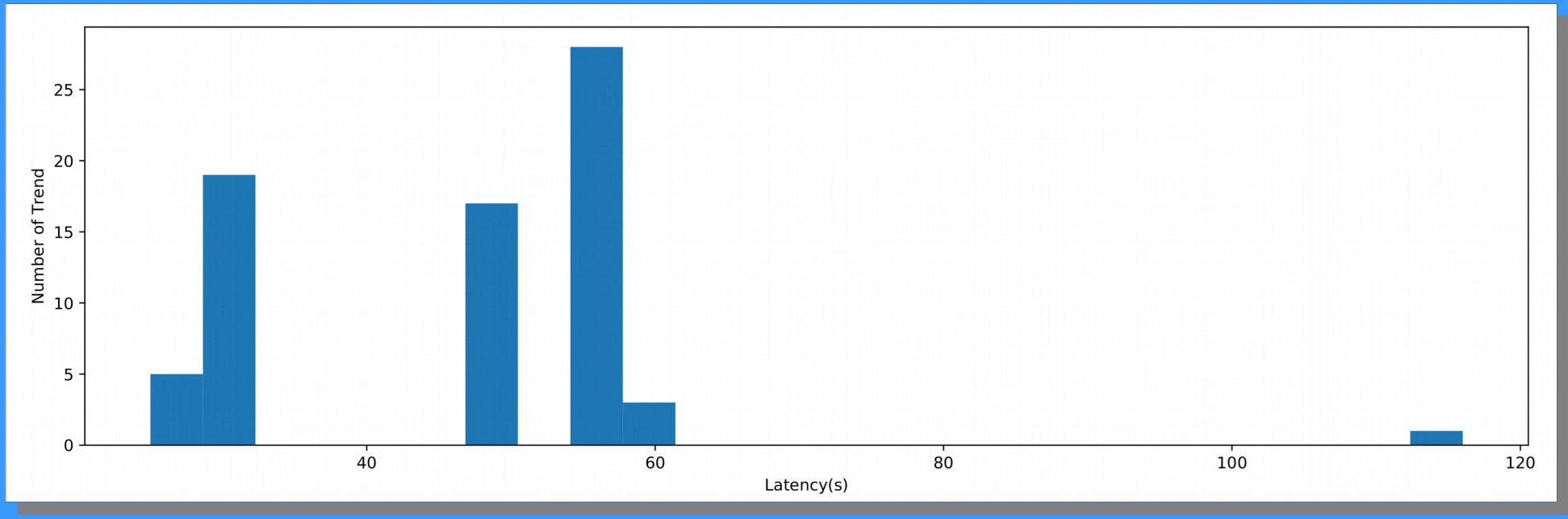
$$C_{total} = C_{metric\_extraction} + C_{detection}$$

Napali	0	10uS
Naive	800uS	10uS

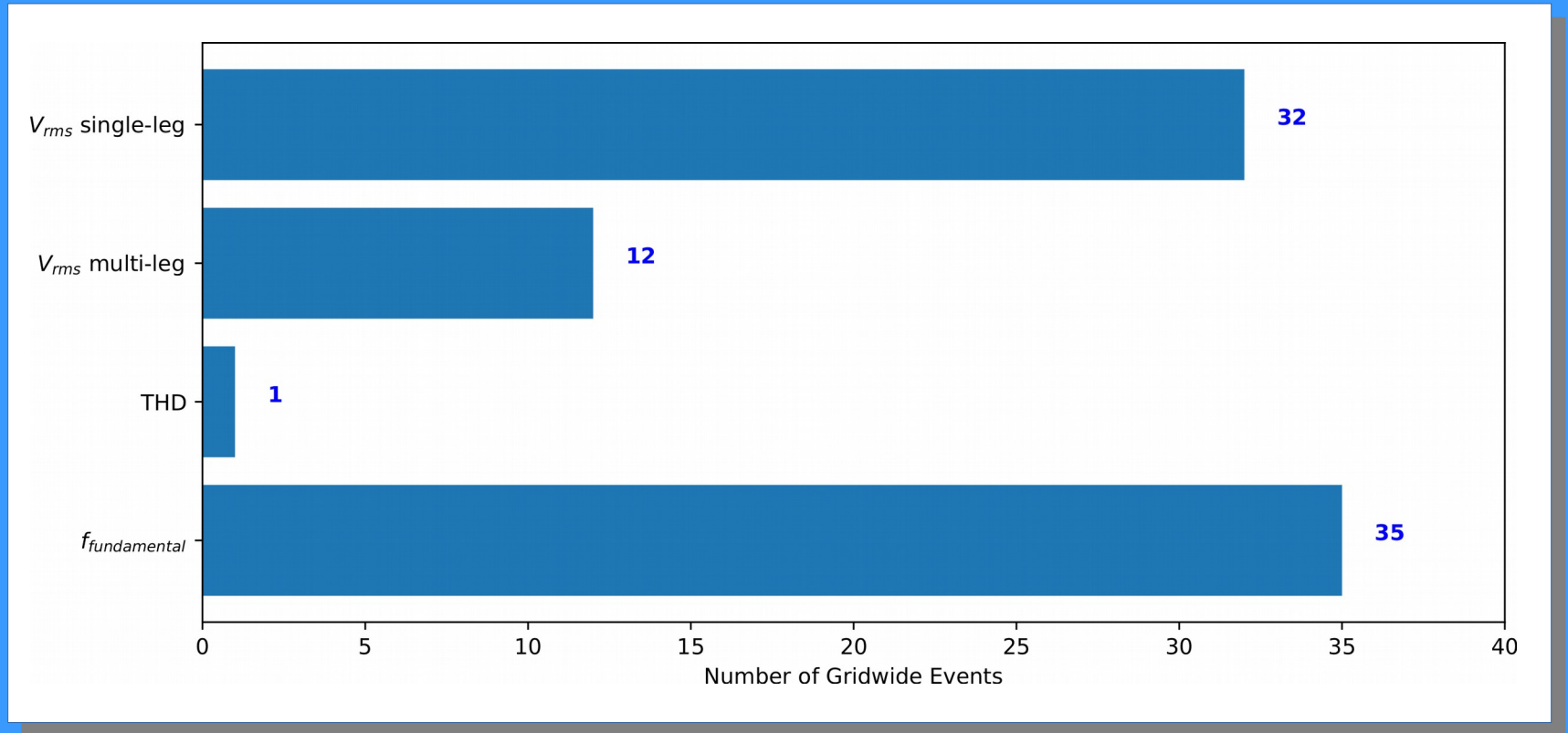
1 device 1 second

Claim: Napali Latency Sensitivity

Late metrics over 24 hours

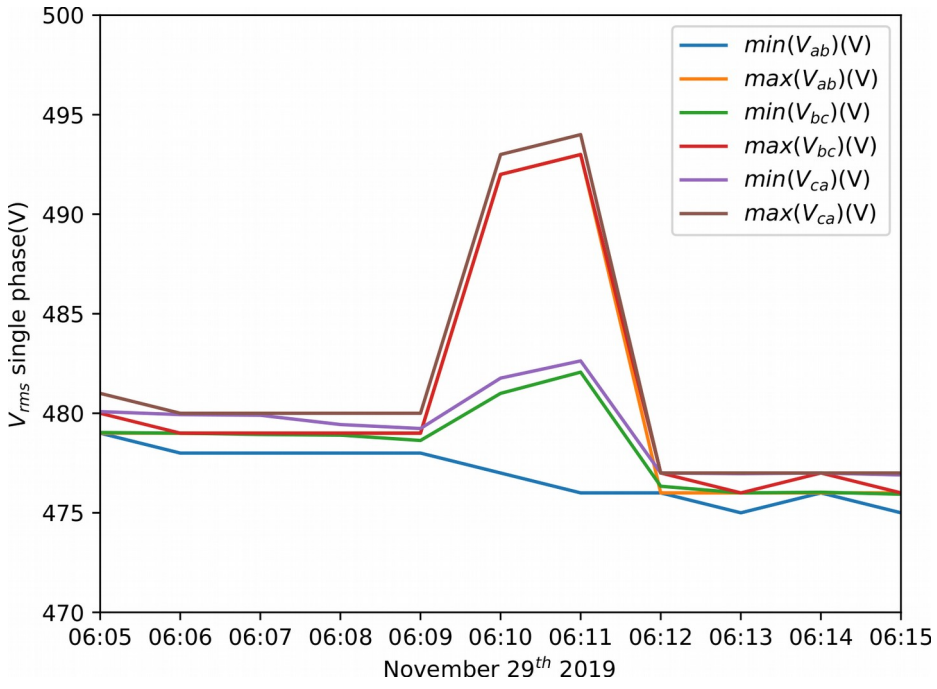


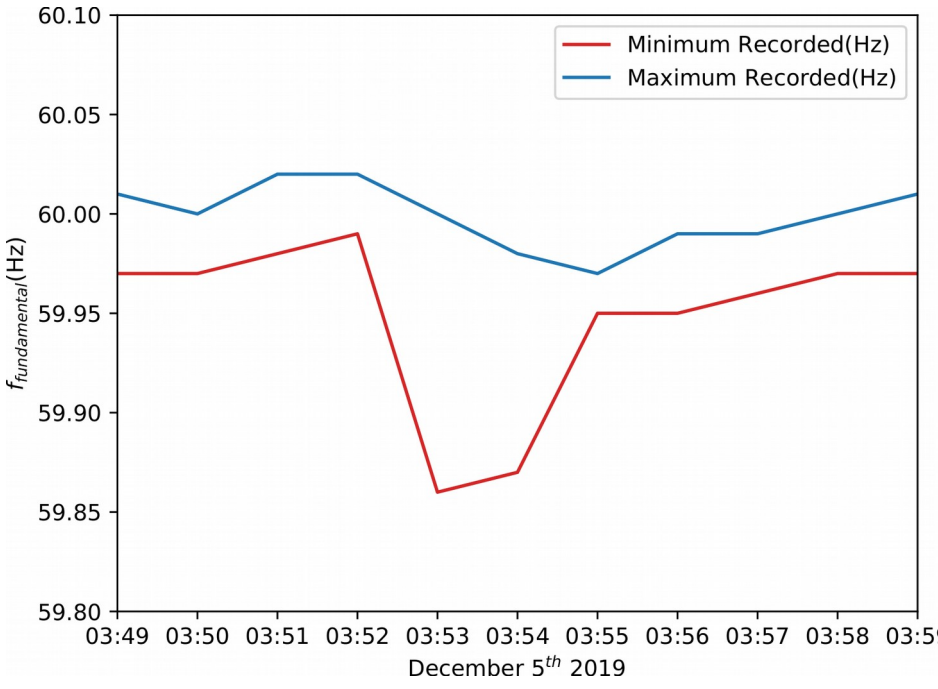
Claim: Temporal locality for event detection



Claim: Temporal locality for event detection

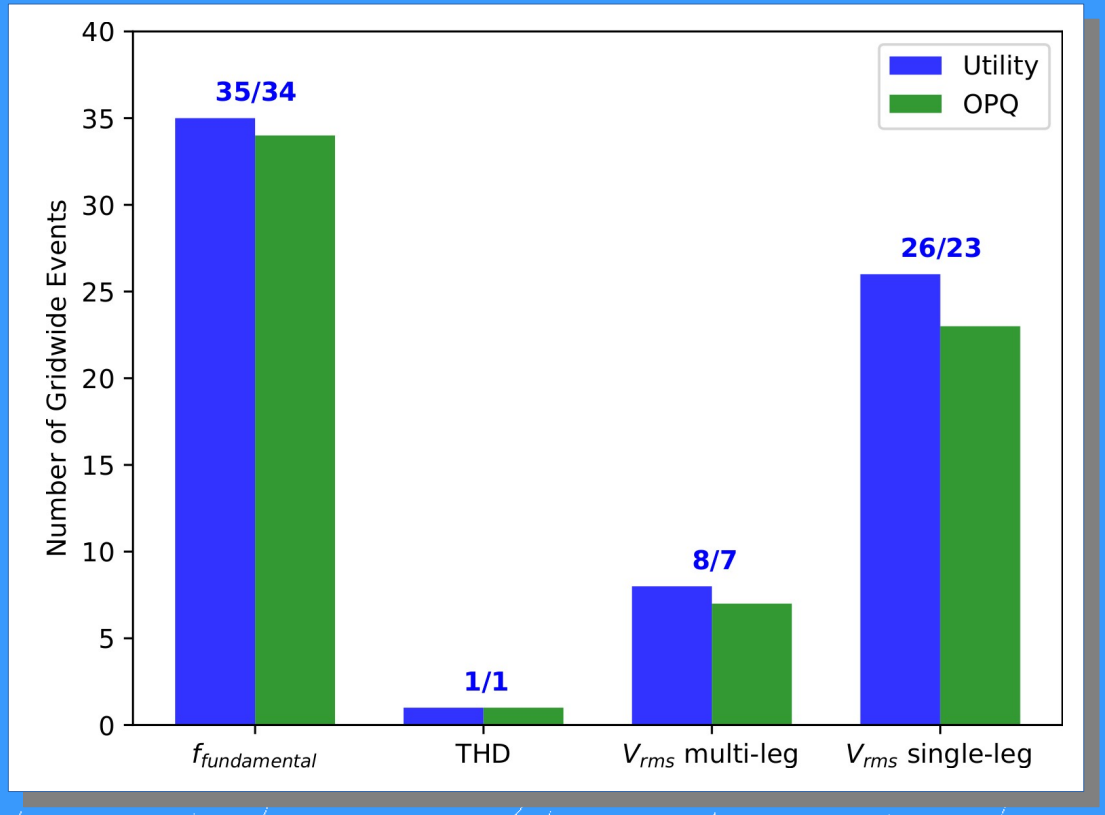
Ground truth event examples.





Claim: Temporal locality for event detection

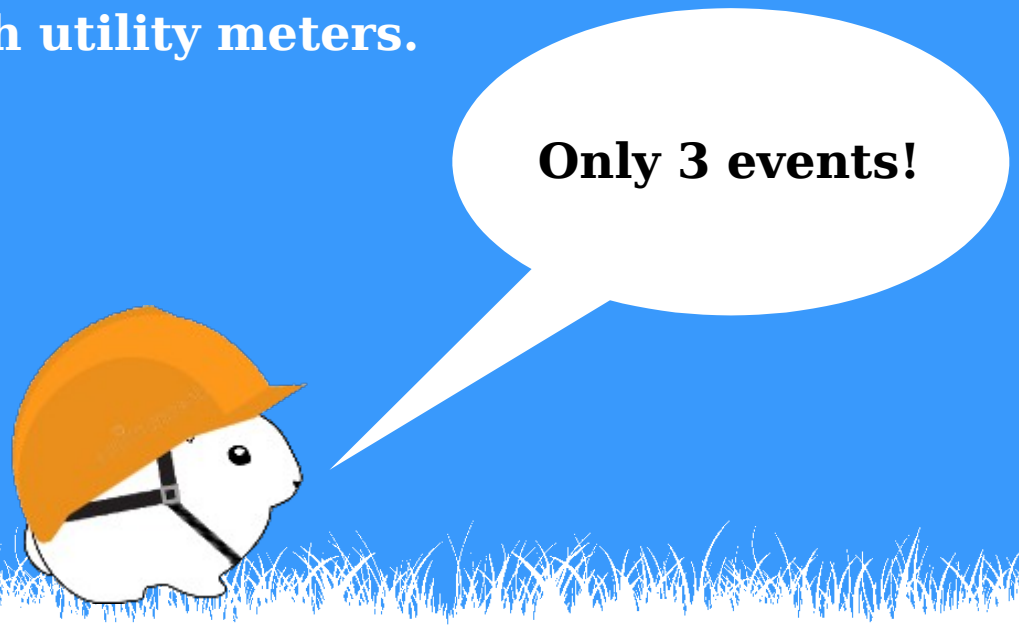
Detected events



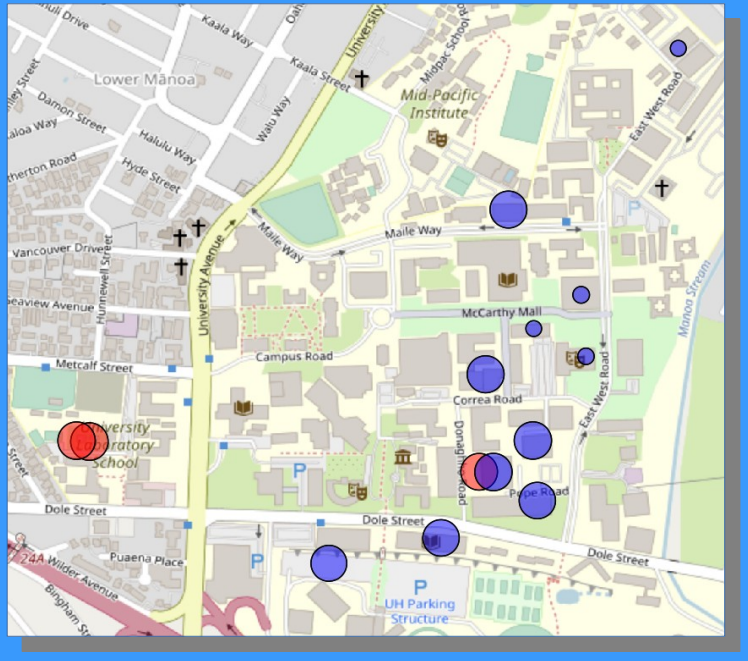
Claim: Sub-threshold Events Detection Capability

1. Select events where:
   - single collocated utility meter passes threshold.
   - one or more non-collocated utility meters passes threshold.

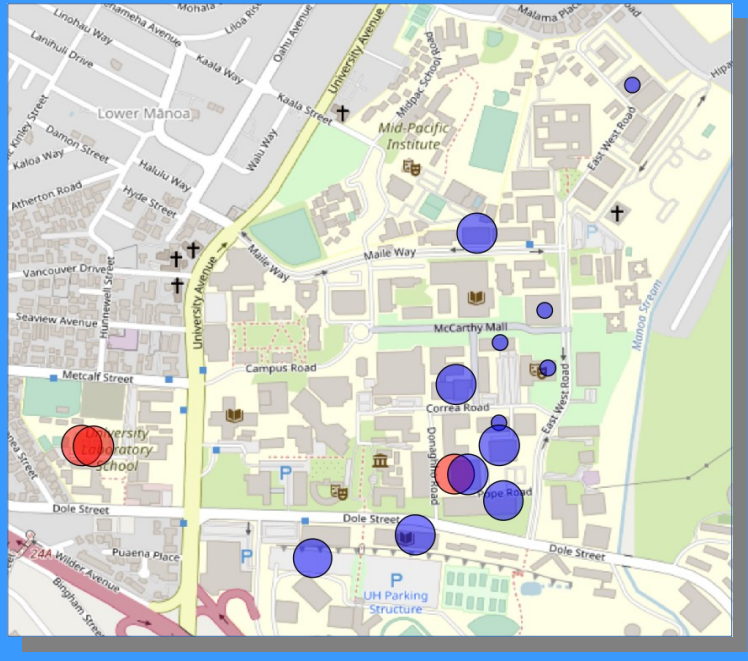
2. Compare the OPQ data with utility meters.



Event #1 and #2

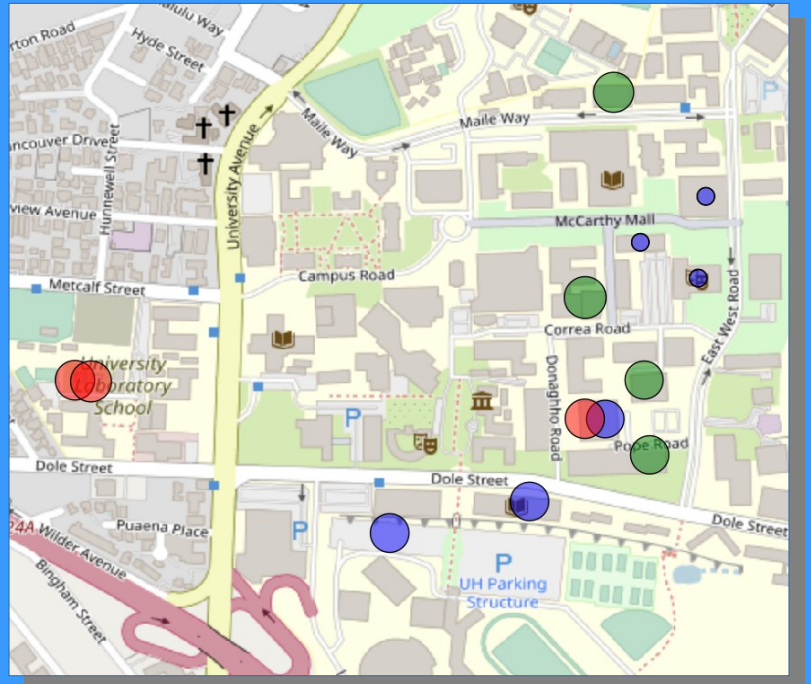


5 Utility Meters
15 OPQ Boxes

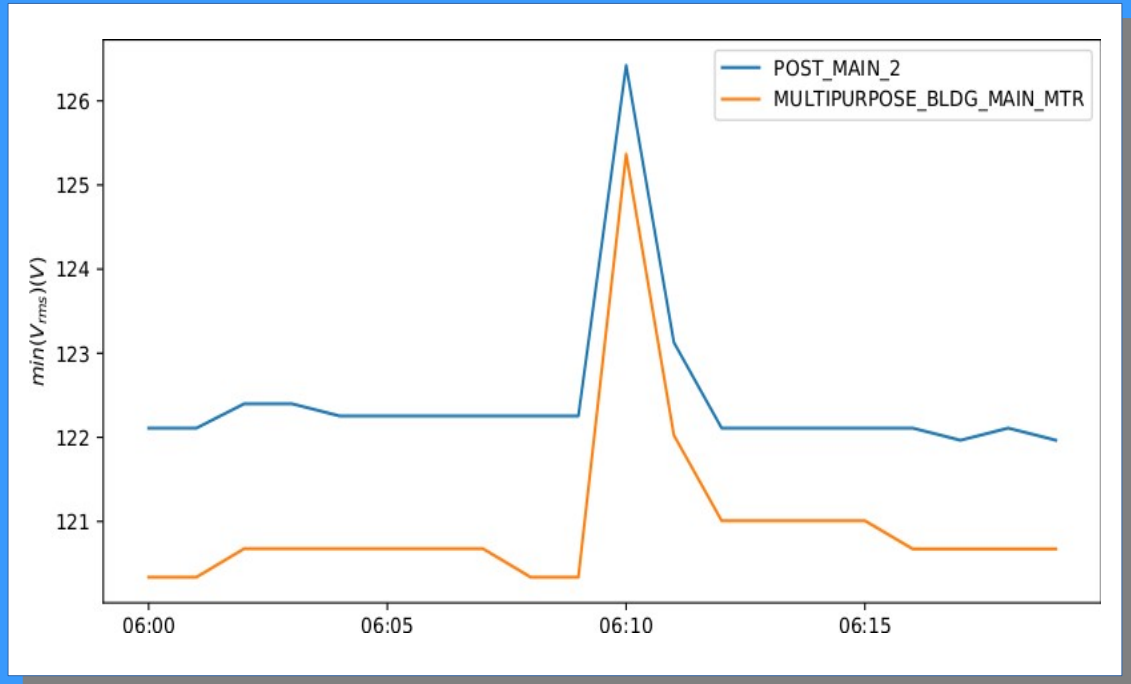


4 Utility Meters
14 OPQ Boxes

Event #3

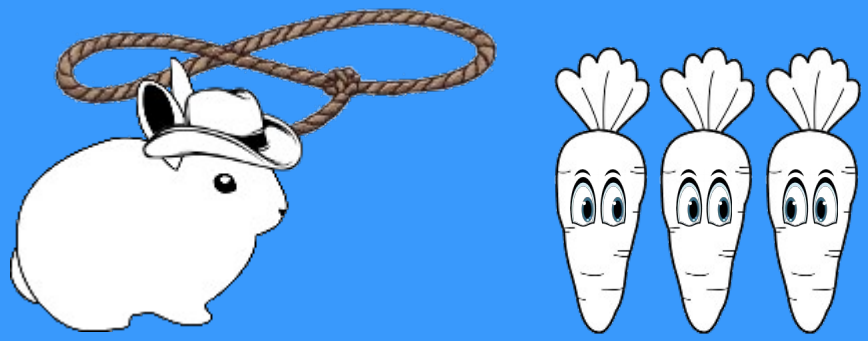


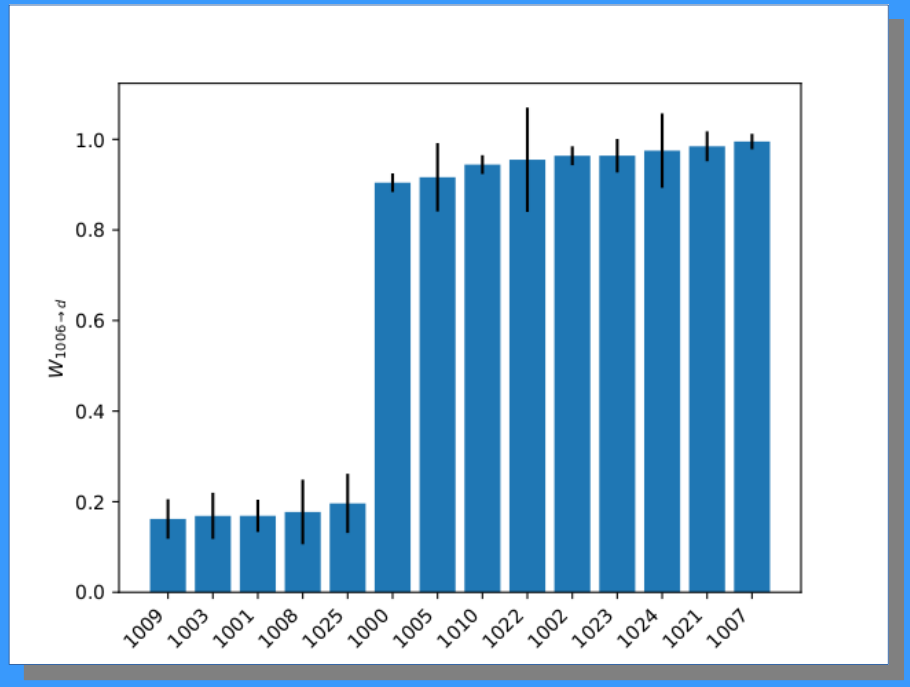
13 OPQ Boxes



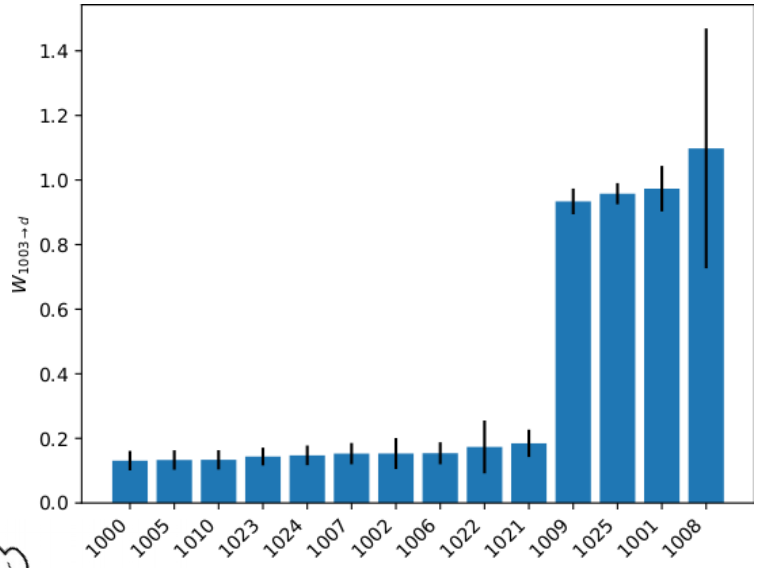
2 Utility Meters

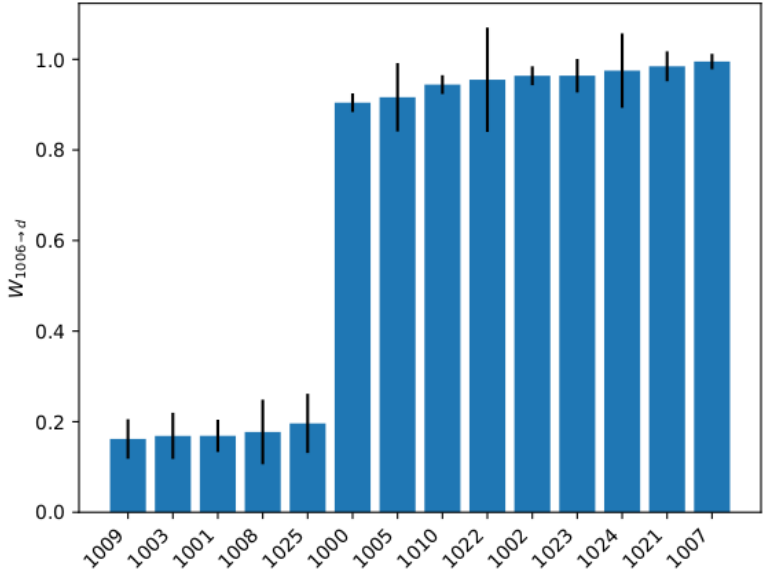
Is it possible to cluster events?





Bifurcation of the UH power Grid

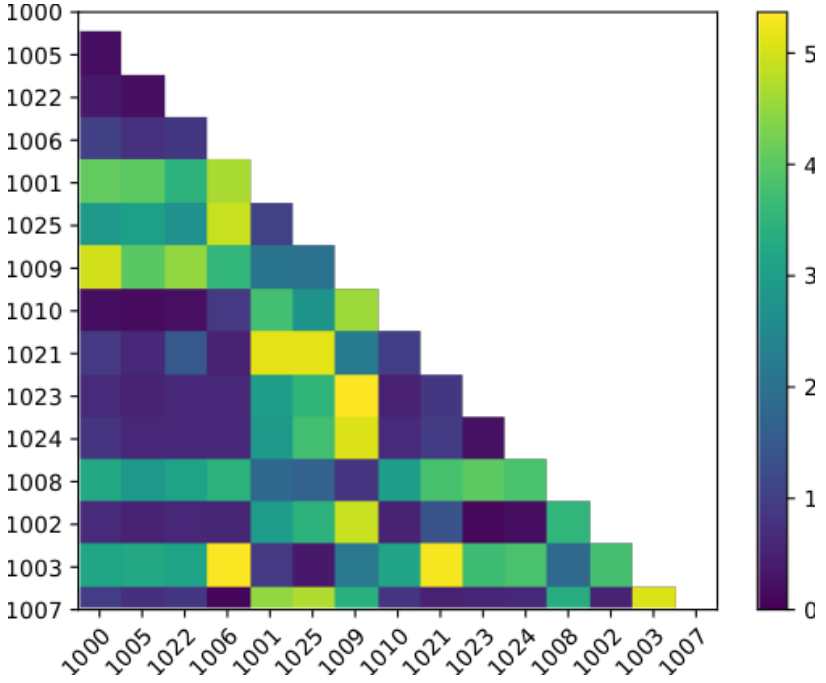




Pairwise Dissimilarity

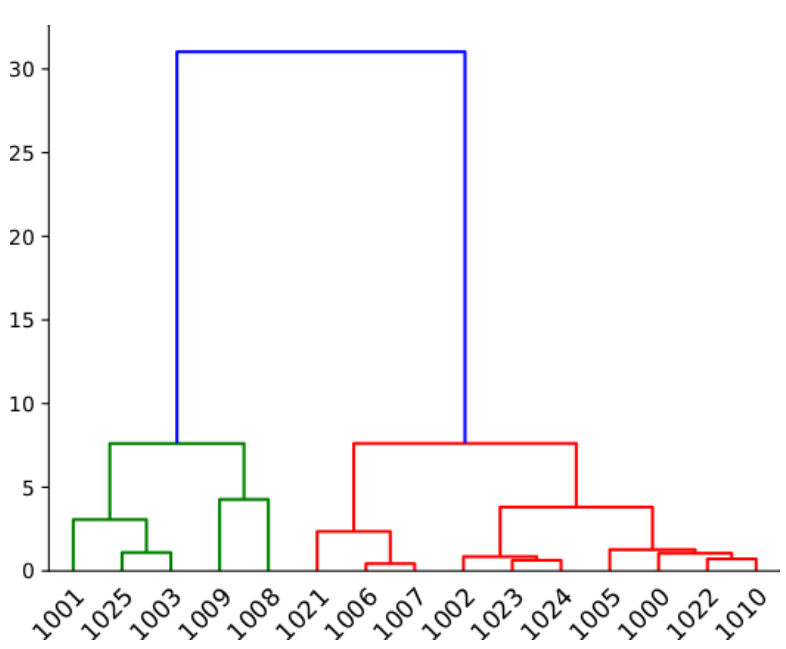
V_{rms}

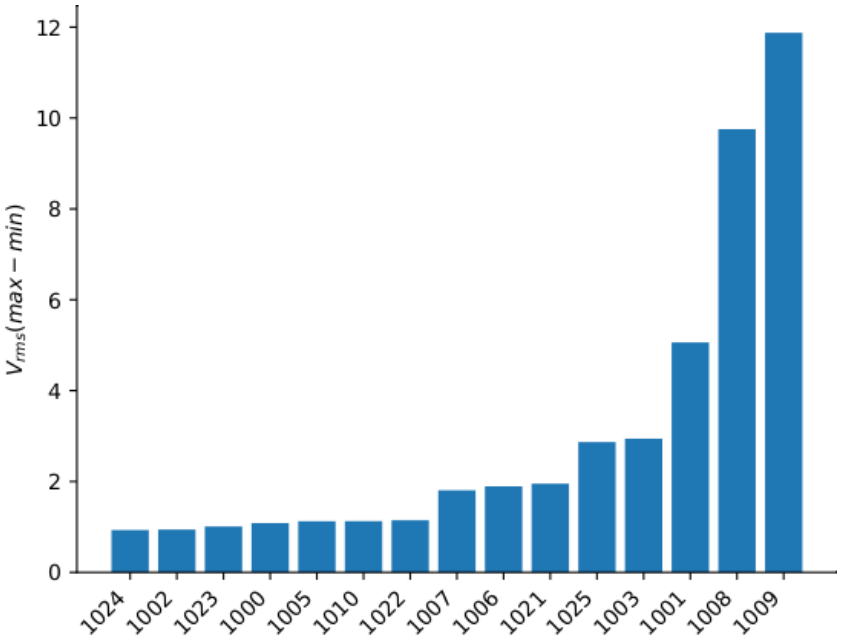
$$D^{rms}_{p \to d} = \frac{1}{n} \sum_{n} |(max(V_{rms}) - min(V_{rms}))_p - ((max(V_{rms}) - min(V_{rms}))_d|$$



Clustering

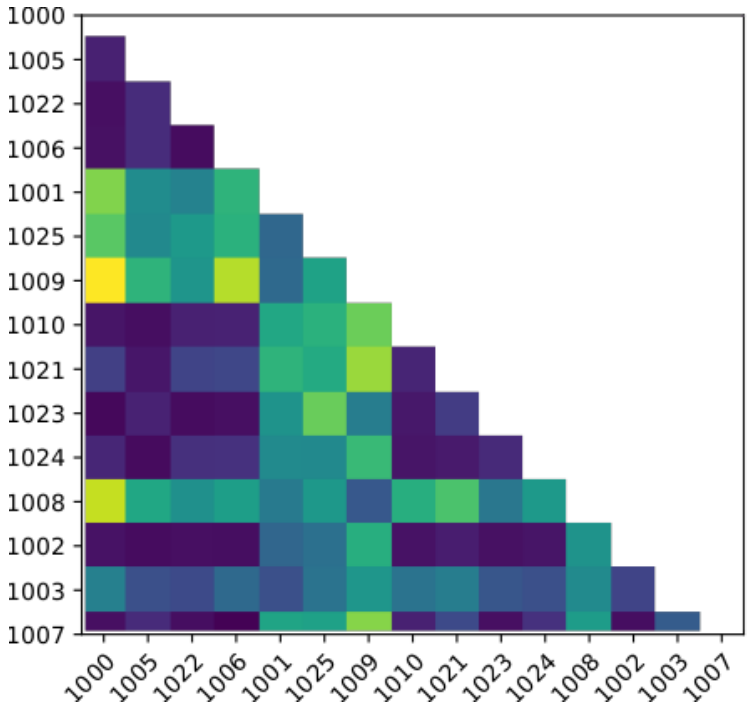
V_{rms}

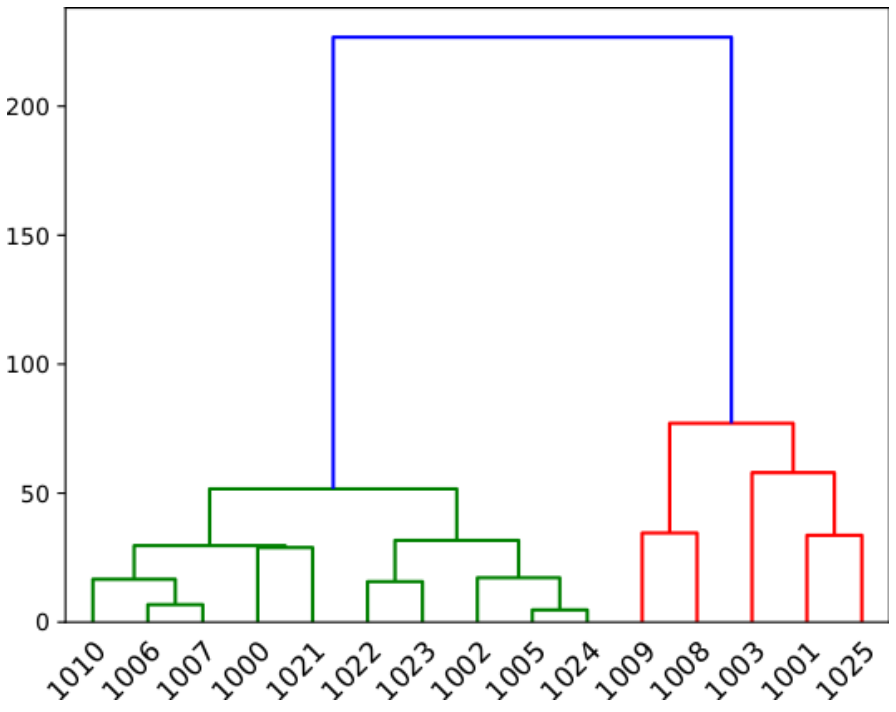




Clustering

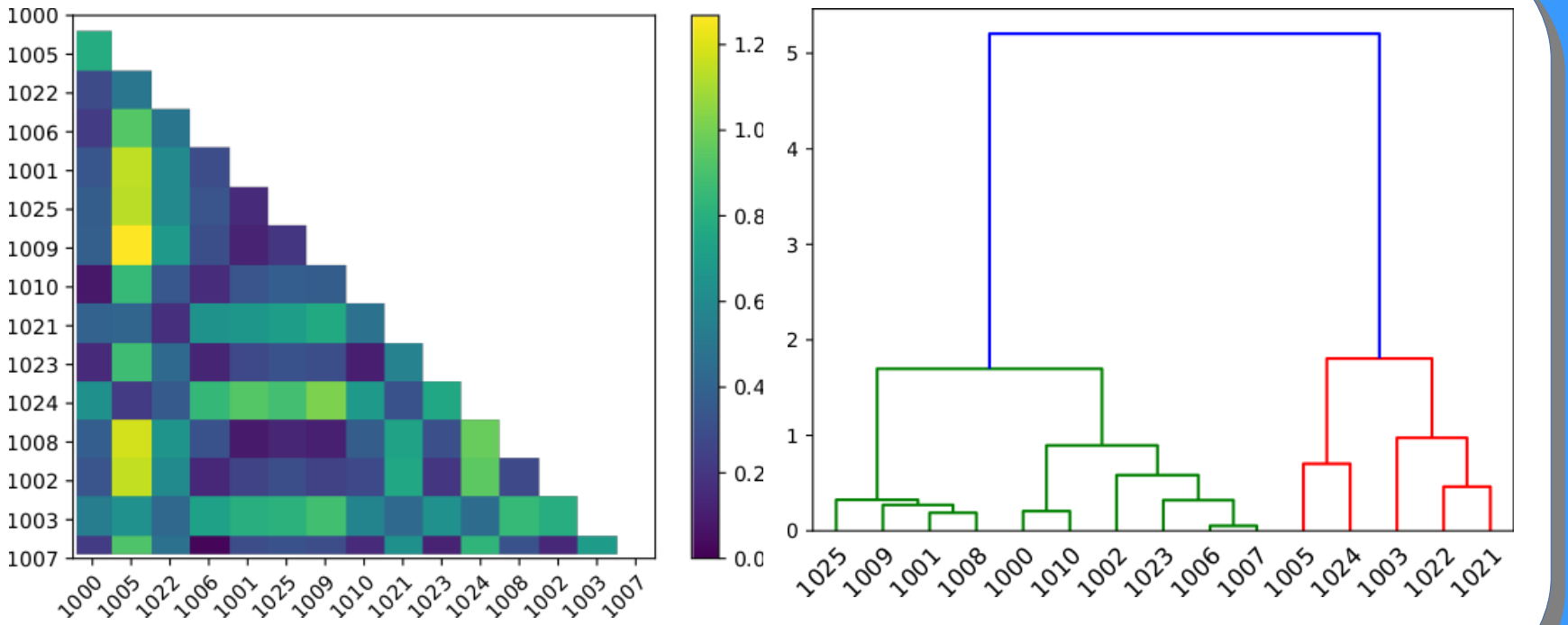
Transients





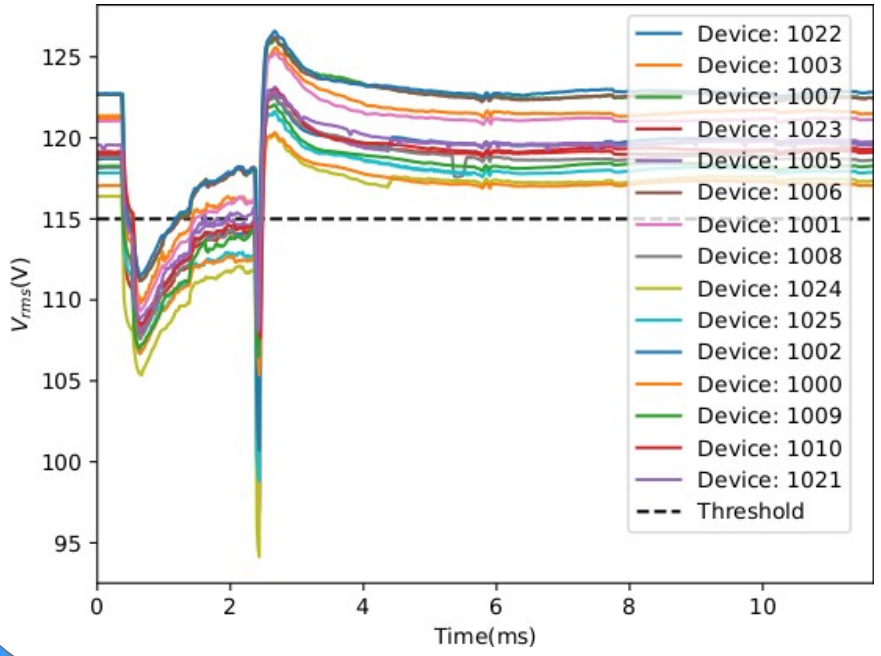
Clustering

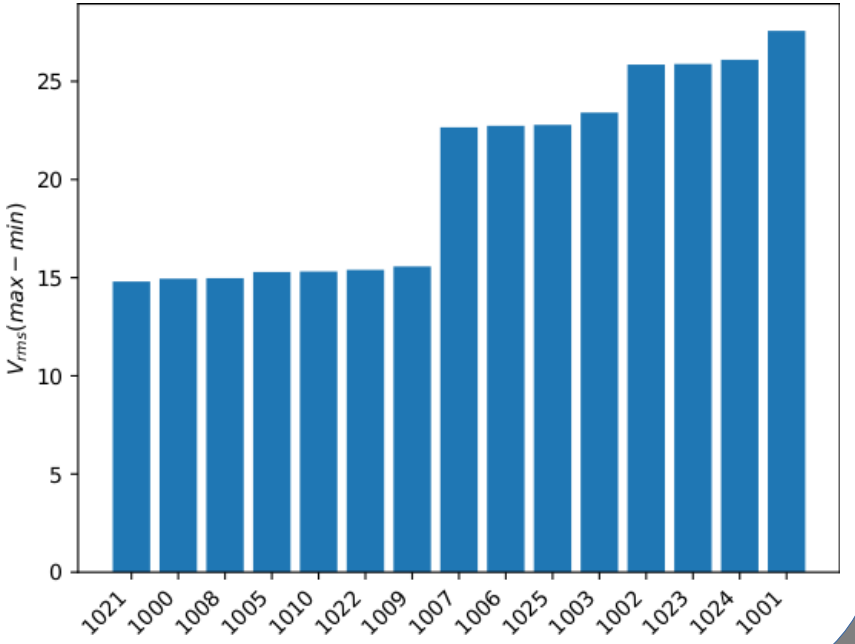
THD



True Gridwide Events

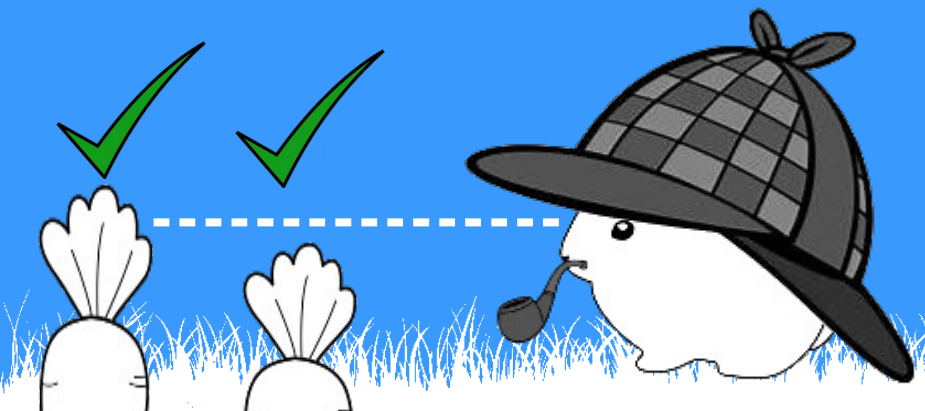
THD



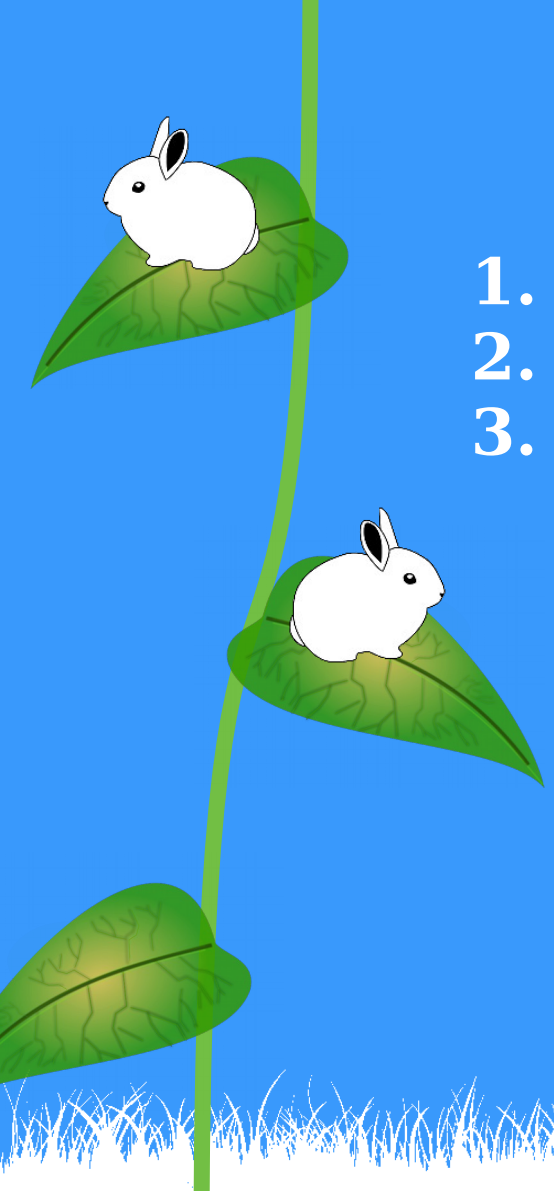


Sub-threshold Triggering

1. Partitioning of the power grid.
2. Localization of anomalies.
3. Napali scalability improvements.



Contributions



1. **OPQ Box:** low cost distributed PQ meter
2. **Napali:** Scalable performant event detection
3. **Sub-threshold Events:**
   - Grid partitioning
   - Event localization

Wide potential for other fields.

Napali in other domains

Lightning detection

Current System:
- Remote area deployment
- Satellite communication

With Napali:
- Metropolitan Area
- Abundant communication

Napali in other domains

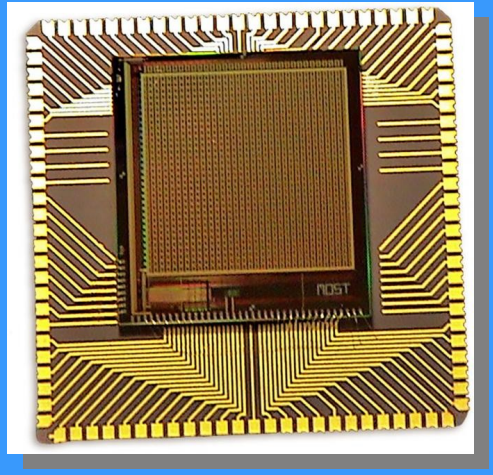
Gunshot Detection

Current System:

- No geographically distributed system in literature.

With Napali:

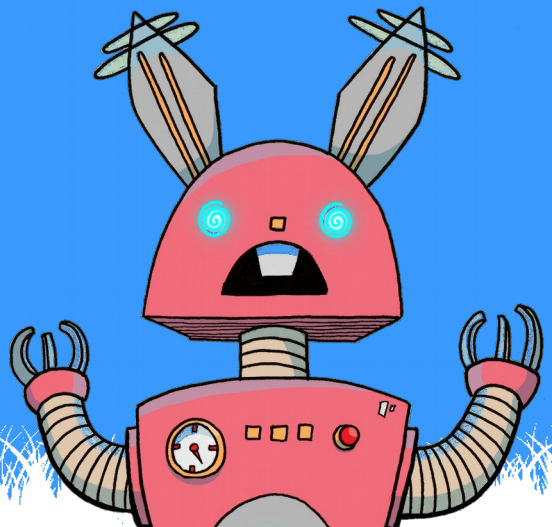
- Metropolitan area coverage.



MOST Sensor
Oceanit 2017

Future Work

1. AI device model to improve scalability
2. Scalability study
3. Privacy study
4. Power outage resiliency
5. Provide intelligence to Utility

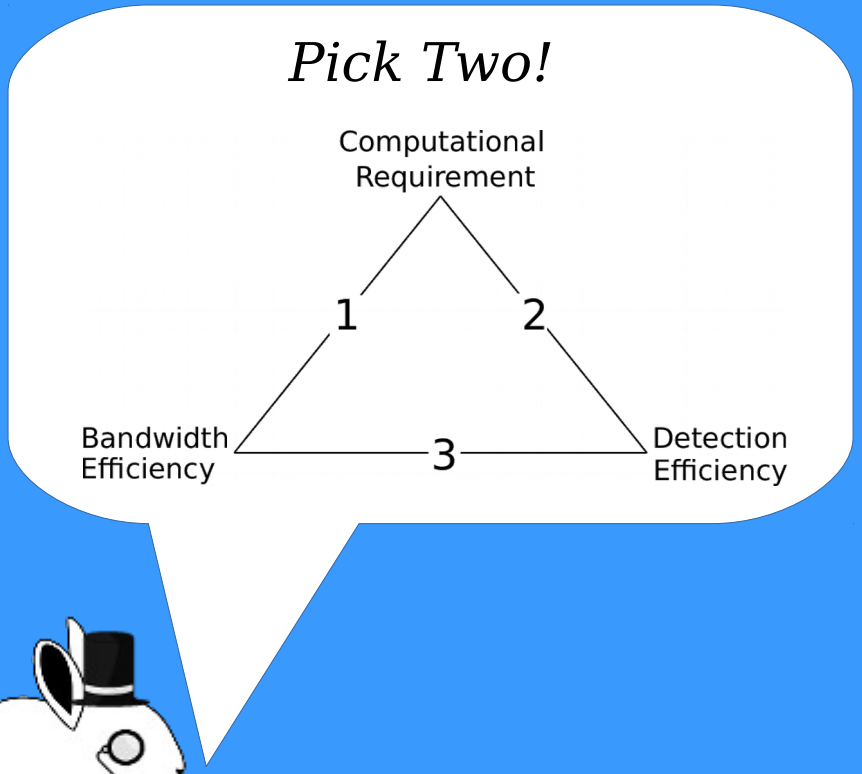


Fishy

Tiger 2012-2019
Turtle 2012-2020

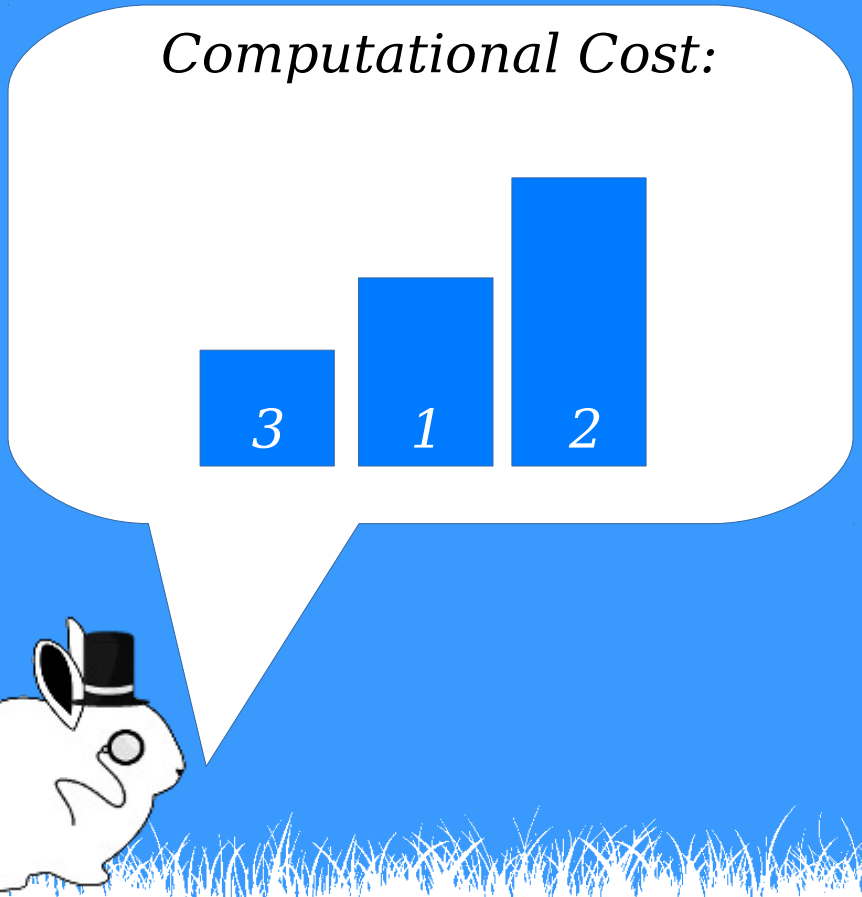

Thanks!

Comparison From Sensors Perspective



1. **Self-Triggered**
2. **Naive**
3. **Napali**

Comparison From Sink Perspective



1. **Self-Triggered**
2. **Naive**
3. **Napali**

Additional Benefits of Napali

Outside the scope of this thesis

1. Increased flexibility with respect to privacy protection.
2. Increased resiliency with respect to power failure