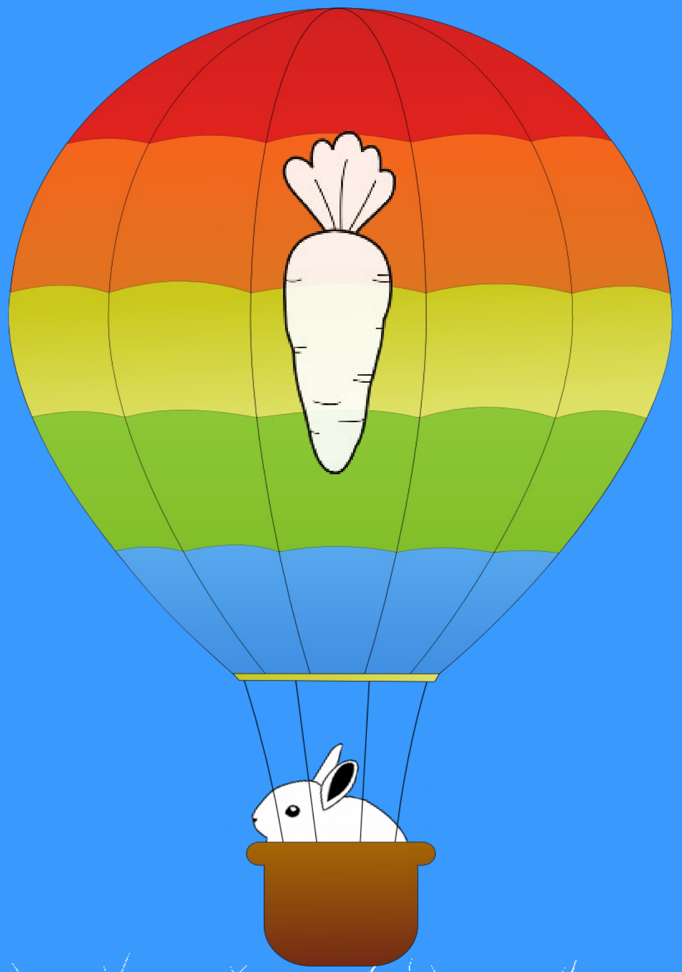
DESIGN, IMPLEMENTATION, AND EVALUATION OF NAPALI: A NOVEL DISTRIBUTED SENSOR NETWORK FOR IMPROVED POWER QUALITY MONITORING.

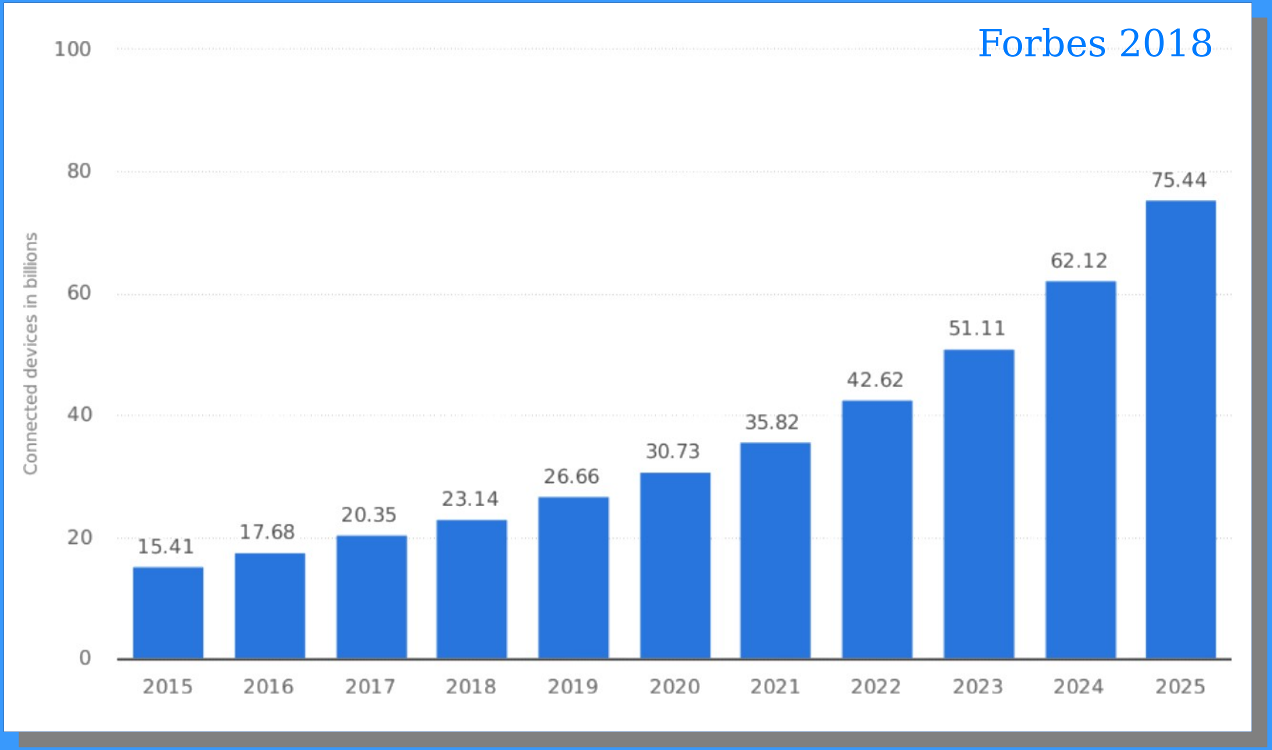
Sergey Negrashov
March 10, 2020,

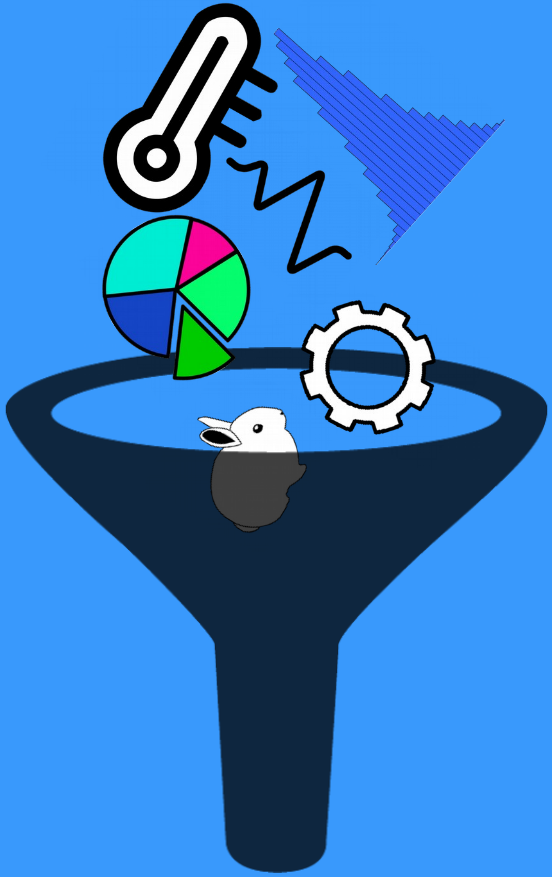
Outline

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

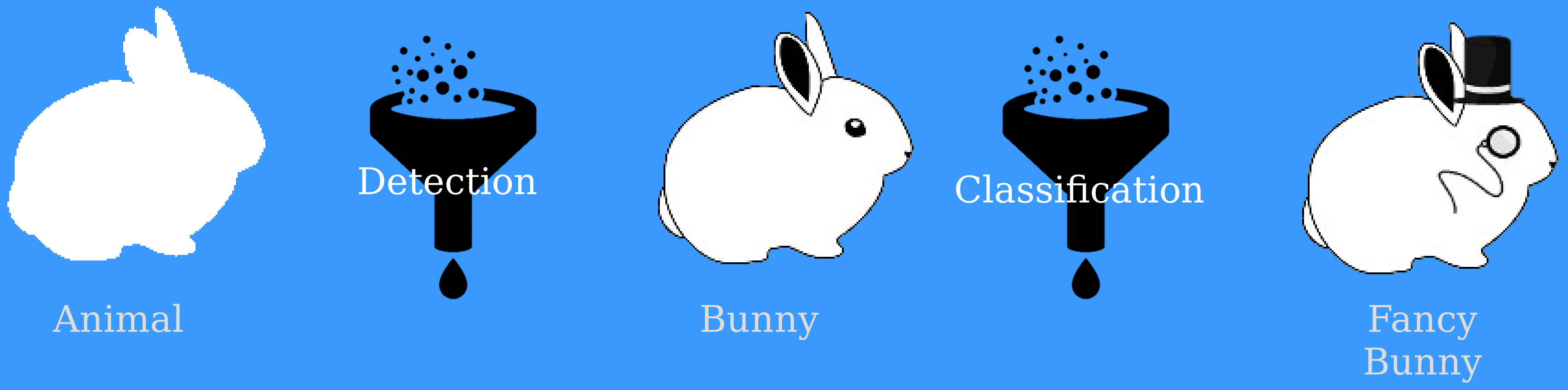


Big Data and IOT





Event Detection

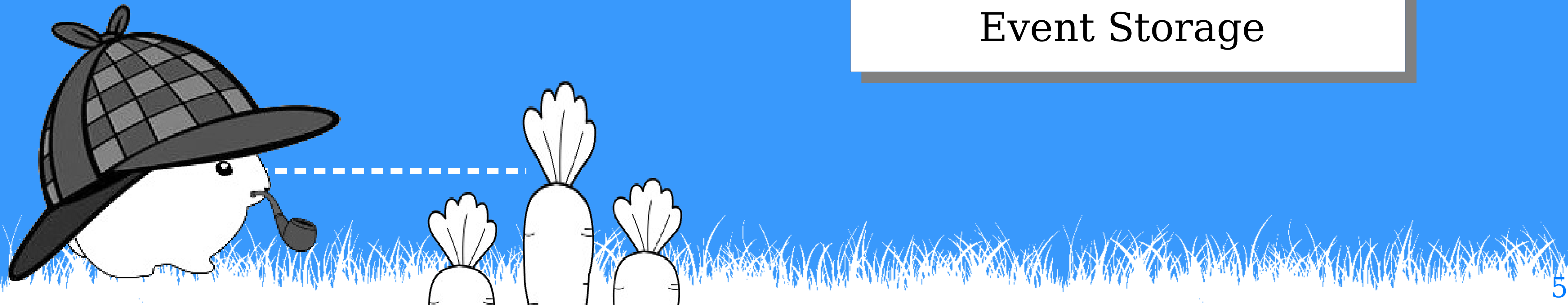


Traditional Methods

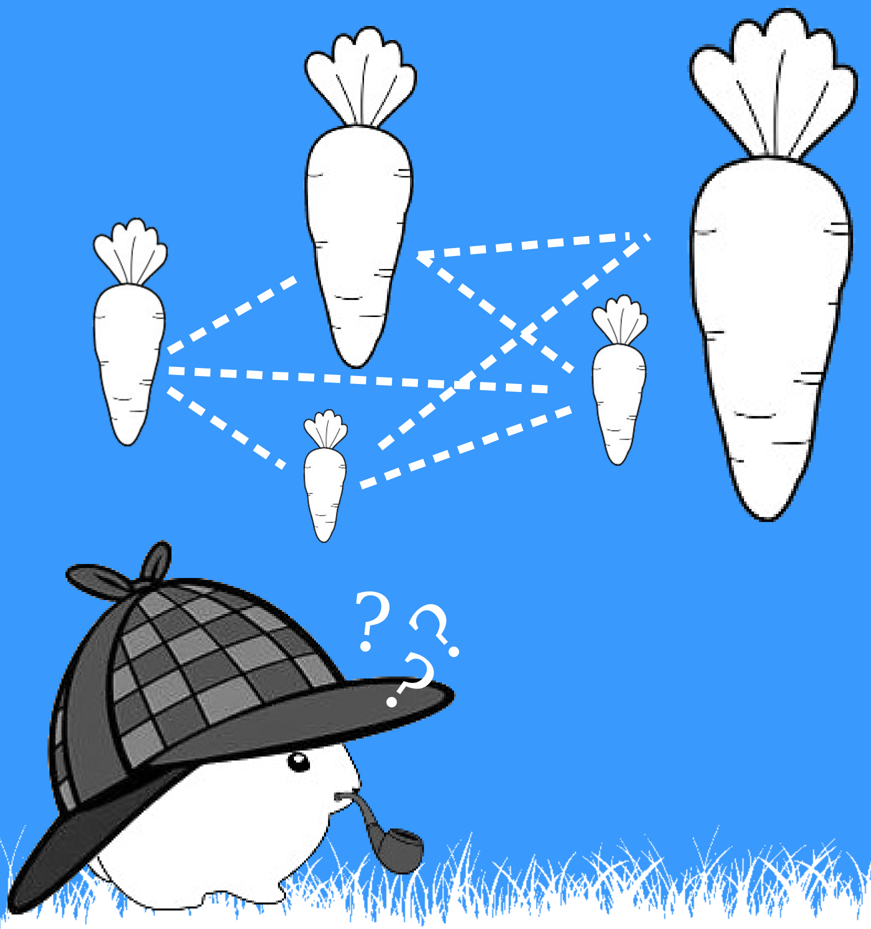
Metric Extraction

Threshold

Event Storage



Distributed Event Detection

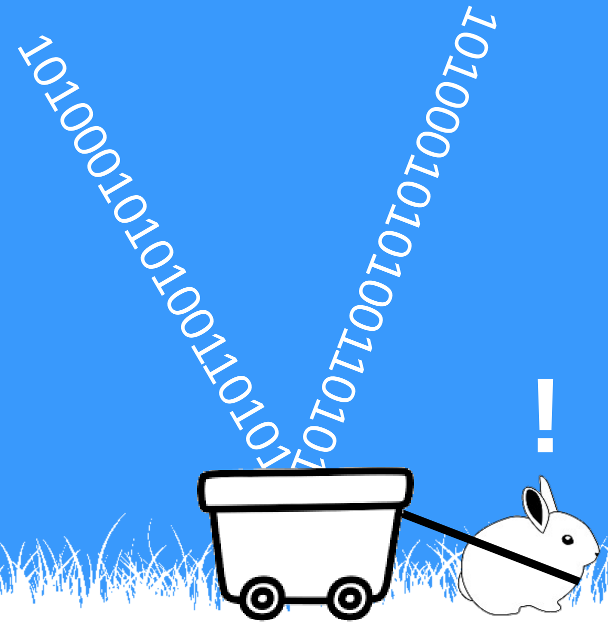


Naive Detection
Send Everything

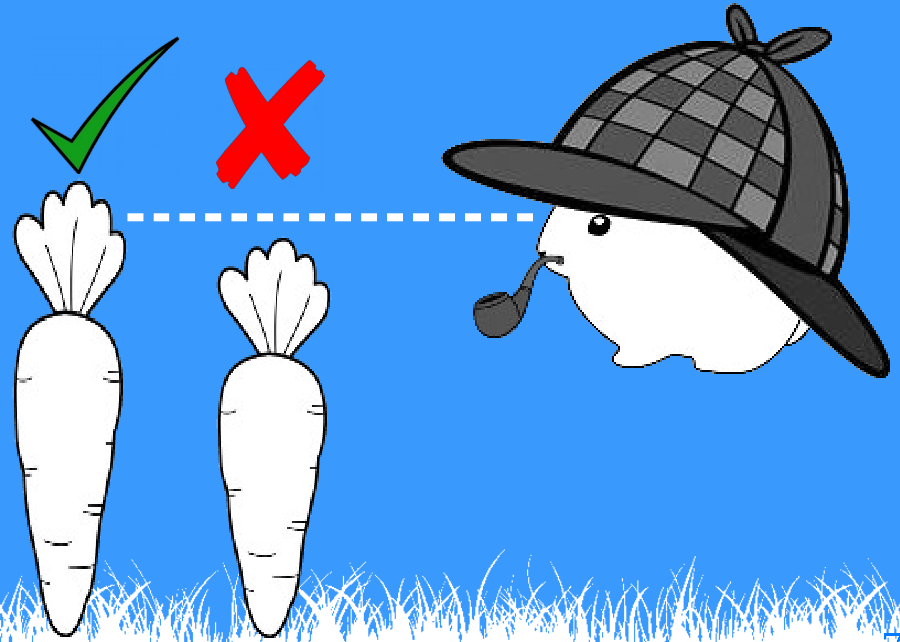
Self-Triggering
Detect Locally

Issues Current Methods

Naive Detection
- Bandwidth
- Memory

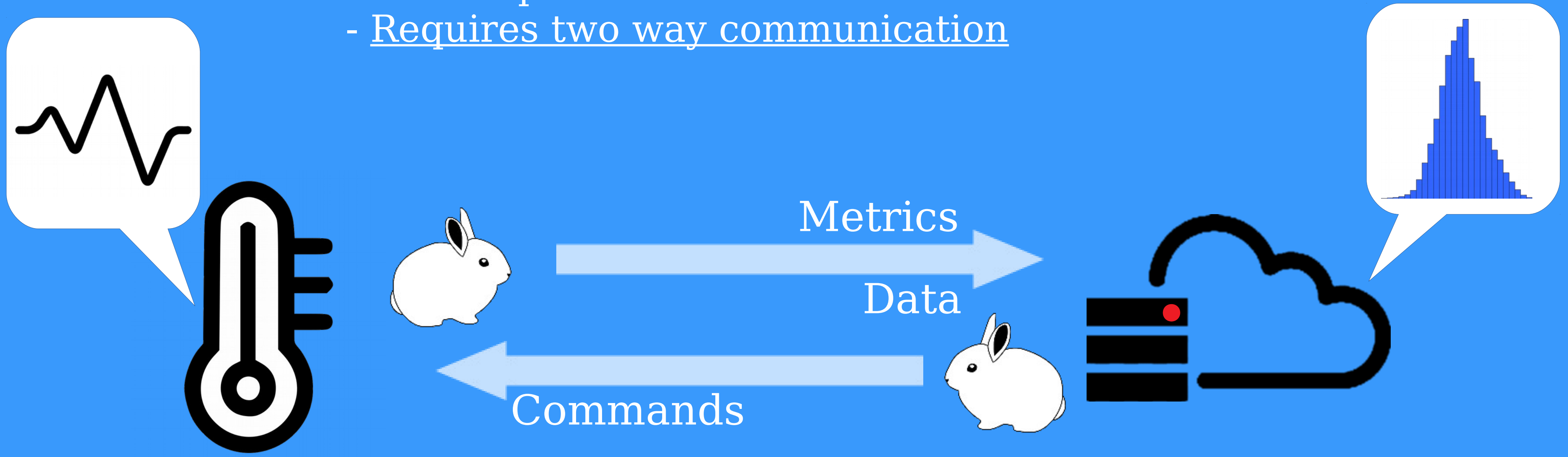


Self-Triggered
- Detection Efficiency



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
- <u>Requires two way communication</u>

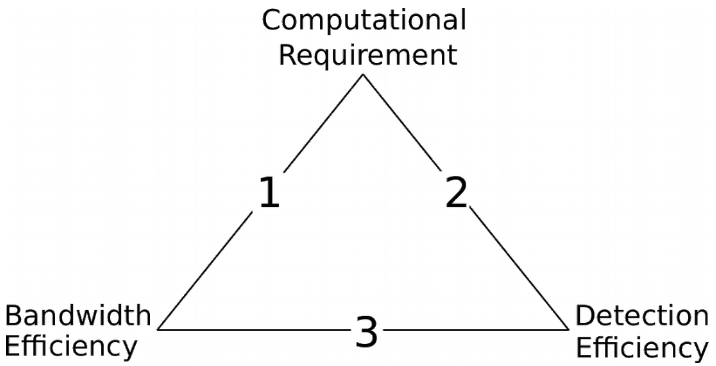


Napali

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

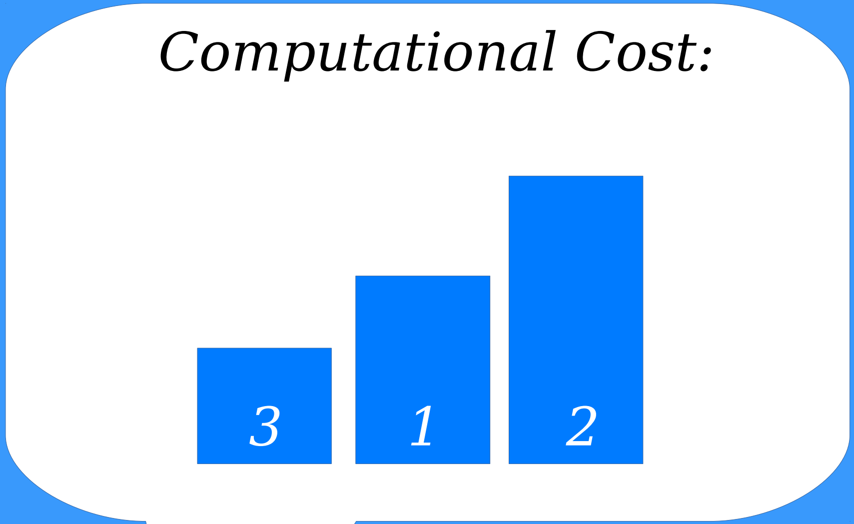
Comparison From Sensors Perspective

Pick Two!



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

Comparison From Sink Perspective



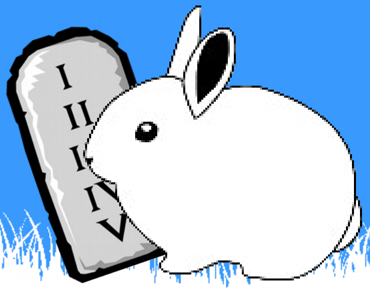
1. **Self-Triggered**
2. **Naive**
3. **Napali**

Claim

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.

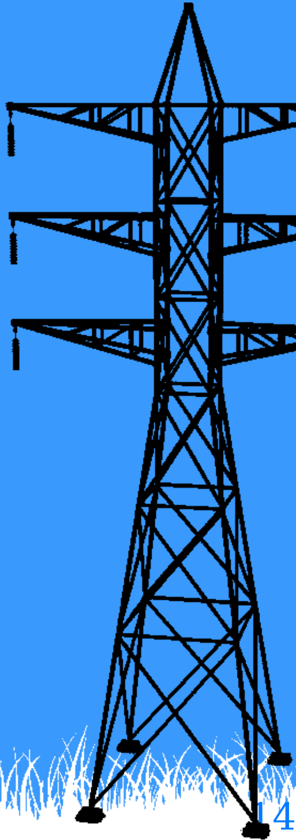
Claims of the Thesis

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

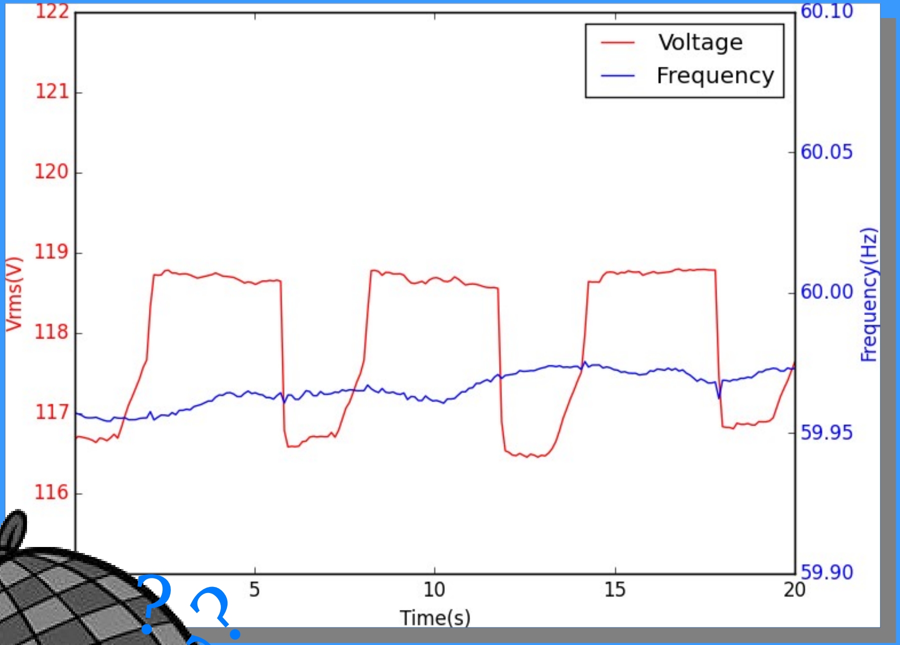


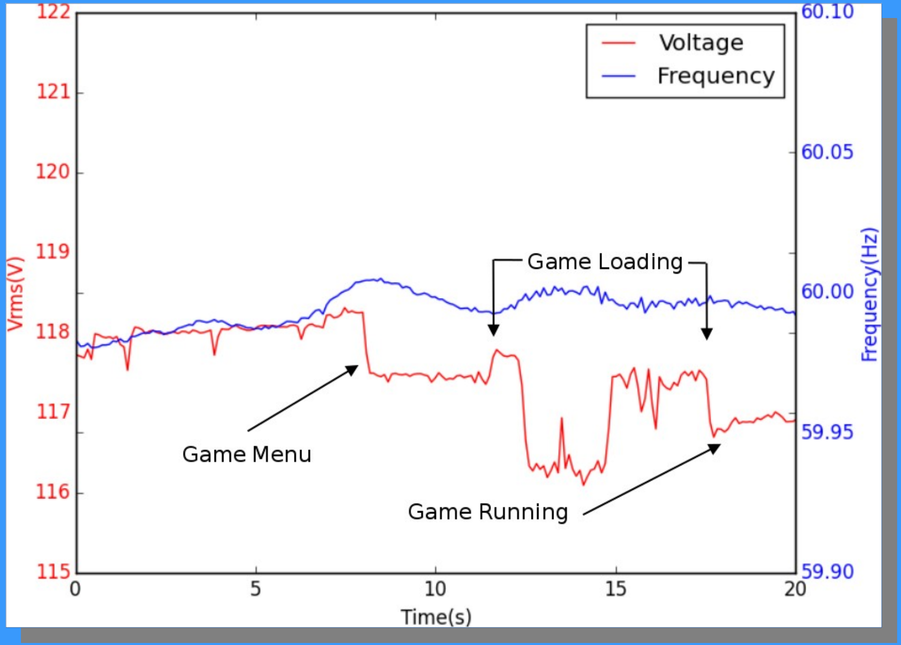
Problem of Power Quality

1. Amplitude
2. Fundamental Frequency
3. Harmonic Distortion
4. Transient

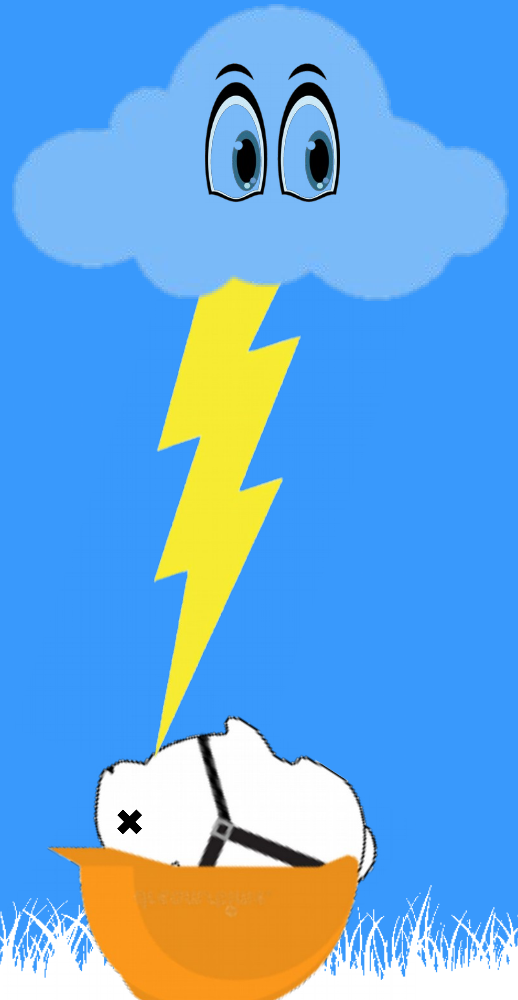


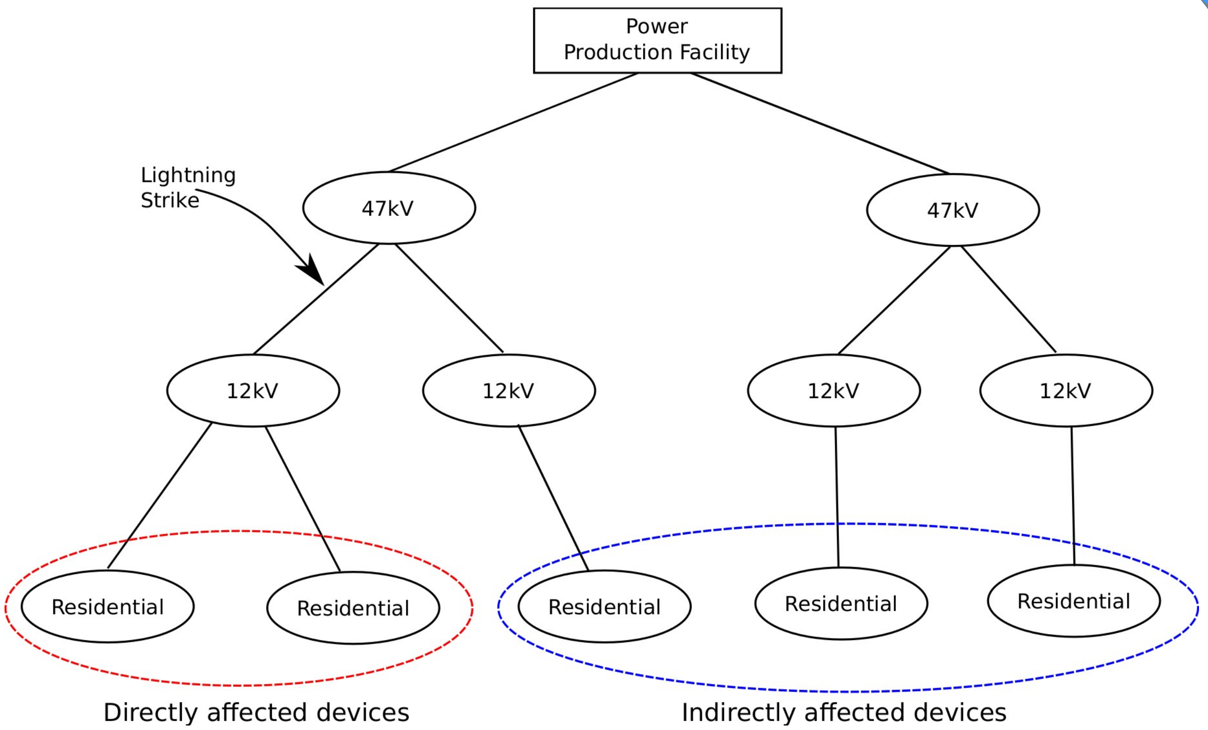
Local Detection Issues



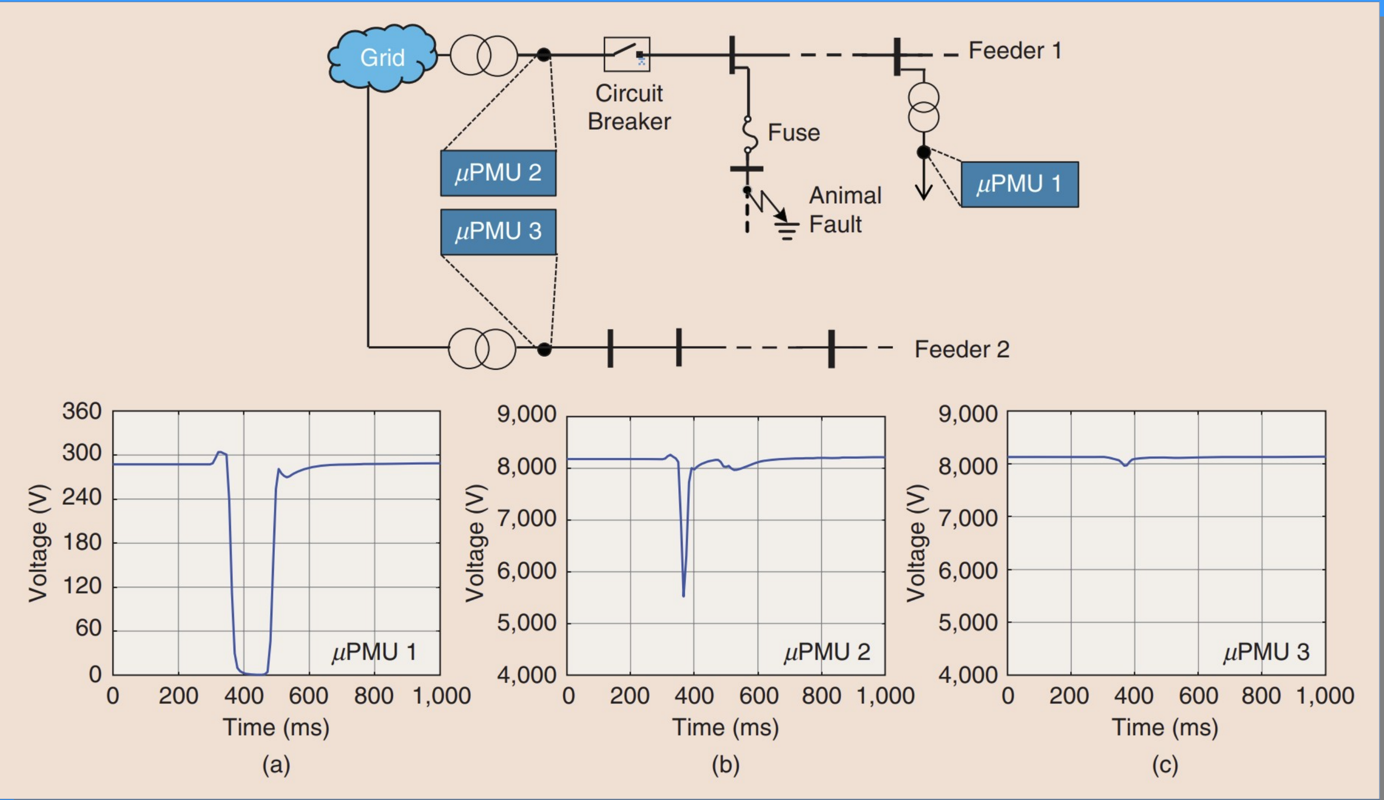


Local Detection Issues

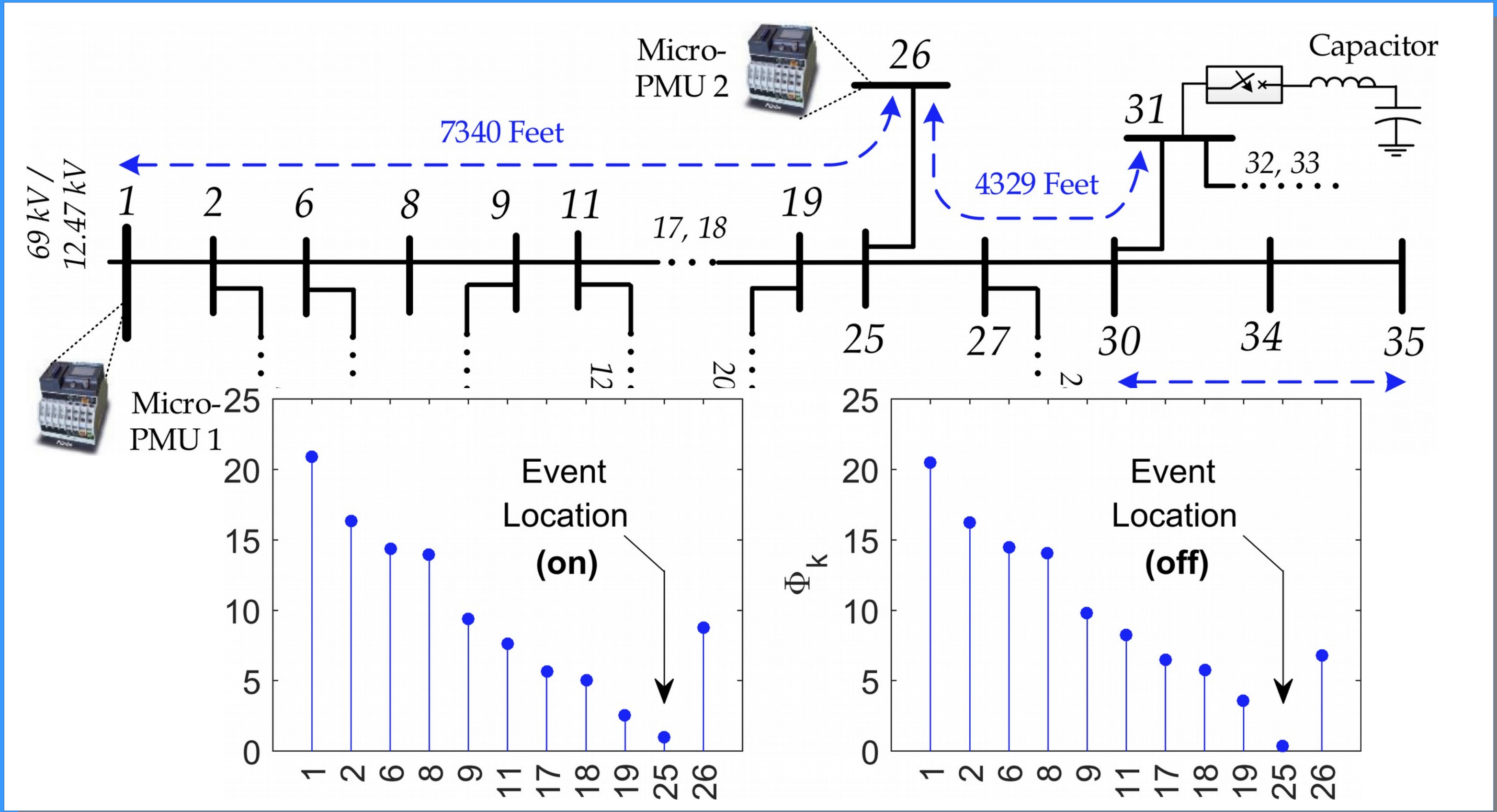




K Kahle. Power converters and power quality. CERN, 2016



Mohsenian-Rad, Hamed, Emma Stewart, and Ed Cortez.
"Distribution synchrophasors: Pairing big data with analytics to create actionable information."
IEEE Power and Energy Magazine (2018)



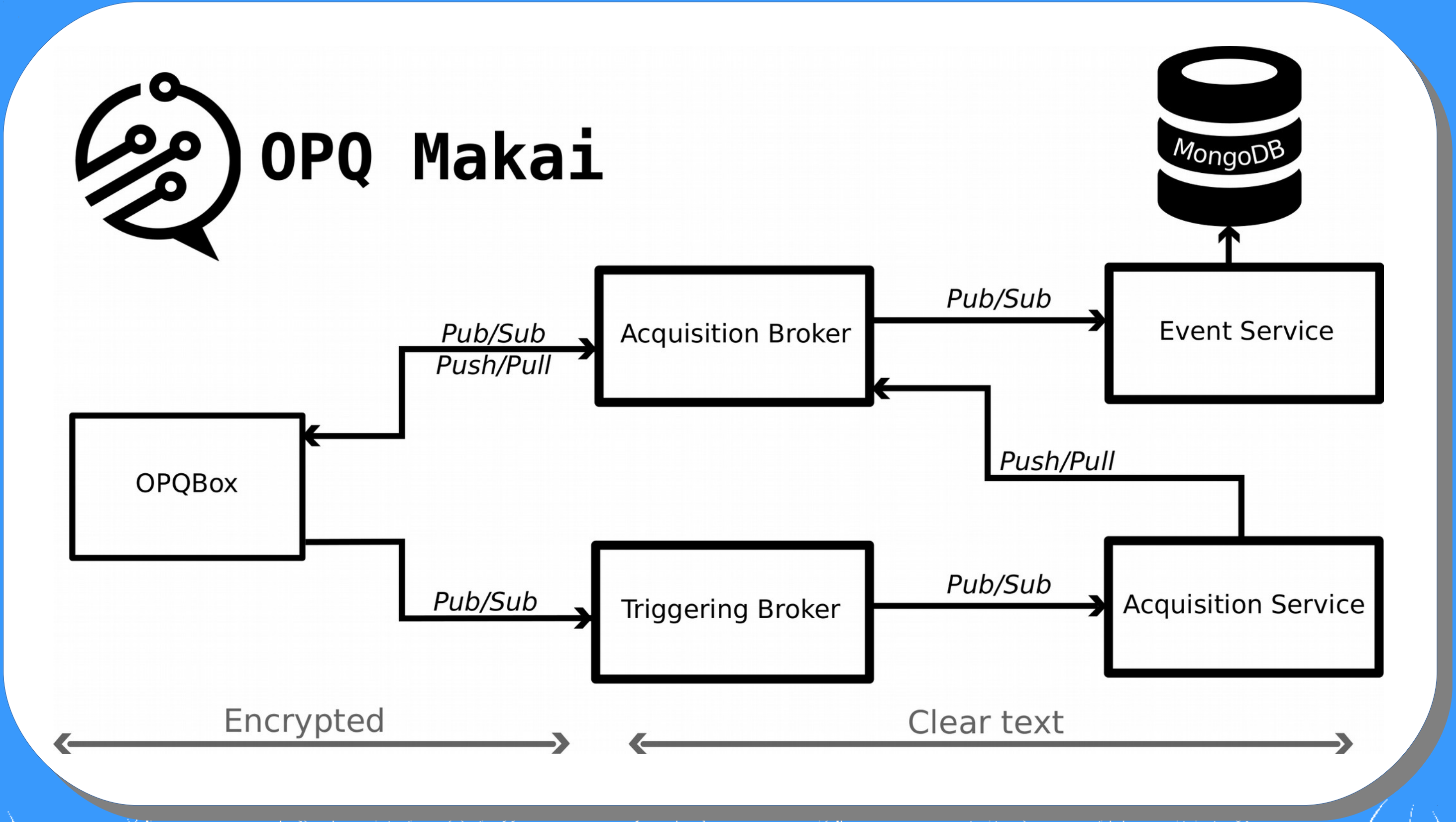
Farajollahi, Mohammad, et al. "Locating the source of events in power distribution systems using micro-PMU data." IEEE Transactions on Power Systems (2018)

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.

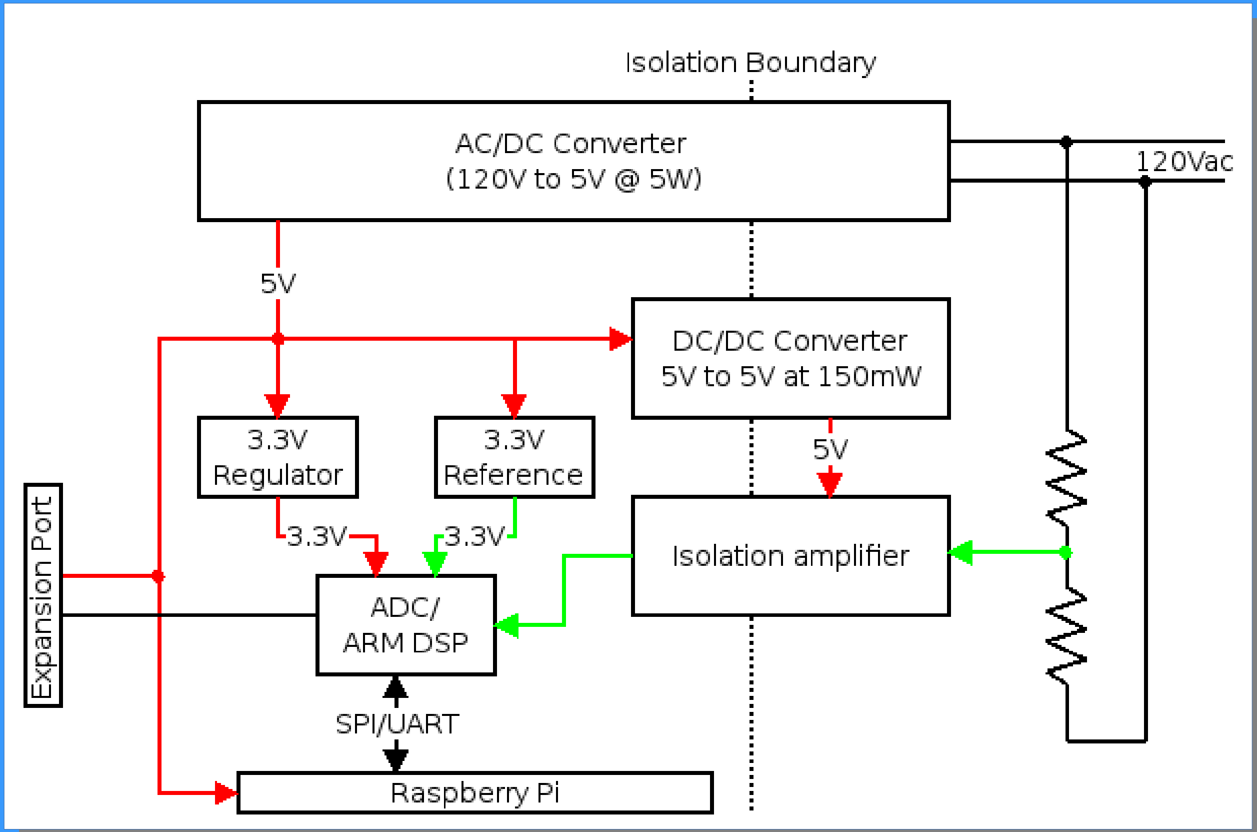
Mohsenian-Rad, Hamed, Emma Stewart, and Ed Cortez. "Distribution synchrophasors: Pairing big data with analytics to create actionable information." IEEE Power and Energy Magazine 16.3 (2018): 26-34.

Open Power Quality
Gridwide event detection



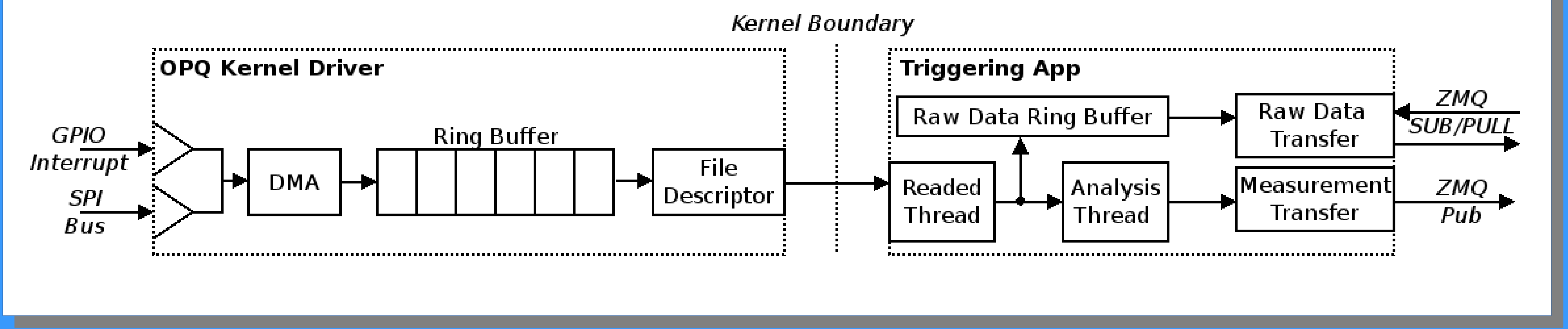
OPQ Box

Hardware



OPQ Box

Software



OPQ Box

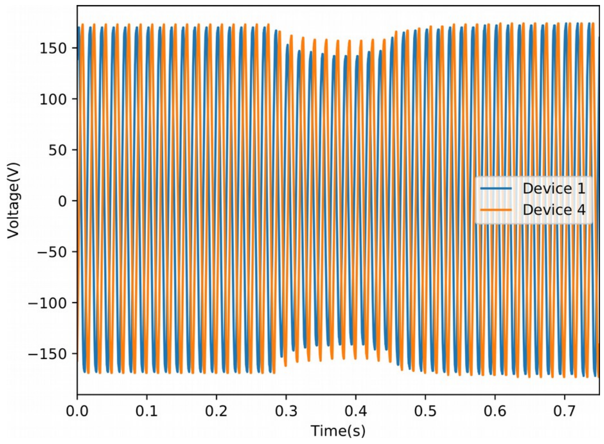
Metrics

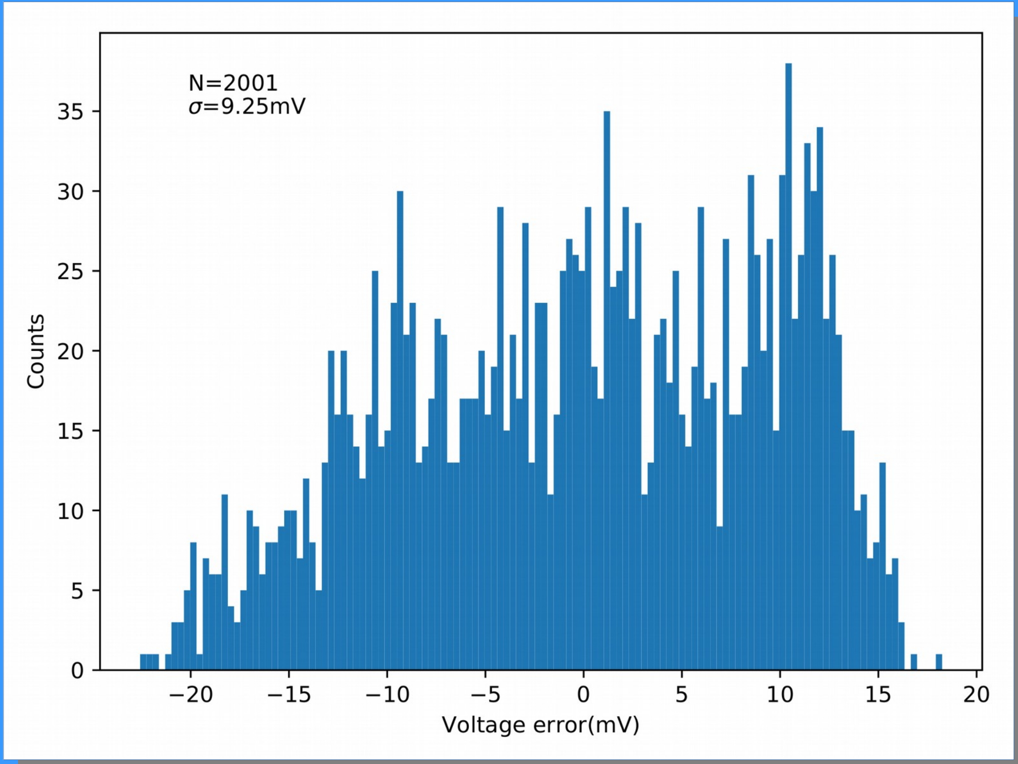
Metrics:
- V_{rms}
- Fundamental Frequency
- THD
- Transient

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

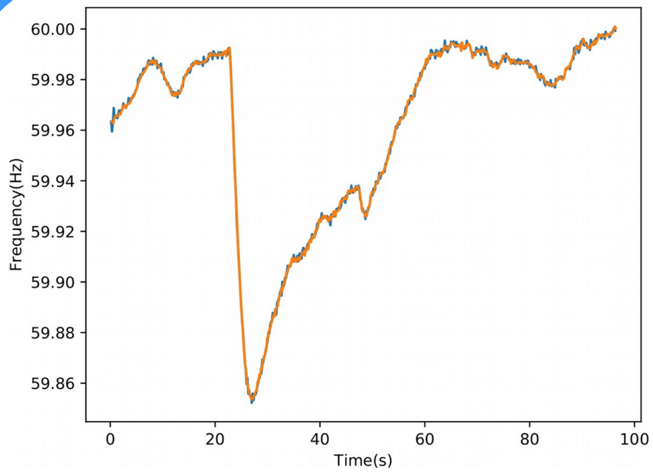
RDRB:
- 1 Hour

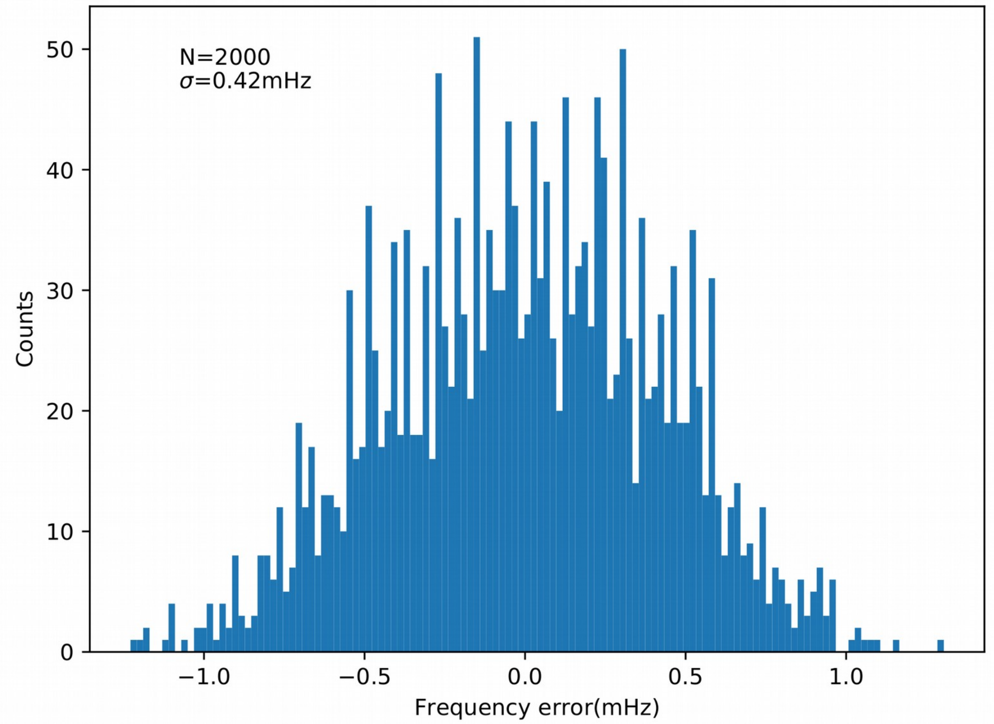
Amplitude(V_{rms})





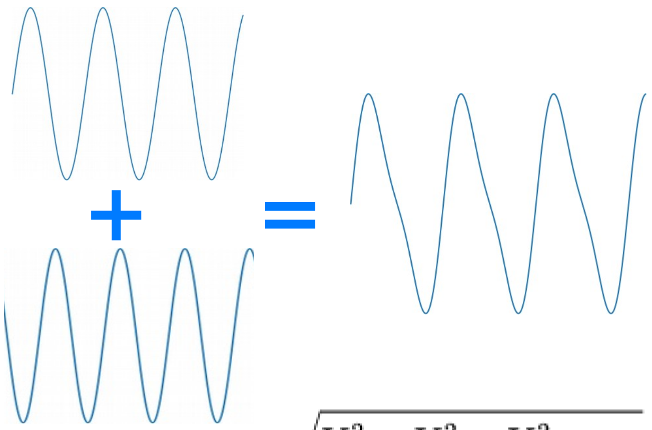
Frequency $f_{fundamental}$



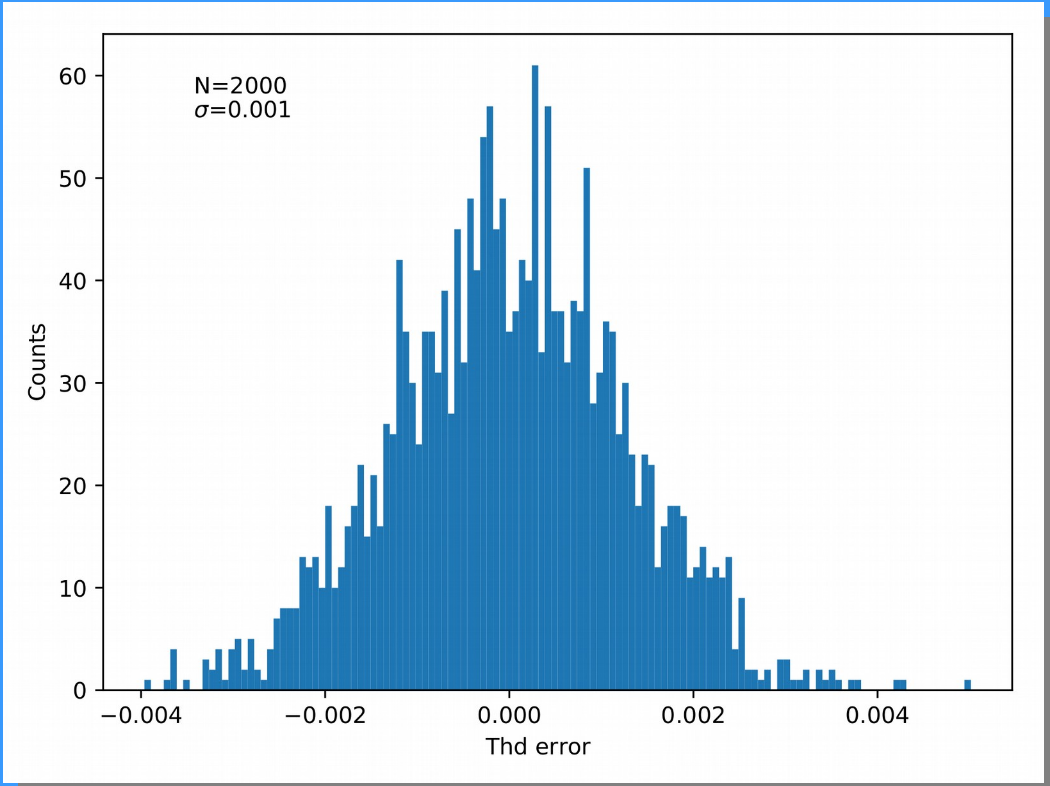


Total Harmonic Distortion

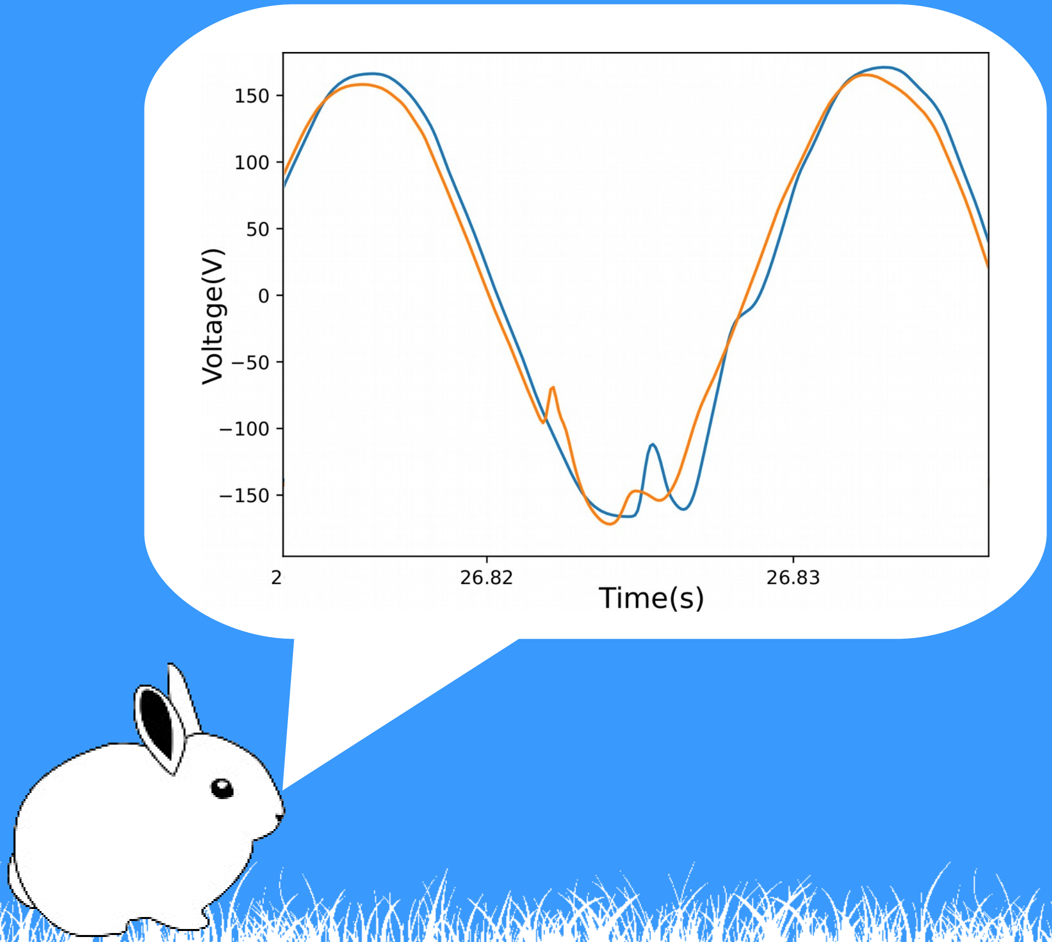
THD



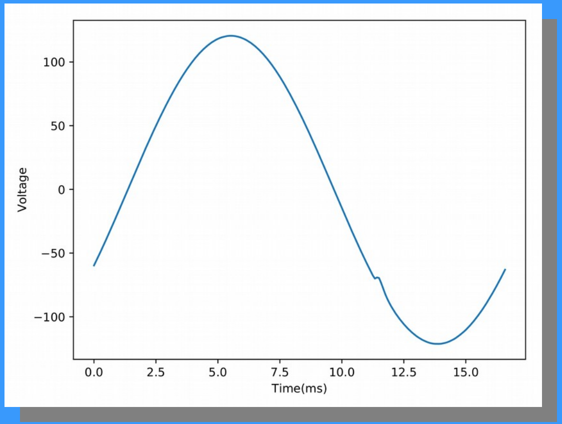
$$\mathrm{THD_F} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$



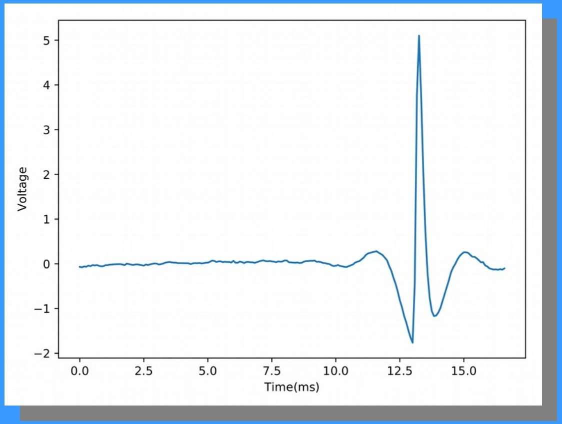
Transients



Voltage(V)
150
100
50
0
−50
−100
−150
2
26.82
26.83
Time(s)



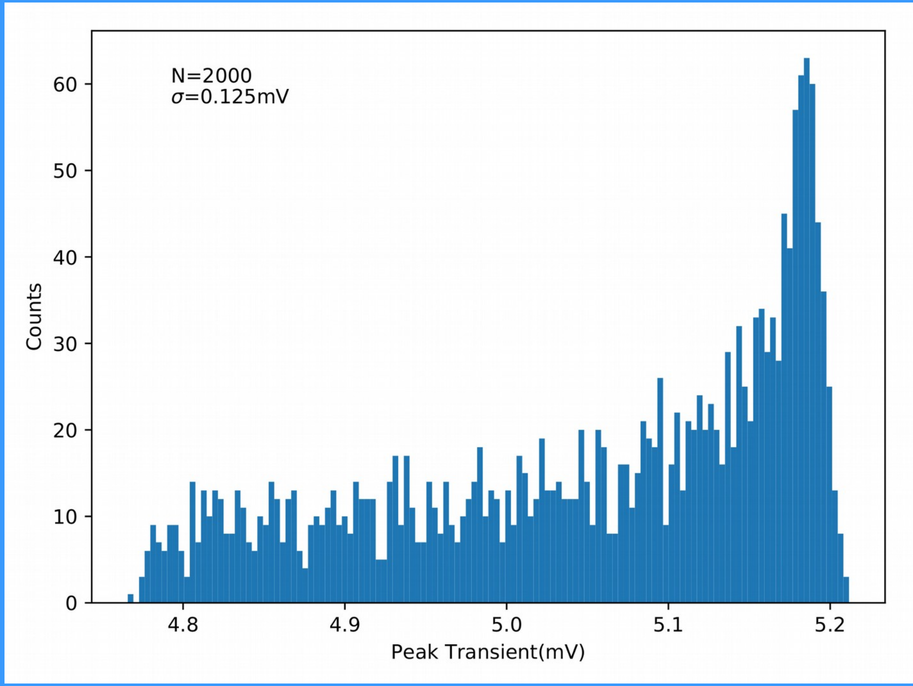
Voltage
100
50
0
−50
−100
0.0
2.5
5.0
7.5
10.0
12.5
15.0
Time(ms)



Voltage
5
4
3
2
1
0
−1
−2
0.0
2.5
5.0
7.5
10.0
12.5
15.0
Time(ms)

OPQ Box

Evaluation of Transients.



THD

Napali Device Model

For each device:
- mean
- std

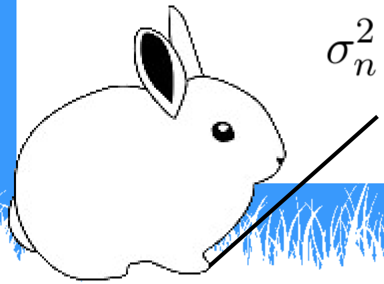
Leaky mean:

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

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

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

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



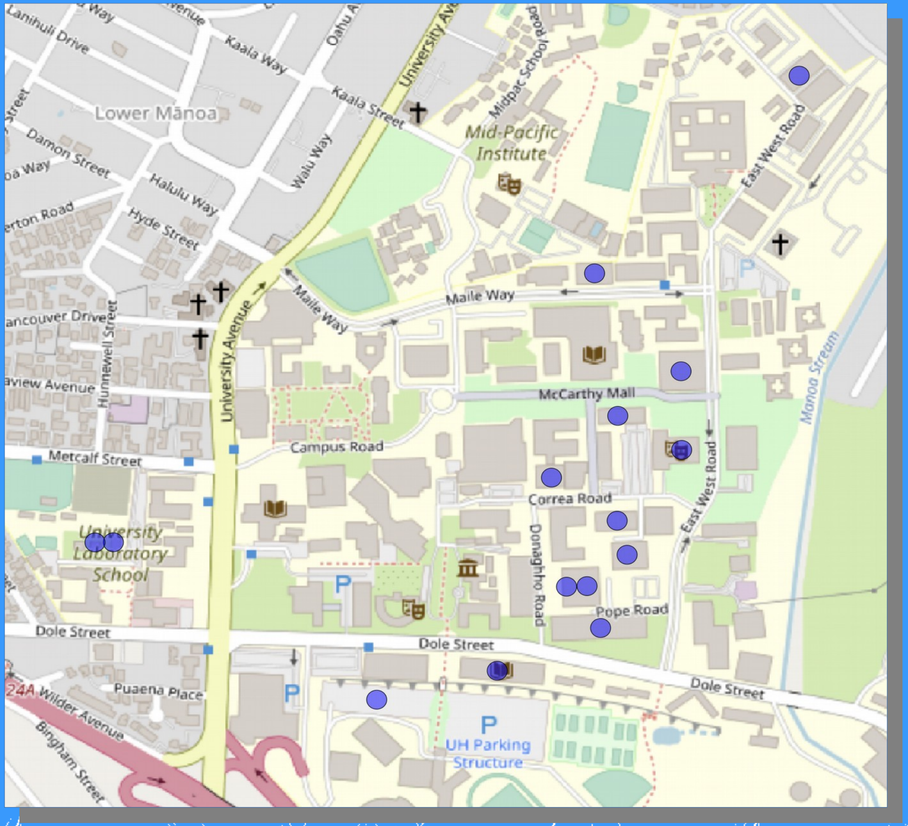
Event chronology:
1. Any device passes threshold.
2. Record any device > 3*std.
3. Wait until all devices are below threshold.
4. If device count is > 1 request data from
   - Devices which passed threshold.
   - Devices with a metric > 3*std.
5. If device count == 1:
   - No request is made.
6. Return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

UH Deployment

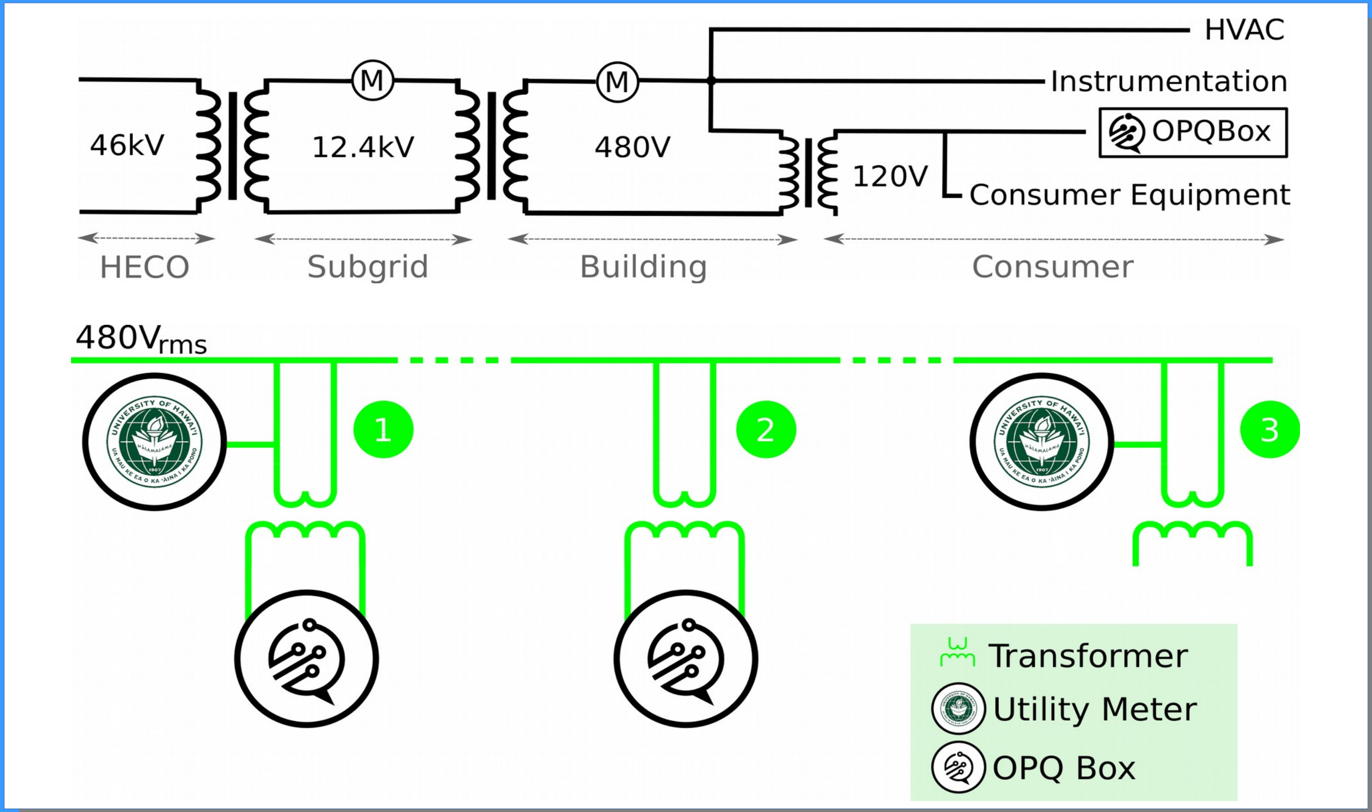
in-situ validation

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

Anyone want a PQ network?

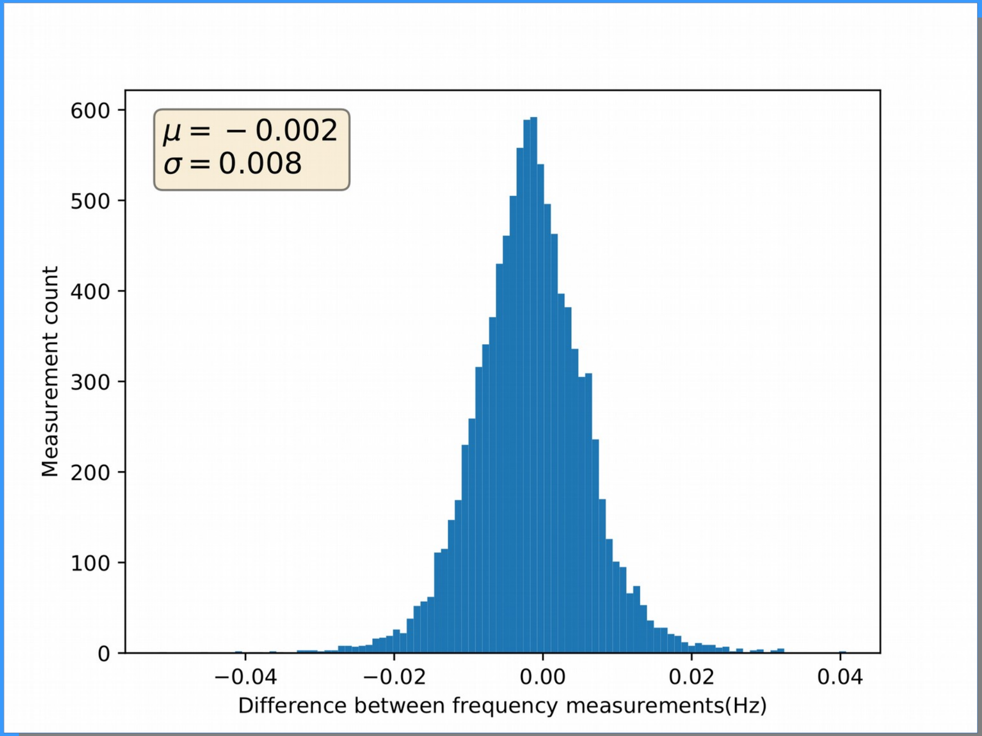


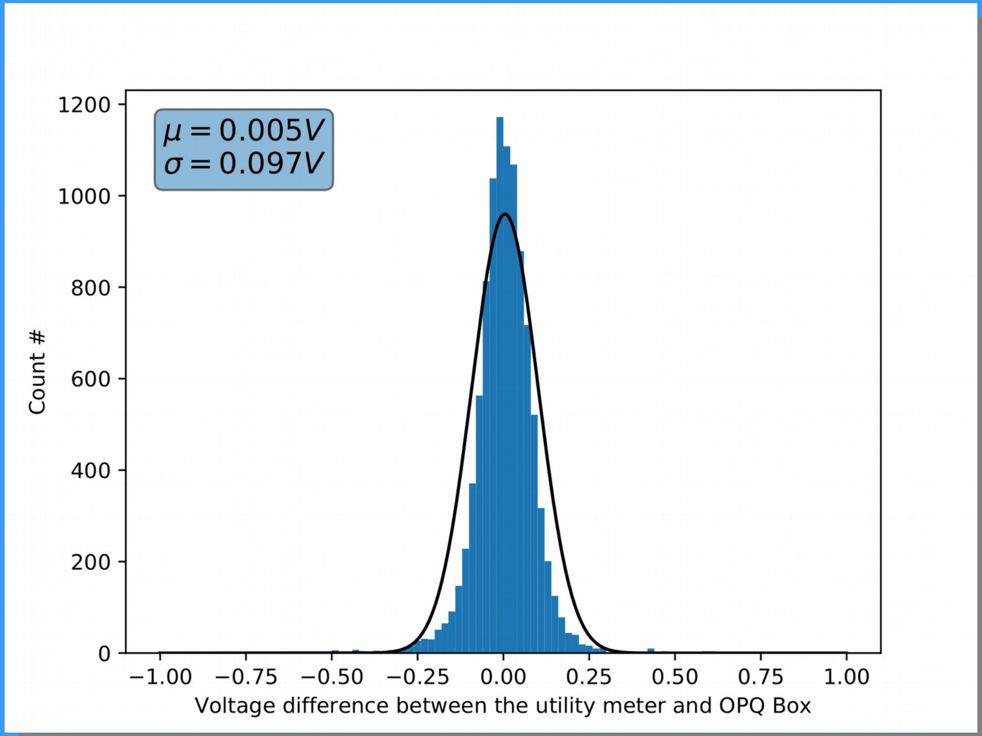
UH Deployment



OPQ Boxes

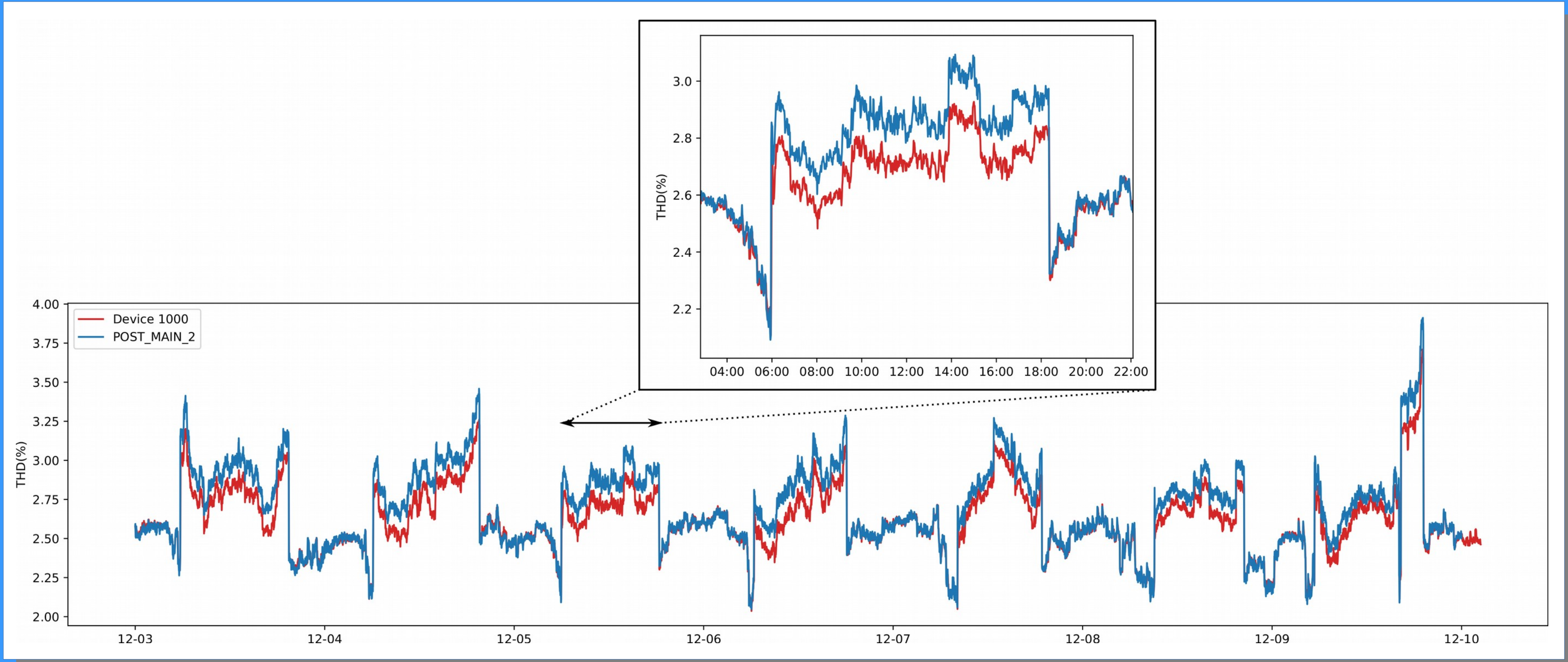
Comparison with UH meters





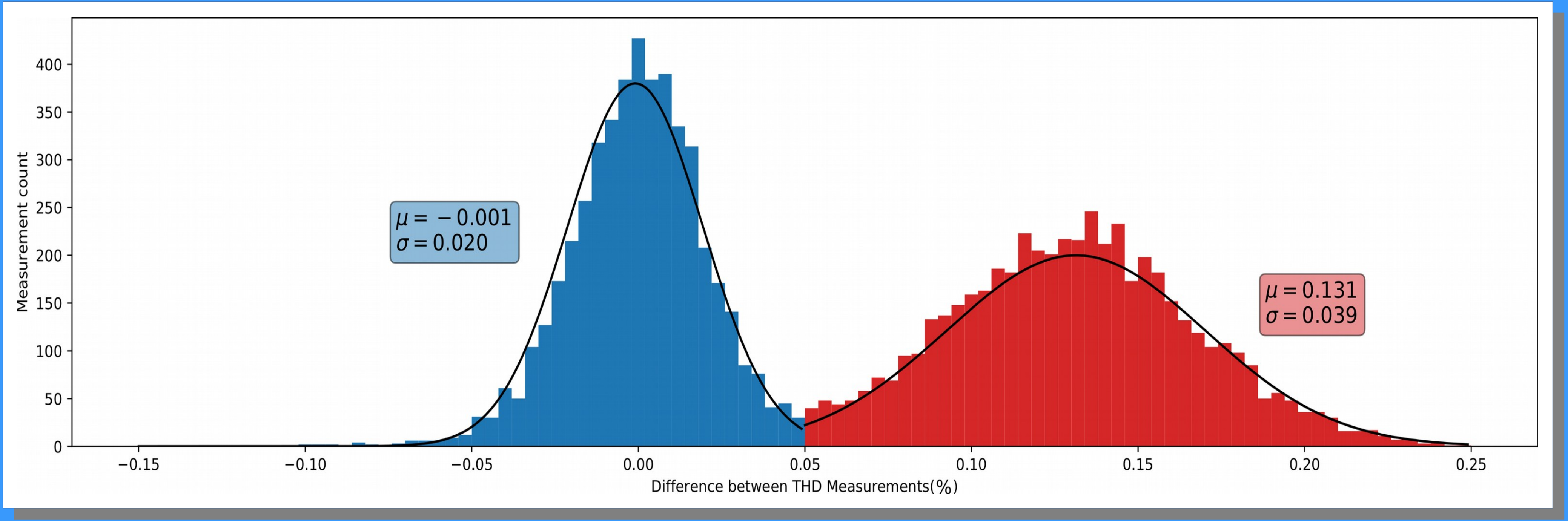
OPQ Boxes

Comparison with UH meters



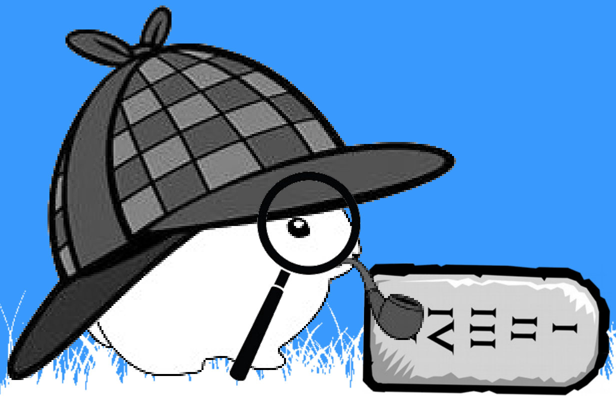
OPQ Boxes

Comparison with UH meters

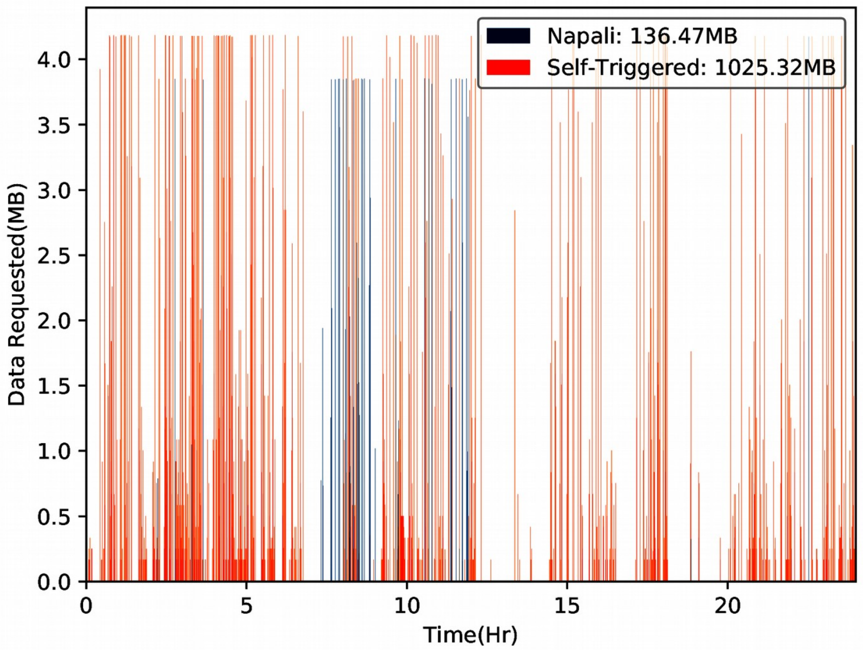


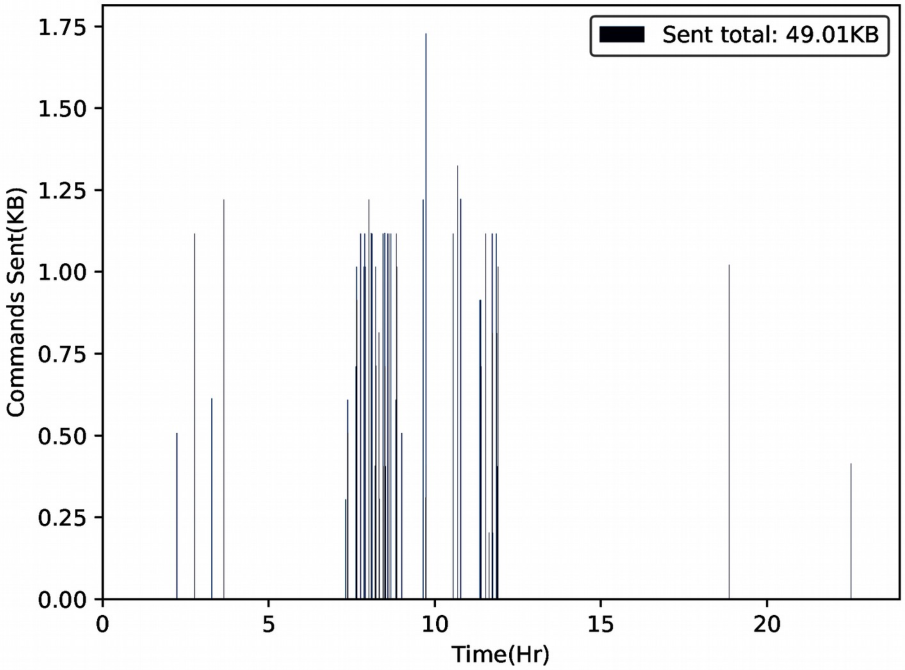
Napali Validation

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

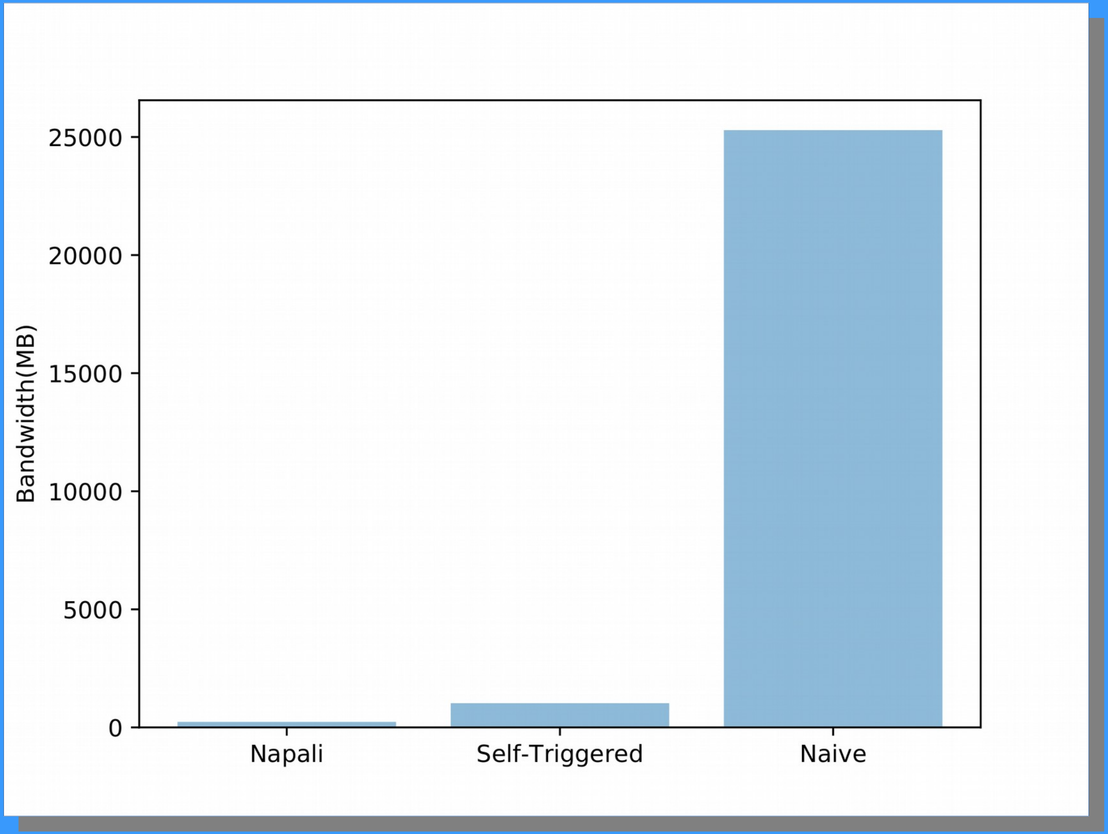


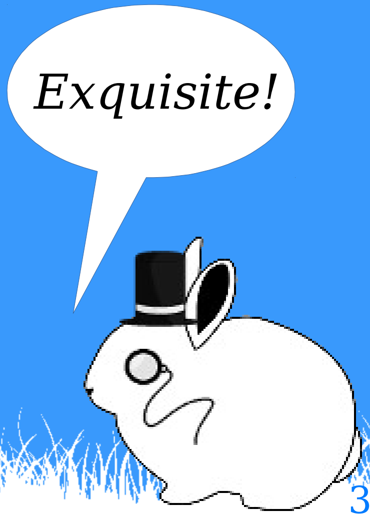
Bandwidth Usage



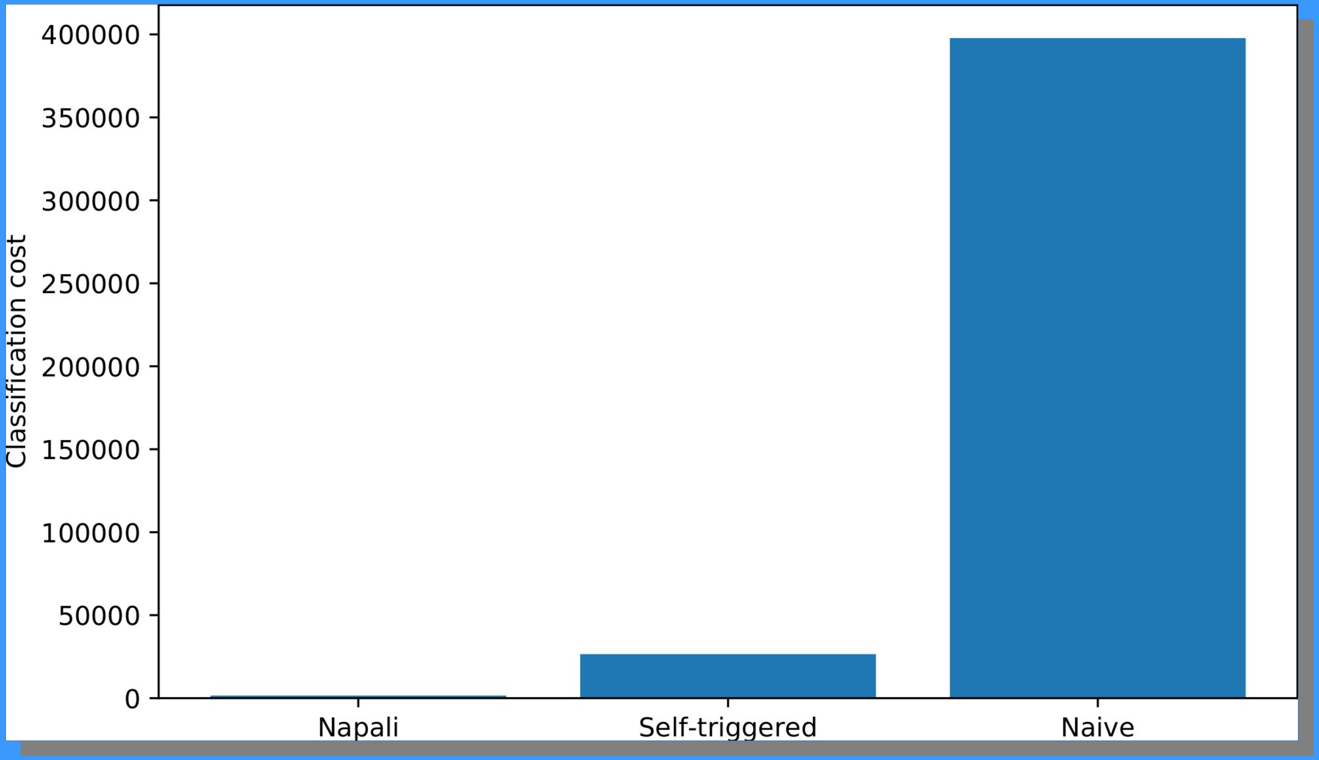


Bandwidth Usage



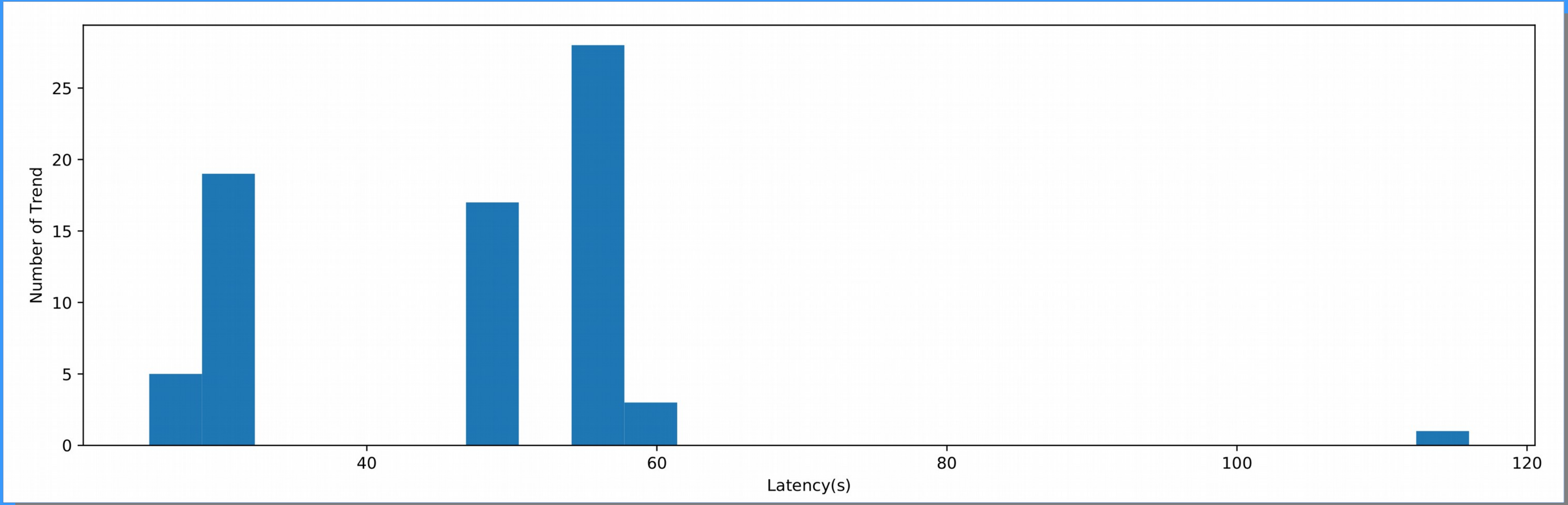


Computational Requirement

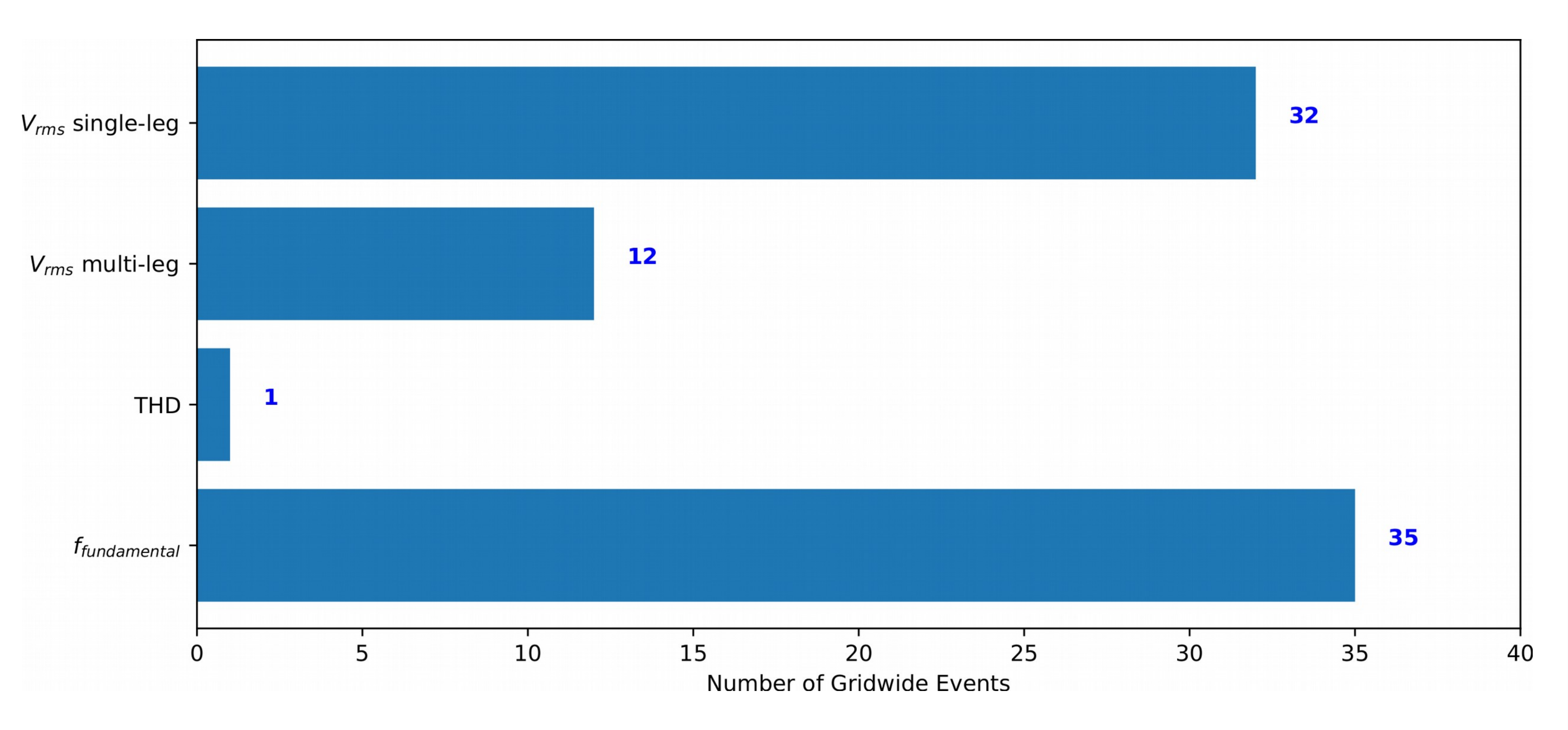


Latency

Late metrics over 24 hours

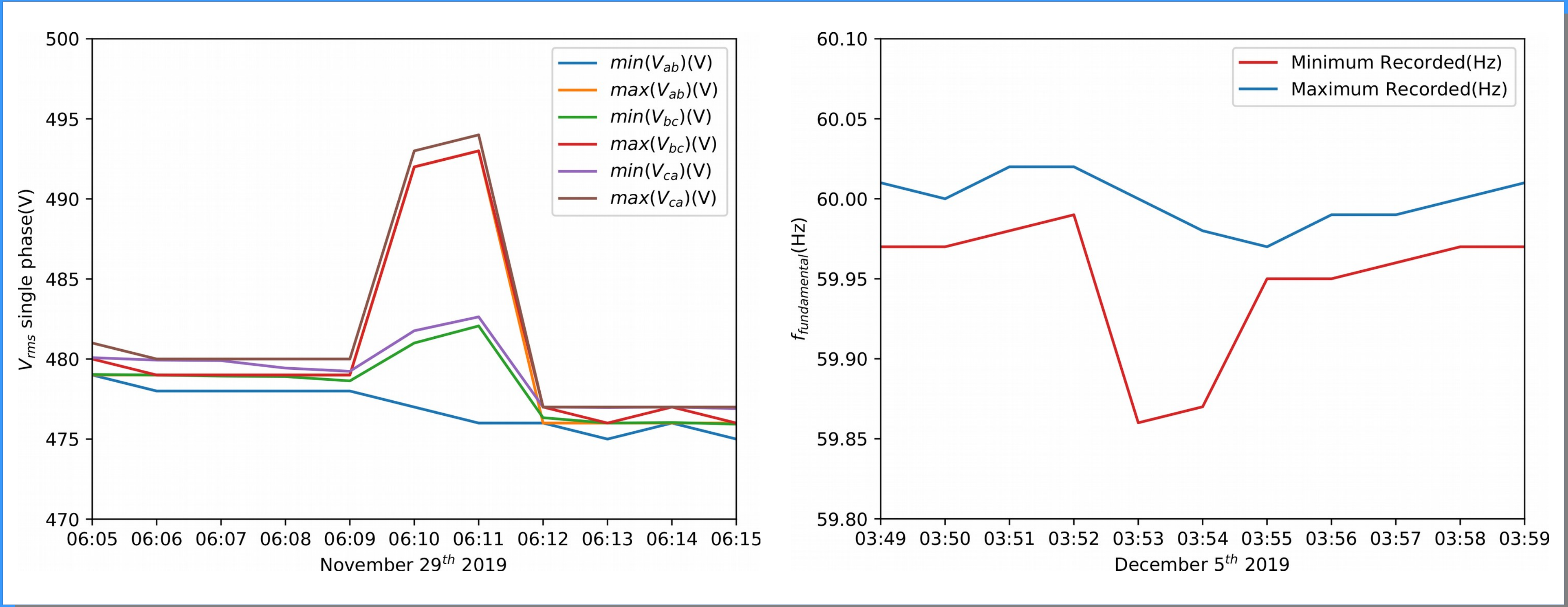


Temporal locality triggering



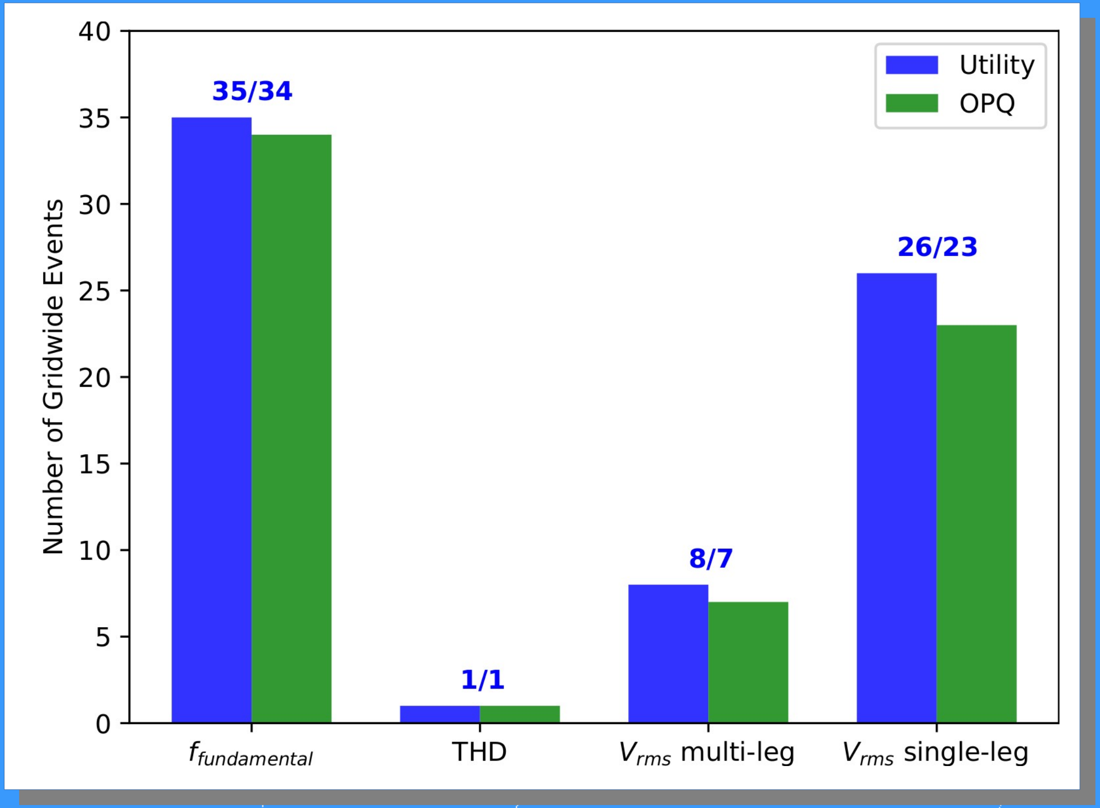
Temporal locality triggering

Ground truth event examples.



Temporal locality triggering

Detected events

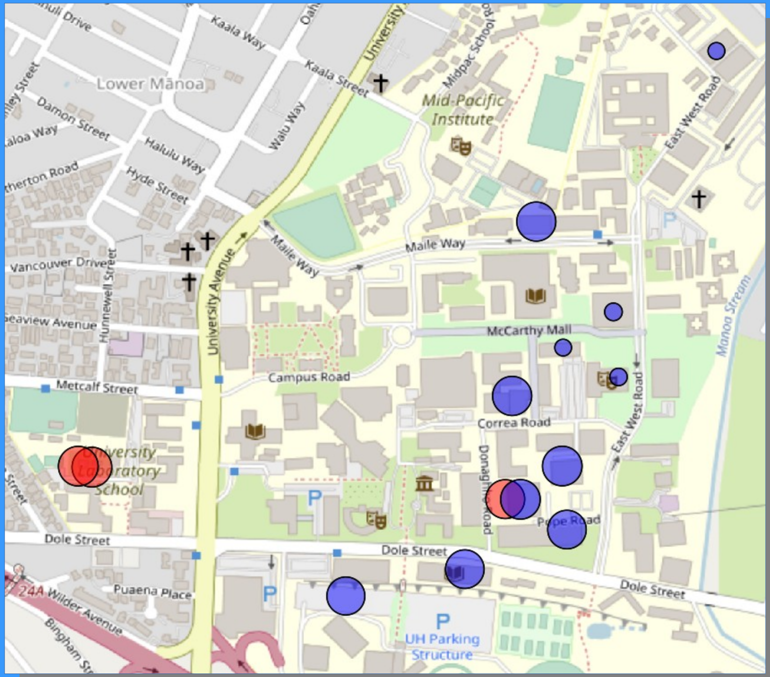


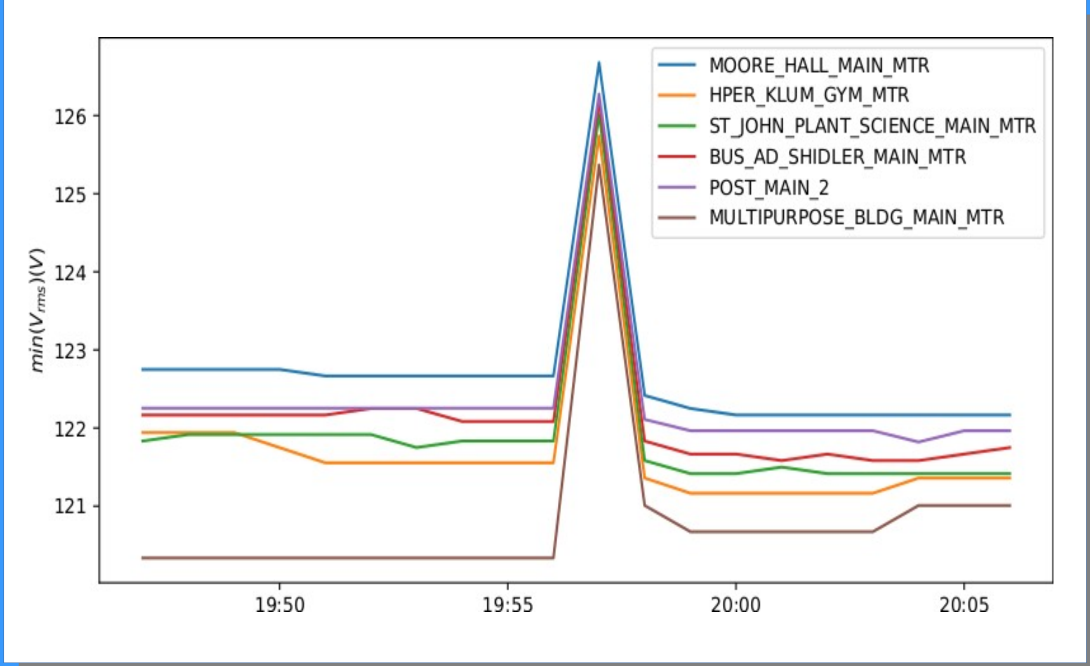
Sub-threshold Events

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

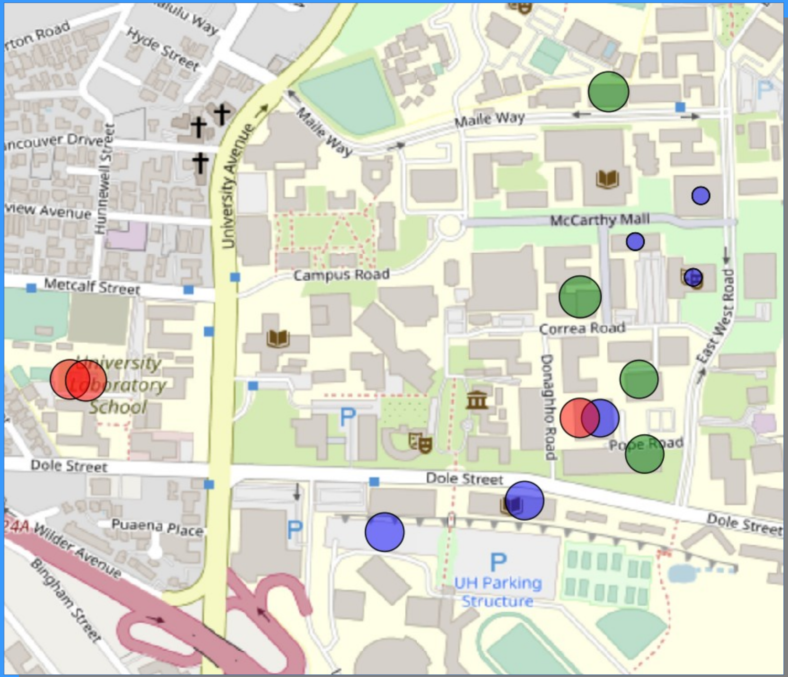
2. Compare the OPQ data with utility meters.

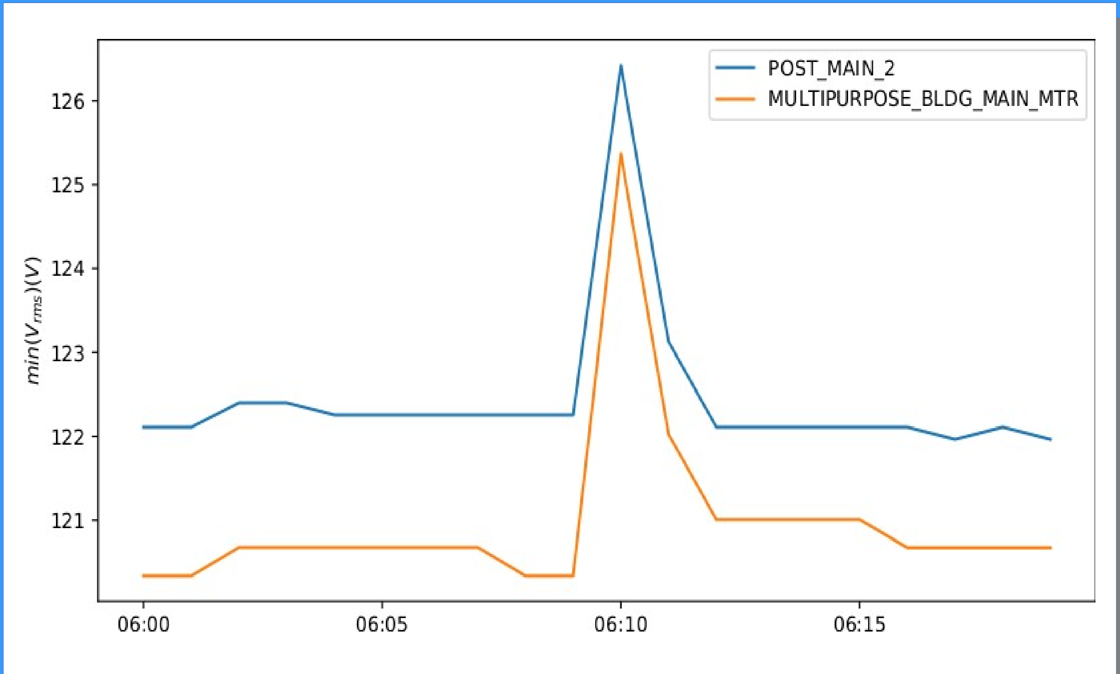
Event #1


Lower Mānoa
Mid-Pacific Institute
Maile Way
McCarthy Mall
Campus Road
Correa Road
Metcalf Street
Dole Street
University Avenue
East West Road
Pope Road
UH Parking Structure
Puaena Place
Wilder Avenue
Manoa Stream
Kaala Street
Kaala Way
Damon Street
Haiulu Way
Hyde Street
Vancouver Drive
Seaview Avenue
Hunnewell Street
Walu Way

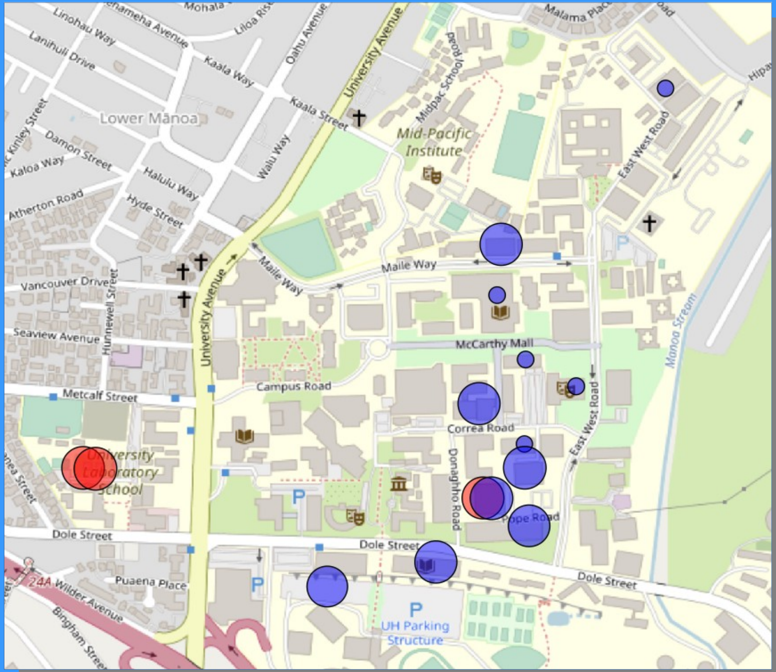

MOORE_HALL_MAIN_MTR
HPER_KLUM_GYM_MTR
ST_JOHN_PLANT_SCIENCE_MAIN_MTR
BUS_AD_SHIDLER_MAIN_MTR
POST_MAIN_2
MULTIPURPOSE_BLDG_MAIN_MTR
$min(V_{rms})(V)$
126
125
124
123
122
121
19:50
19:55
20:00
20:05

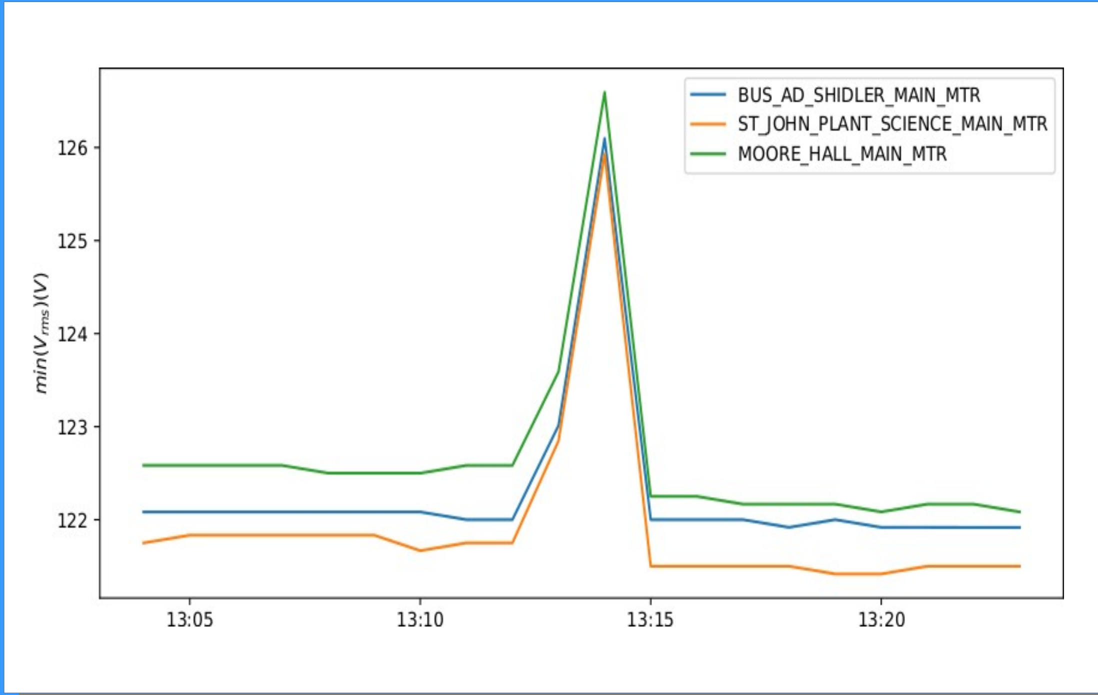
Event #2


Maile Way
McCarthy Mall
Campus Road
Correa Road
Metcalf Street
University Avenue
Hunnewell Street
University Laboratory School
Donaghho Road
Pope Road
East-West Road
Dole Street
Puaena Place
Wilder Avenue
Bingham Street
Hyde Street
UH Parking Structure


POST_MAIN_2
MULTIPURPOSE_BLDG_MAIN_MTR
$min(V_{rms})(V)$
126
125
124
123
122
121
06:00
06:05
06:10
06:15

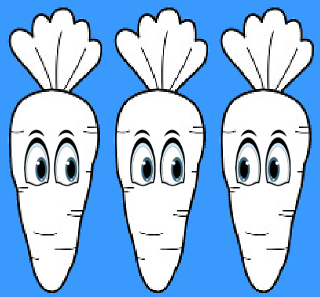
Event #3

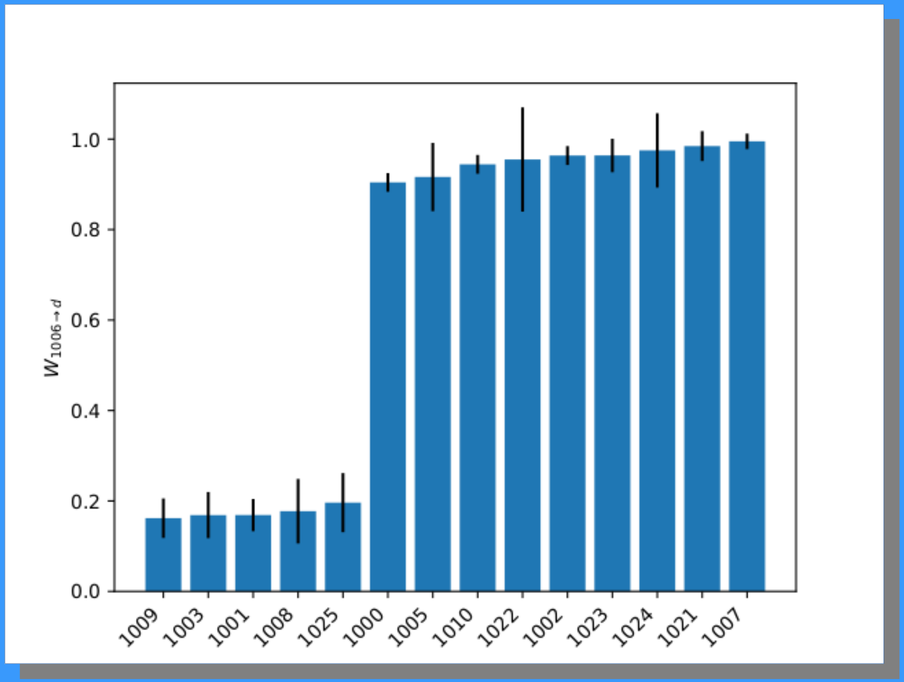




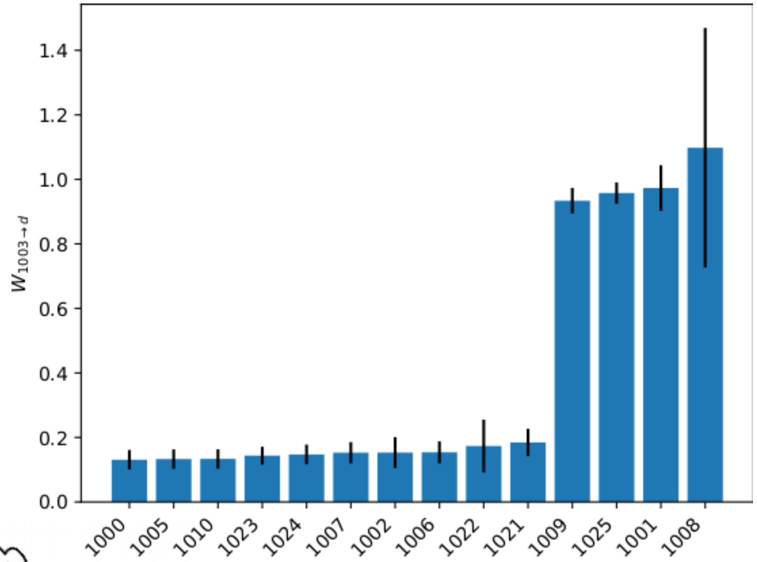
BUS_AD_SHIDLER_MAIN_MTR
ST_JOHN_PLANT_SCIENCE_MAIN_MTR
MOORE_HALL_MAIN_MTR
$min(V_{rms})(V)$
126
125
124
123
122
13:05
13:10
13:15
13:20

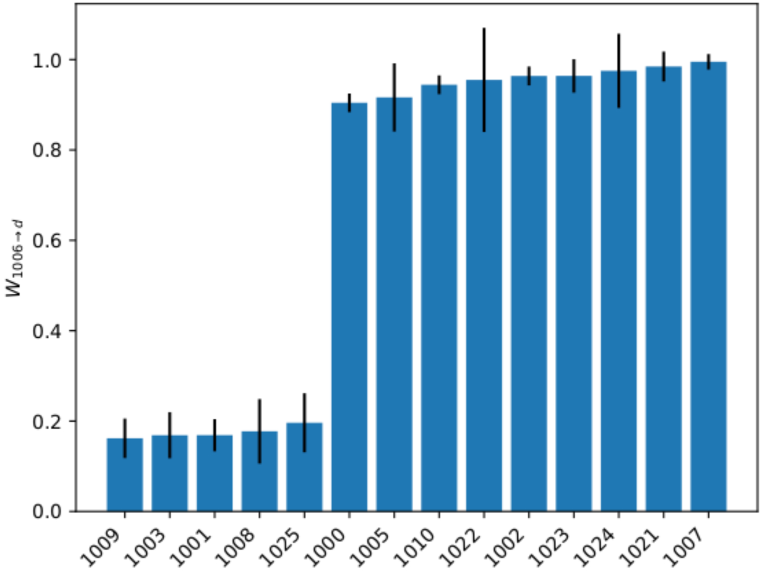
Event Clustering





Common Event

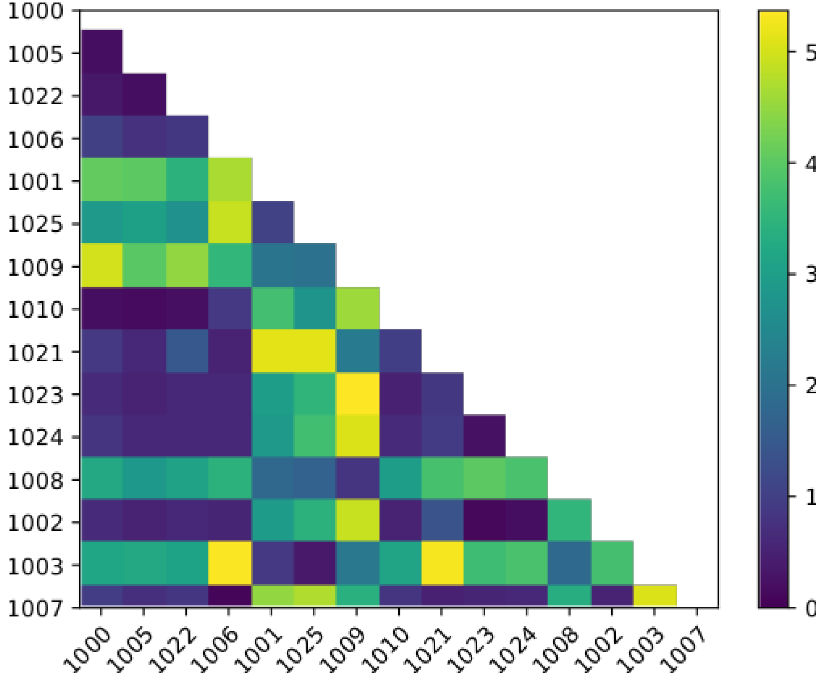




Pairwise Dissimilarity

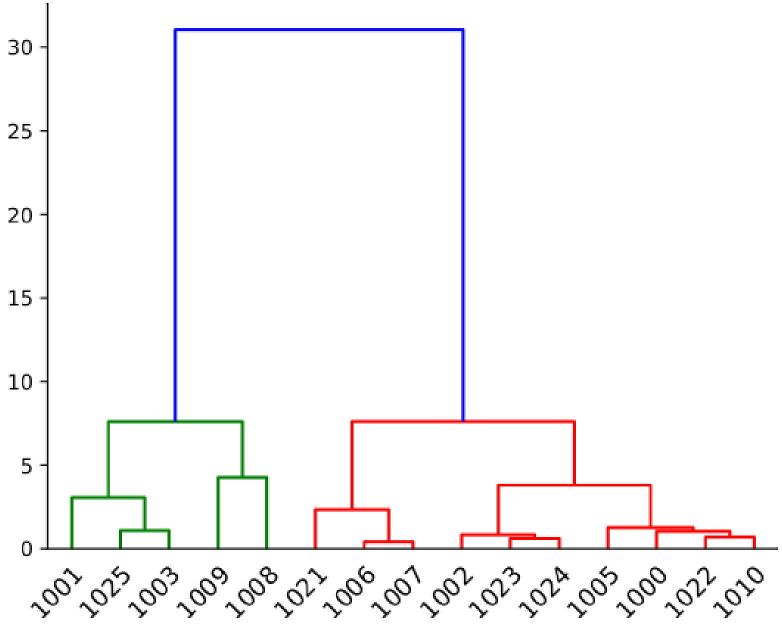
V_{rms}

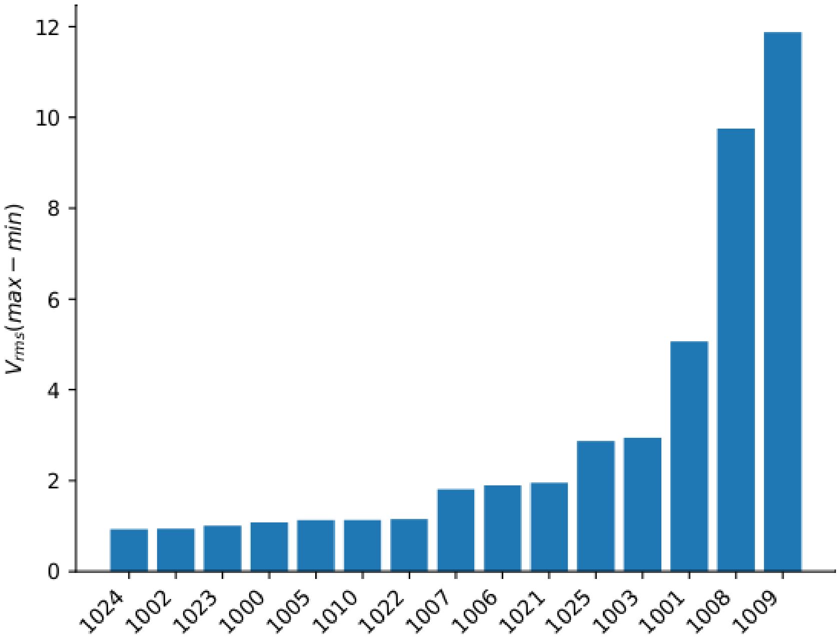
$$D^{rms}_{p \to d} = \frac{1}{n} \sum_{n} |(max(V_{rms}) - min(V_{rms}))_p - ((max(V_{rms}) - min(V_{rms}))_d|$$



Clustering

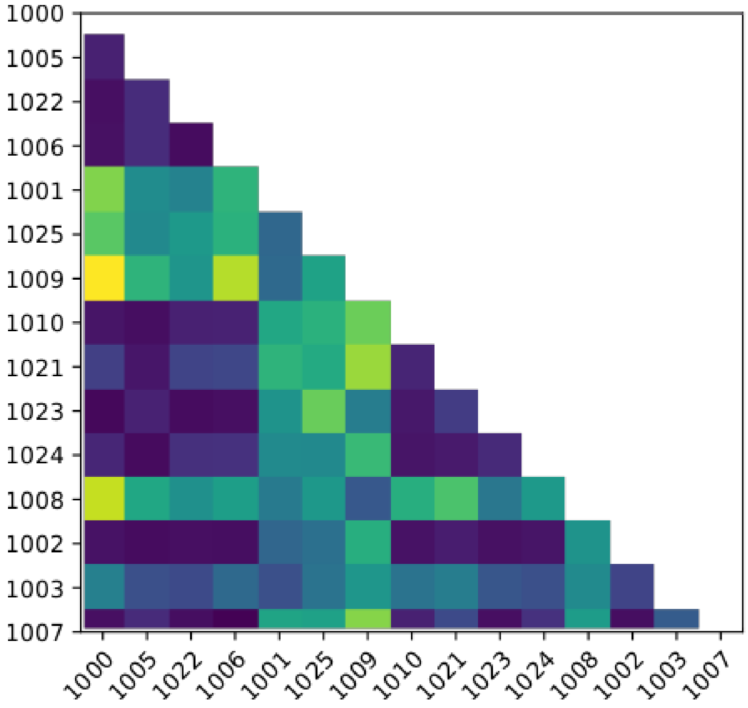
V_{rms}

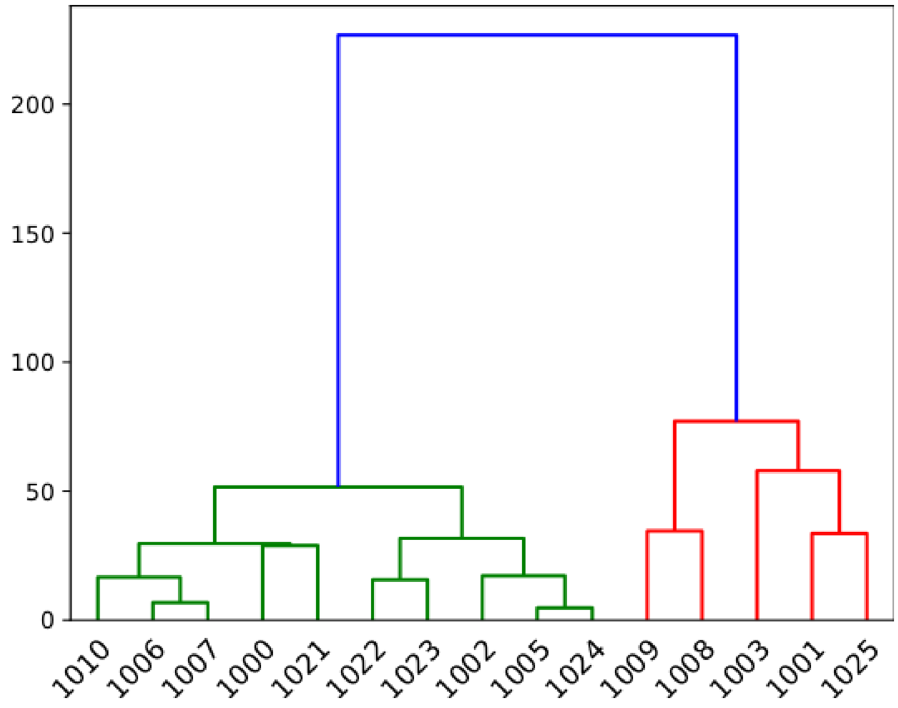




Clustering

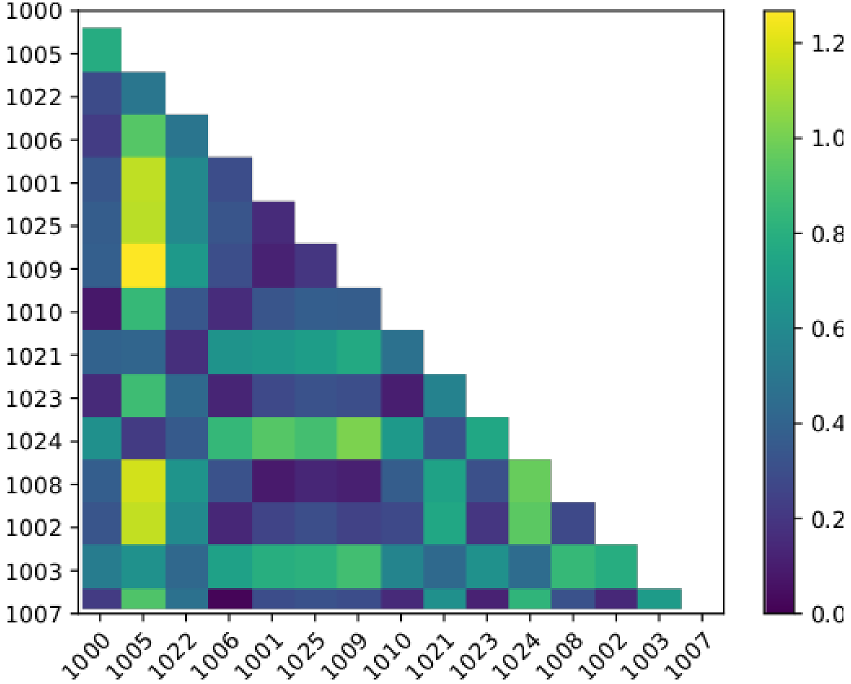
Transients

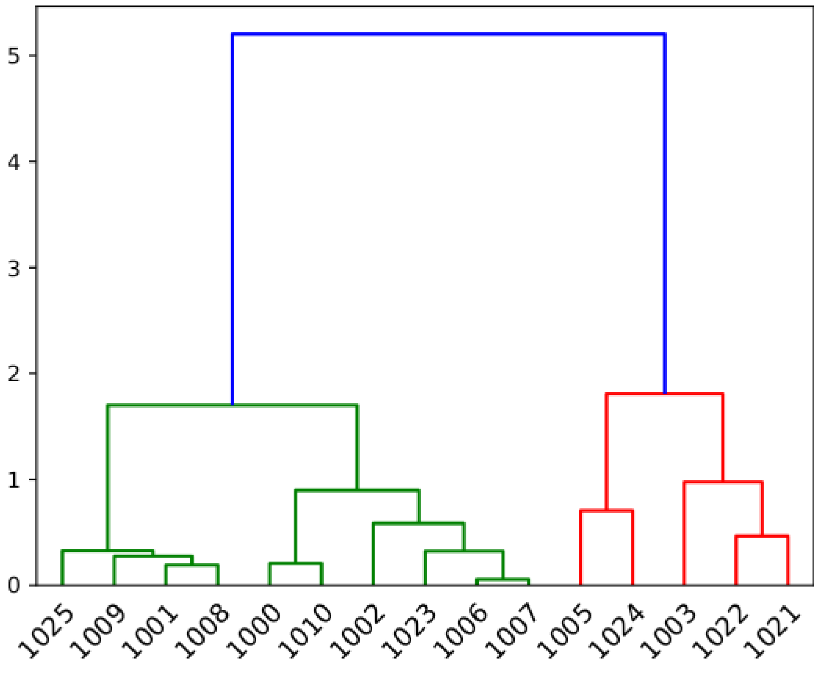




Clustering

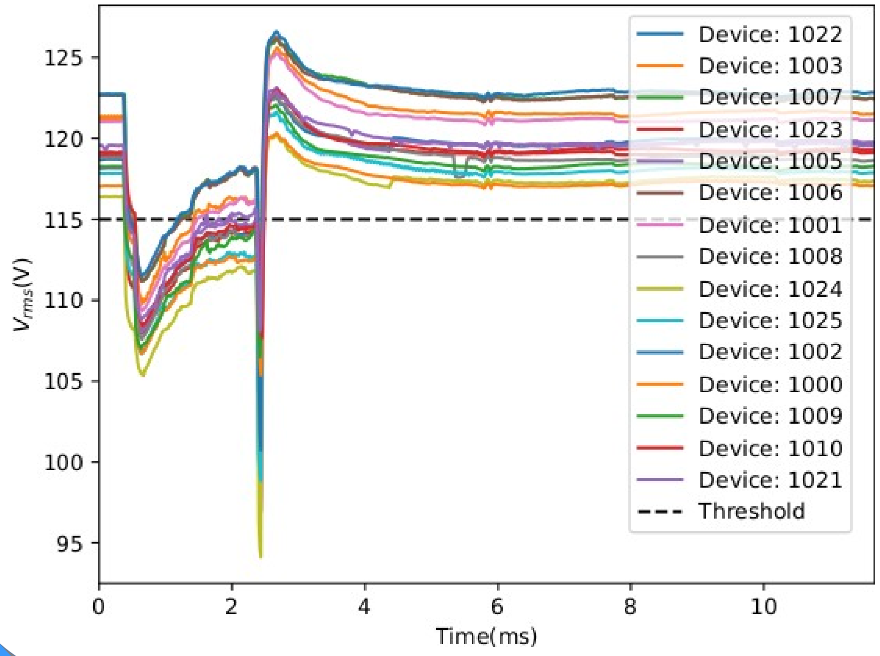
THD

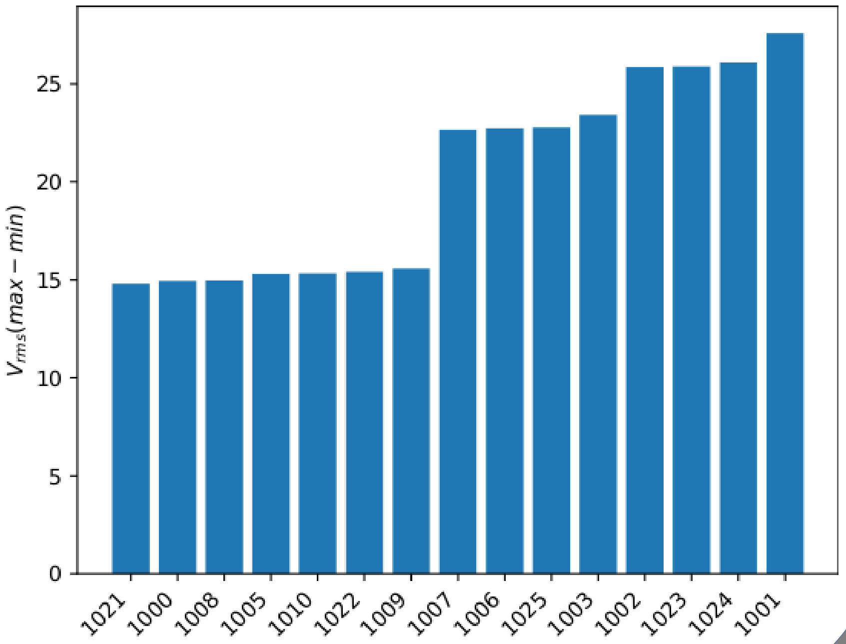




True Gridwide Events

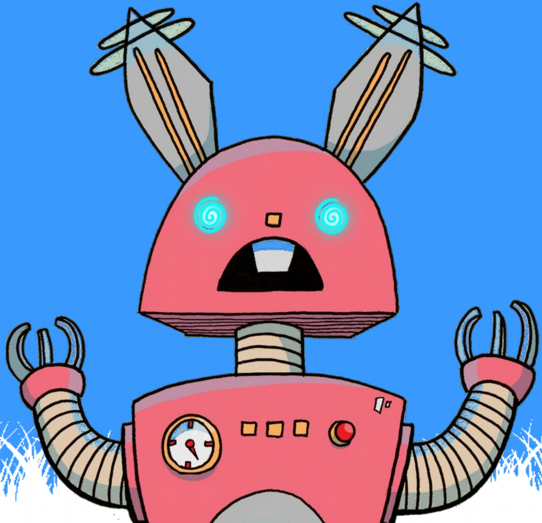
THD





Future Work

1. AI instead of statistical model
2. Scalability study
3. Privacy study
4. Power outage resiliency
5. Integration with Utility
6. Move to other domains



Turtle and Fishy

Tiger
2012-2019


Thanks!

Claim

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

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