Opportunistic Hybrid Communications Systems for Distributed PV Coordination

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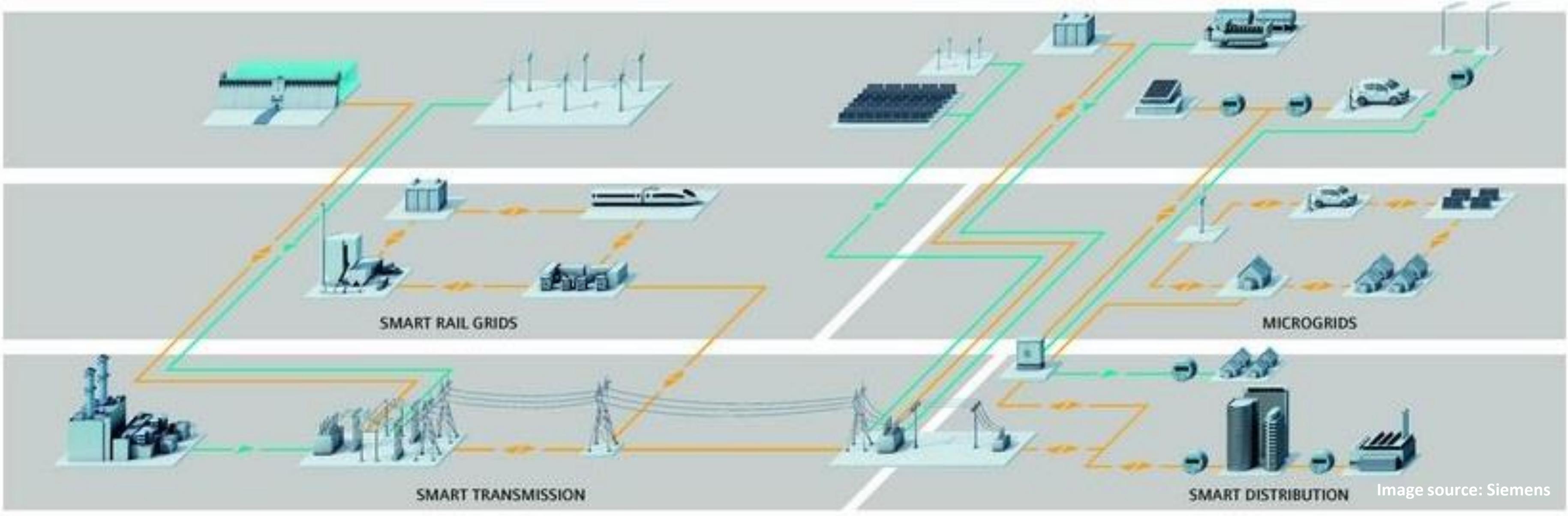
SuNLaMP Workshop, Argonne National Laboratory, Chicago, IL

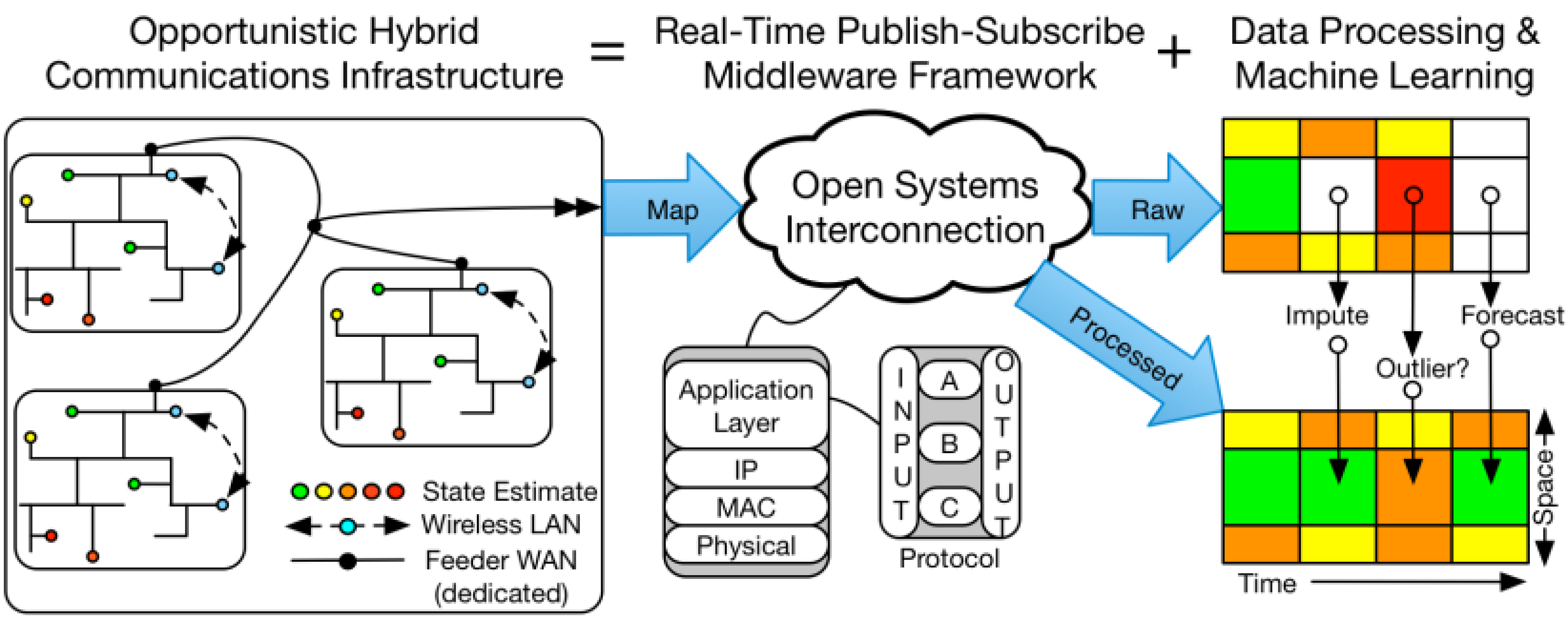
Project Innovation

- The current state of the art grid is sensor starved
- At the transmission level, grid operators have no visibility into the current amount of distributed PV generation
- At the distribution level, there is the need to have more visibility into DER output and two-way communication (?)



Objective: Communicate the state of the grid from the inverter to the system operator

Project Objectives



- Full-scale, operational implementation of the opportunistic hybrid communication system:
  - **Hybrid:** various communications pathways, e.g. SCADA, PLC, Zigbee, etc.
  - **Opportunistic:** route messages through each of these systems based on recent data about latency and availability to ensure reliable message passing.

Distributed State Estimation Algorithms for PV System and Distribution System

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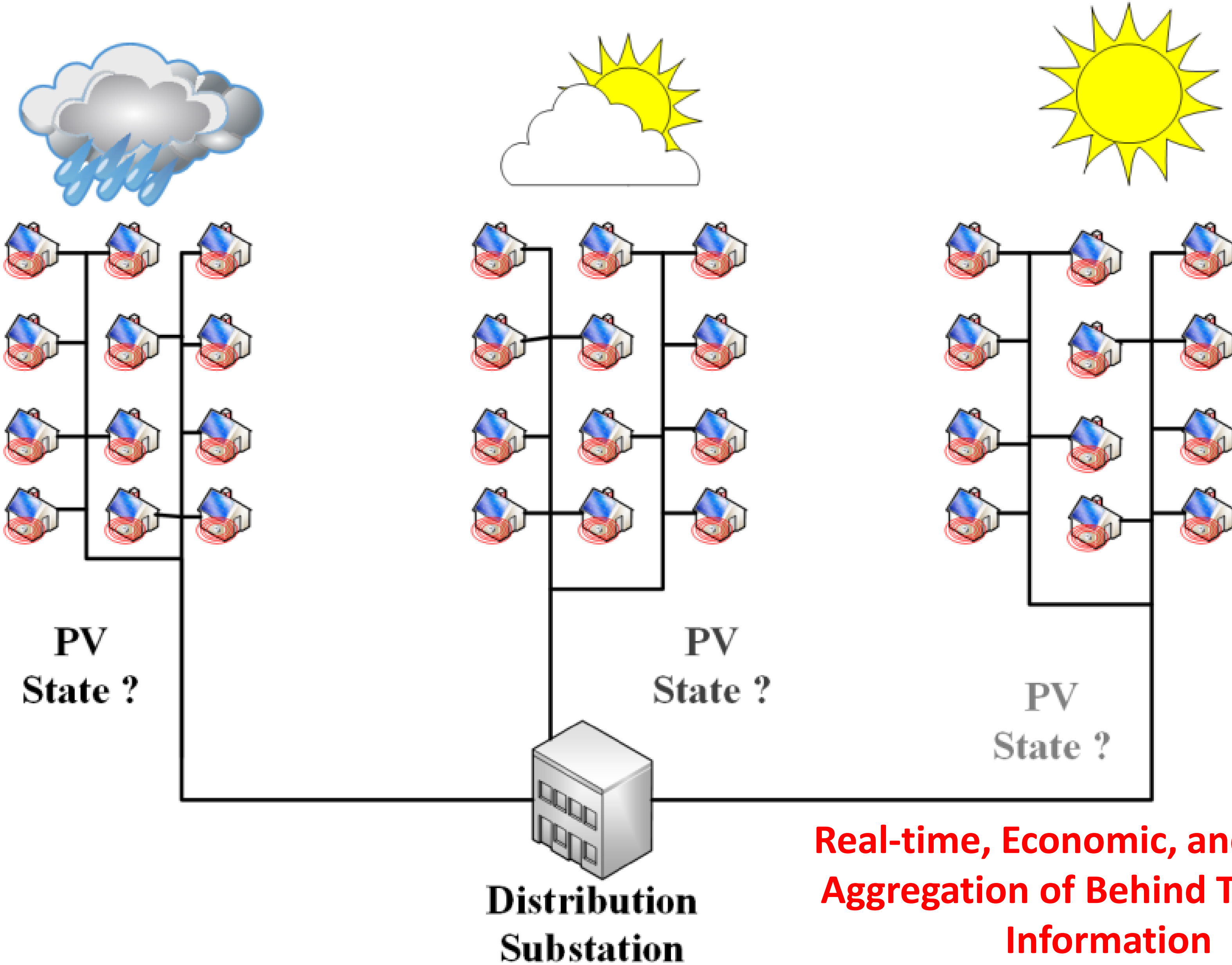
Distribution Network with High Penetrated PVs

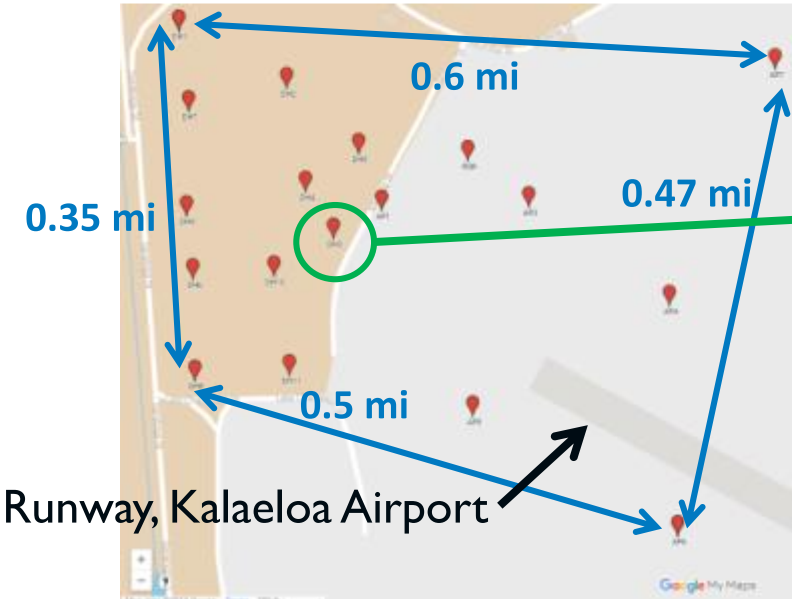


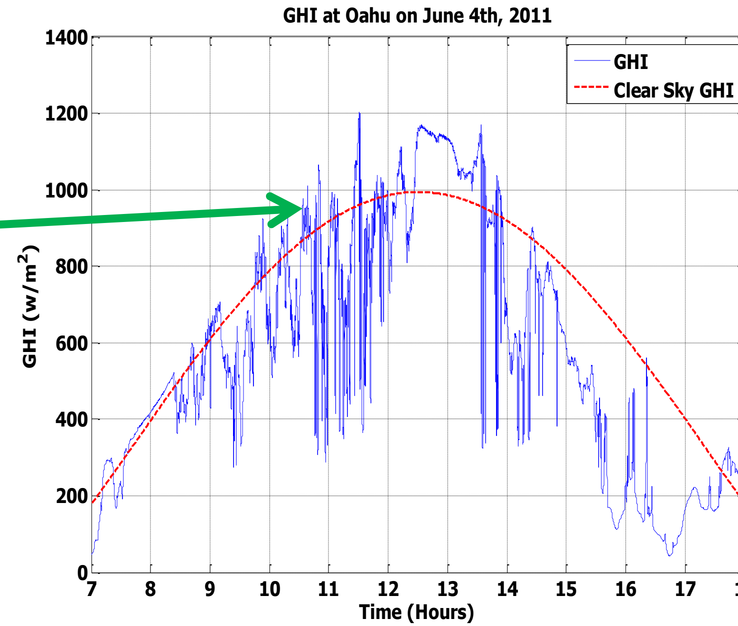
Real-time, Economic, and Scalable Aggregation of Behind The Meter Information

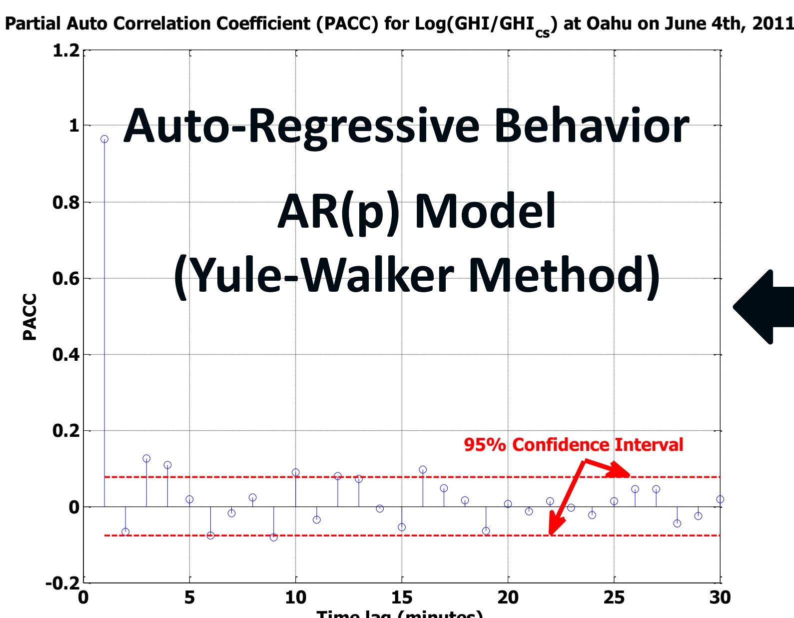
PV System State Estimation

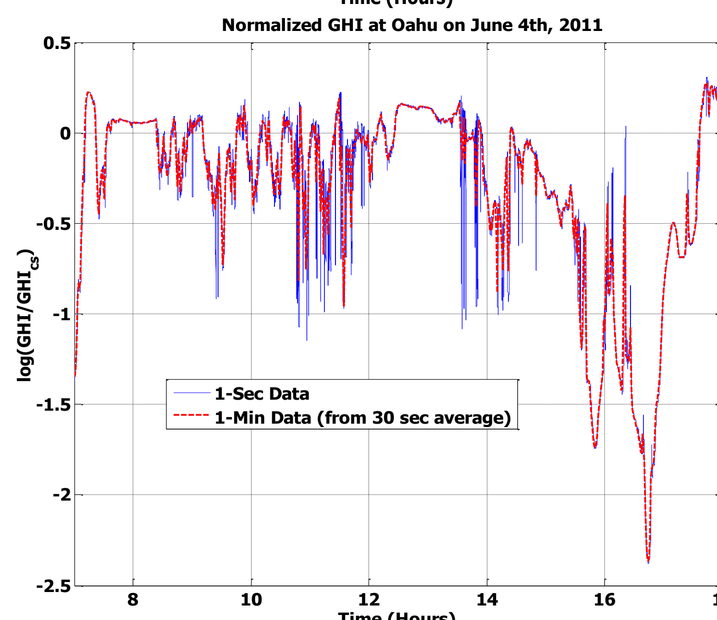
- PV States: PV inverter AC power output
- Kalman Filter: Temporal dynamic state estimation
  - Multi-rate: Under-sampling of measurements
  - Event-driven: Regular sampling in case of significant event
- Kriging: Spatial estimation at unobserved location

Irradiance Time Series Model at 1-min Resolution



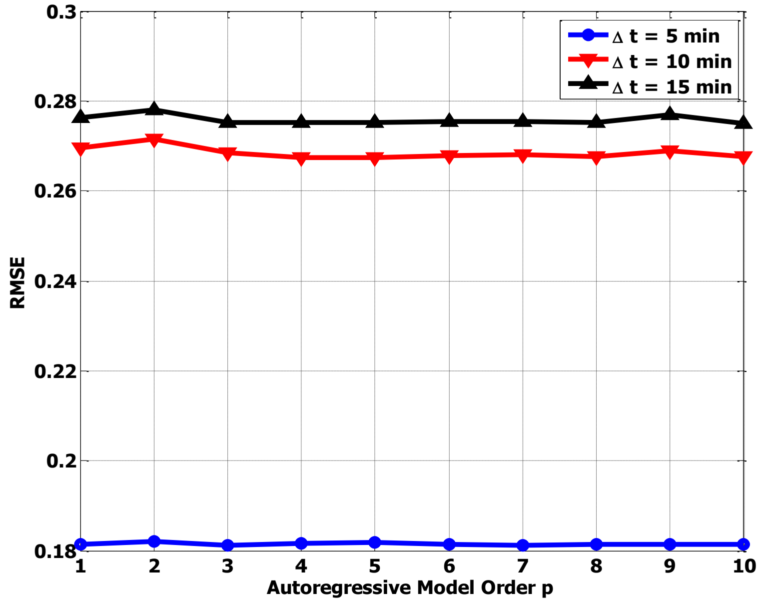


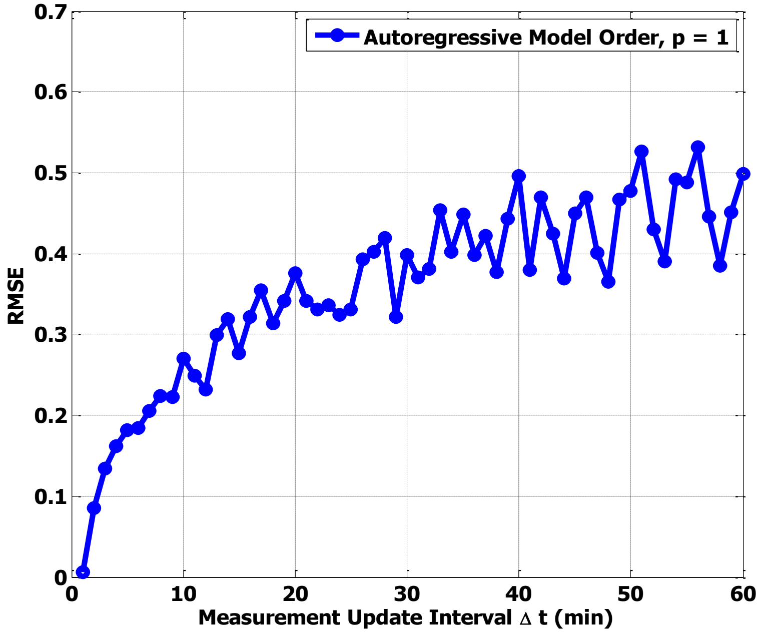




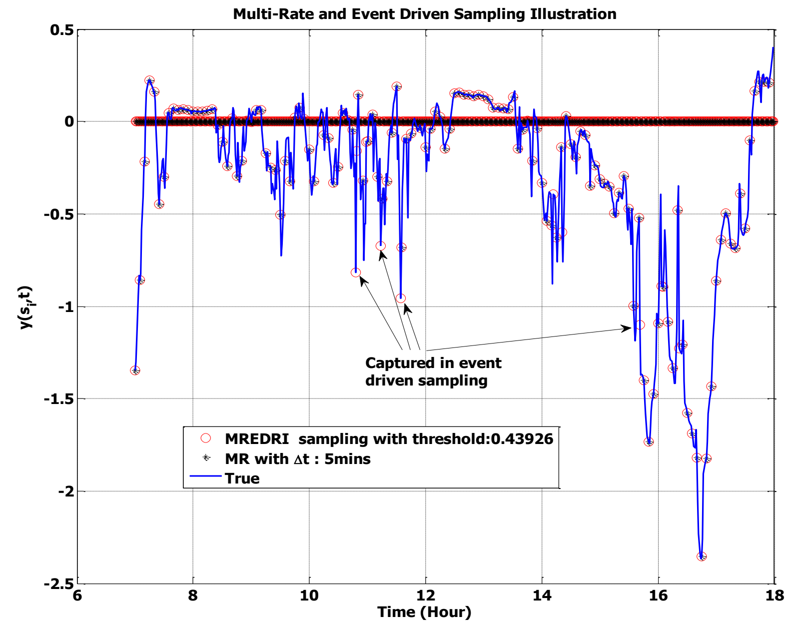
Kalman Filter from AR(p) Model

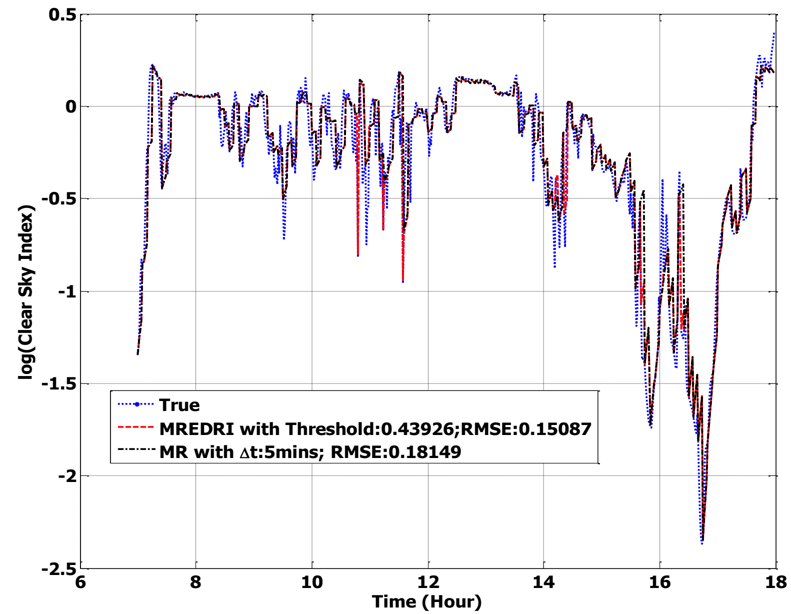
Multi-Rate Approach





Event Driven Approach



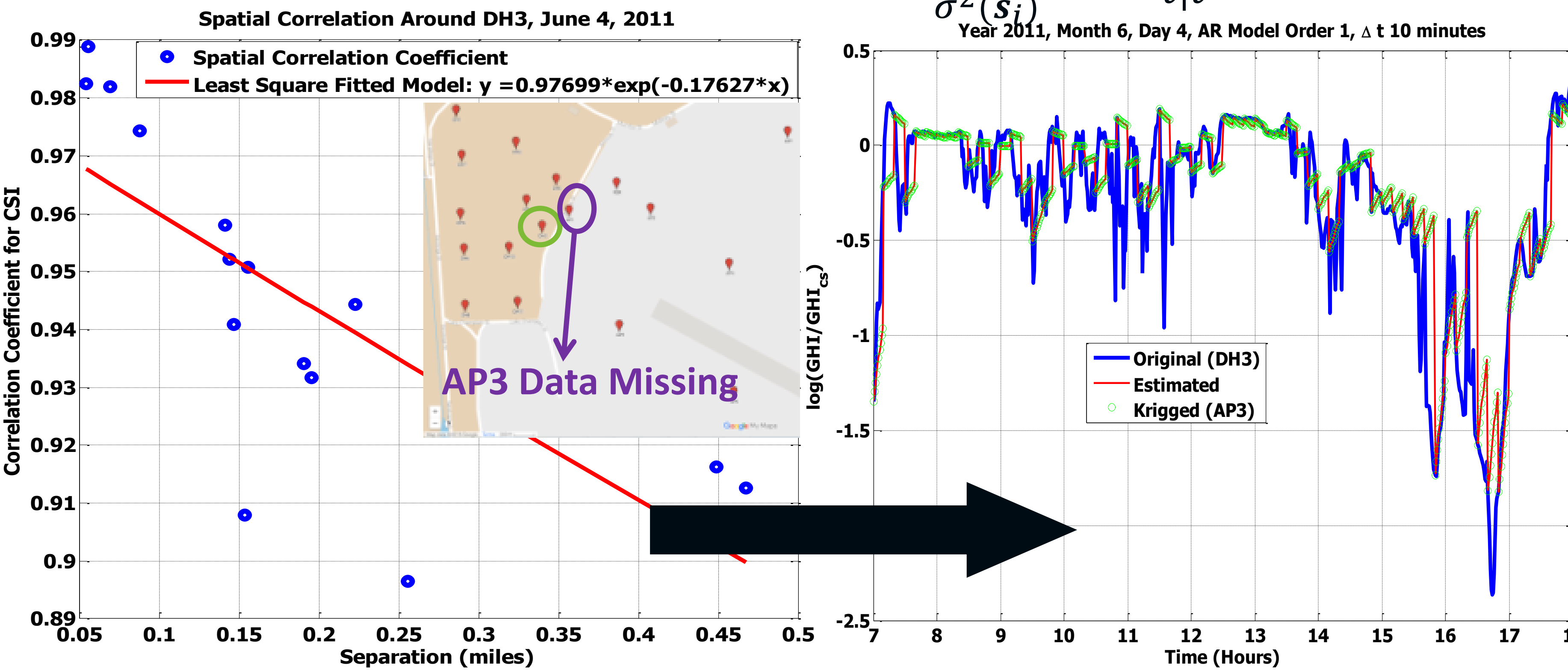


Kalman Filter with Kriging: Spatial LMMSE Estimate

- n GHI sensors: $\mathcal{S} = \{\boldsymbol{s}_1, \boldsymbol{s}_2, \dots \boldsymbol{s}_n\}$; Spatial covariance: $\boldsymbol{C}_{\mathcal{S}}$
- Spatial observation at time t,

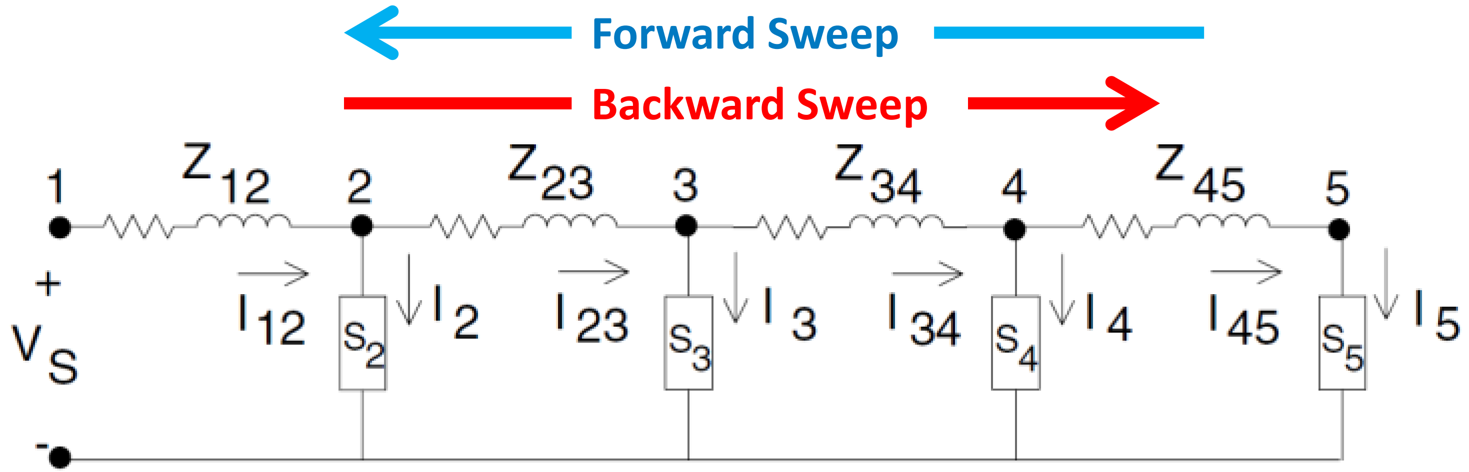
$$\boldsymbol{y}_t = \begin{bmatrix} y(\boldsymbol{s}_1, t) \\ \vdots \\ y(\boldsymbol{s}_n, t) \end{bmatrix}$$

- Observed: $y(\boldsymbol{s}_i, t)$; Unobserved: $y(\boldsymbol{s}_{j \neq i}, t)$
- $\widehat{\boldsymbol{x}}_{t|t}$ from $y(\boldsymbol{s}_i)$ and Multi-Rate and Event Driven Kalman filter.
- LMMSE: $\hat{y}(\boldsymbol{s}_{j \neq i}, t) = \frac{C(\boldsymbol{s}_i, \boldsymbol{s}_{j \neq i})}{\sigma^2(\boldsymbol{s}_i)} \boldsymbol{h}^T \widehat{\boldsymbol{x}}_{t|t}$



Power System State Estimation in Distribution Systems

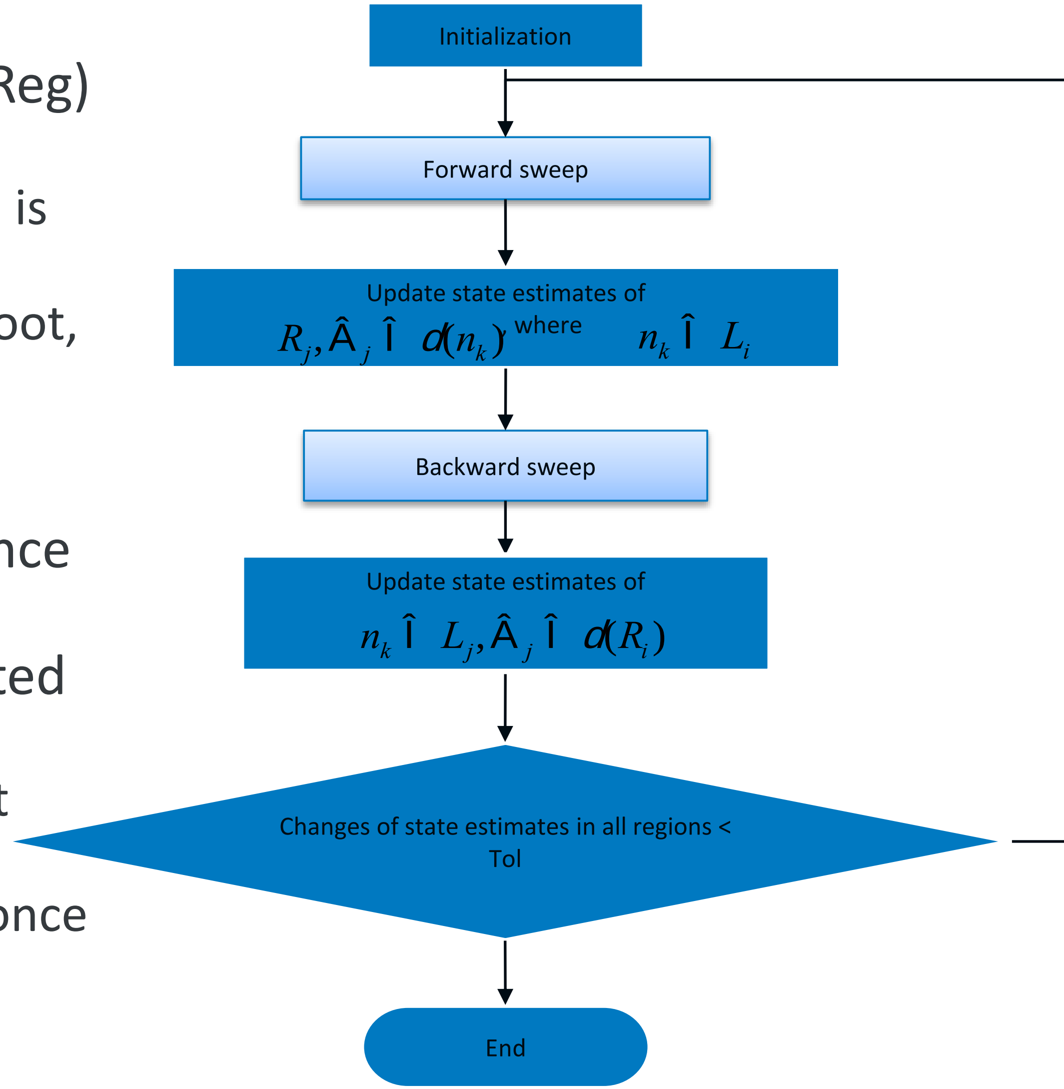
- Radial topology
- Ladder iterative (LI) technique[1]
  - State variables: three-phase complex voltages at each node
  - Network reduction
    - Combine nodes connected by zero-impedance lines, such as fuses, switches etc.
  - In each iteration, update node voltage and branch current



[1] William H. Kersting, Distribution System Modeling and Analysis, Third Edition, CRC Press, 2012.

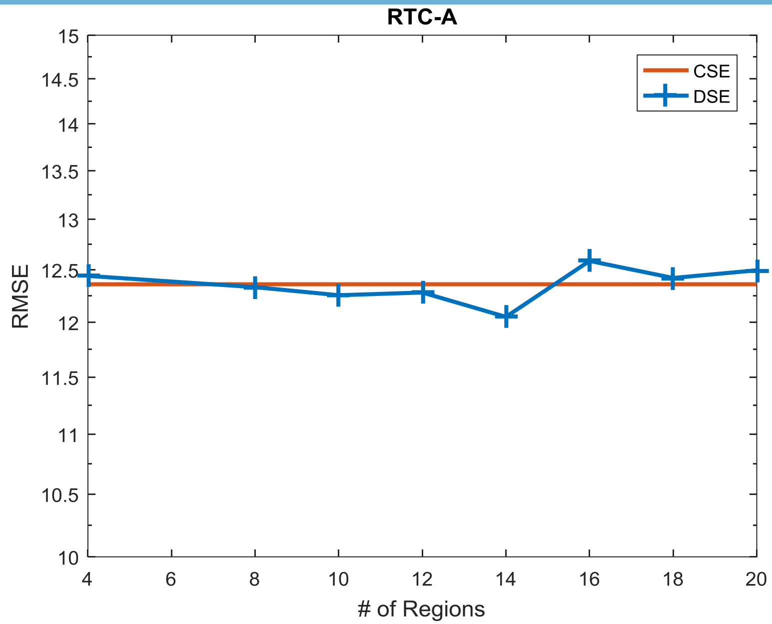
Distributed Ladder Iterative State Estimation (DiLISE)

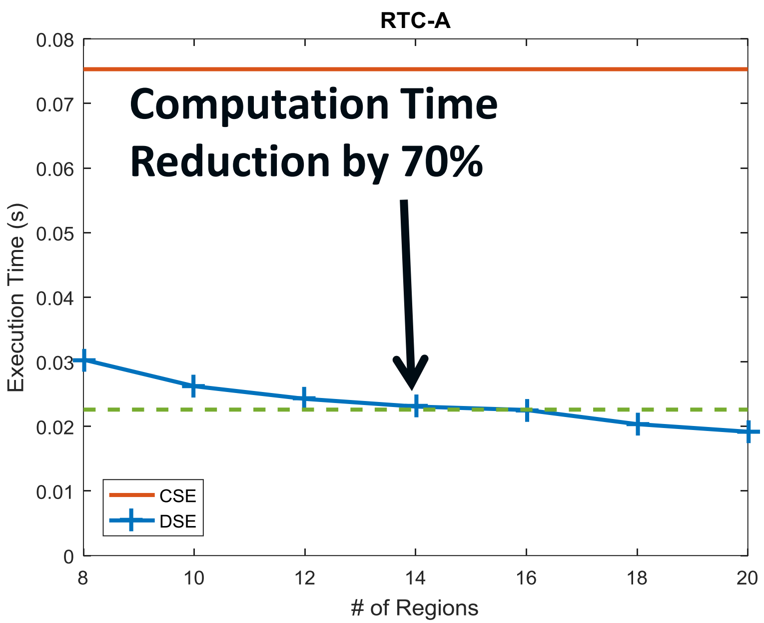
- Automatic Regionalization (Au-Reg) based on spectral clustering [1]
  - The subnetwork in each region is still radial
  - Each subnetwork has its own root, from which the forward sweep starts.
- The master process scans the topology of the network only once before the iterations start
- Voltages and currents are updated asynchronously
  - Computationally more efficient because of no waiting
  - No need for a master process once the iterations start



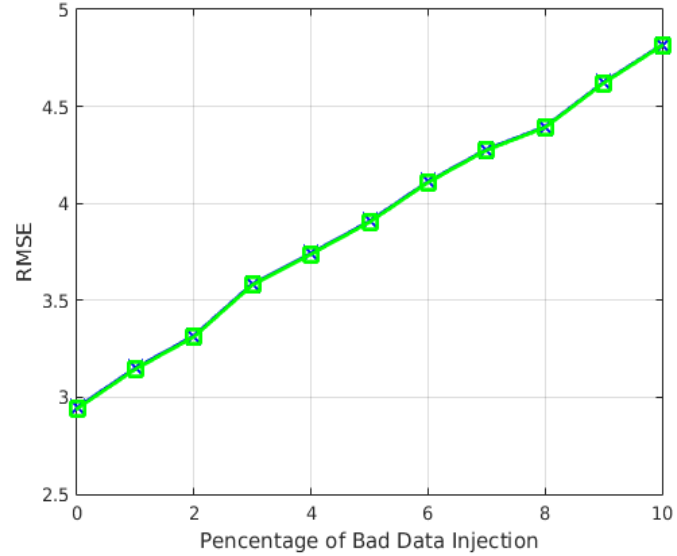
[1] D. Wang et al., "Automatic Regionalization Algorithm for Distributed State Estimation in Power Systems", in *IEEE Global Conference on Signal and Information Processing*, pp. 1-6, 2016 (invited)

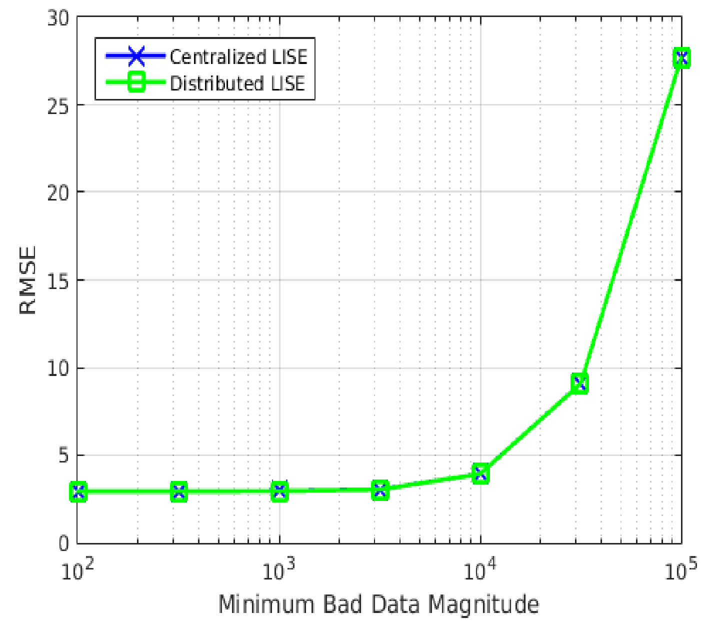
DiLISE Performance





Impact of Bad Data



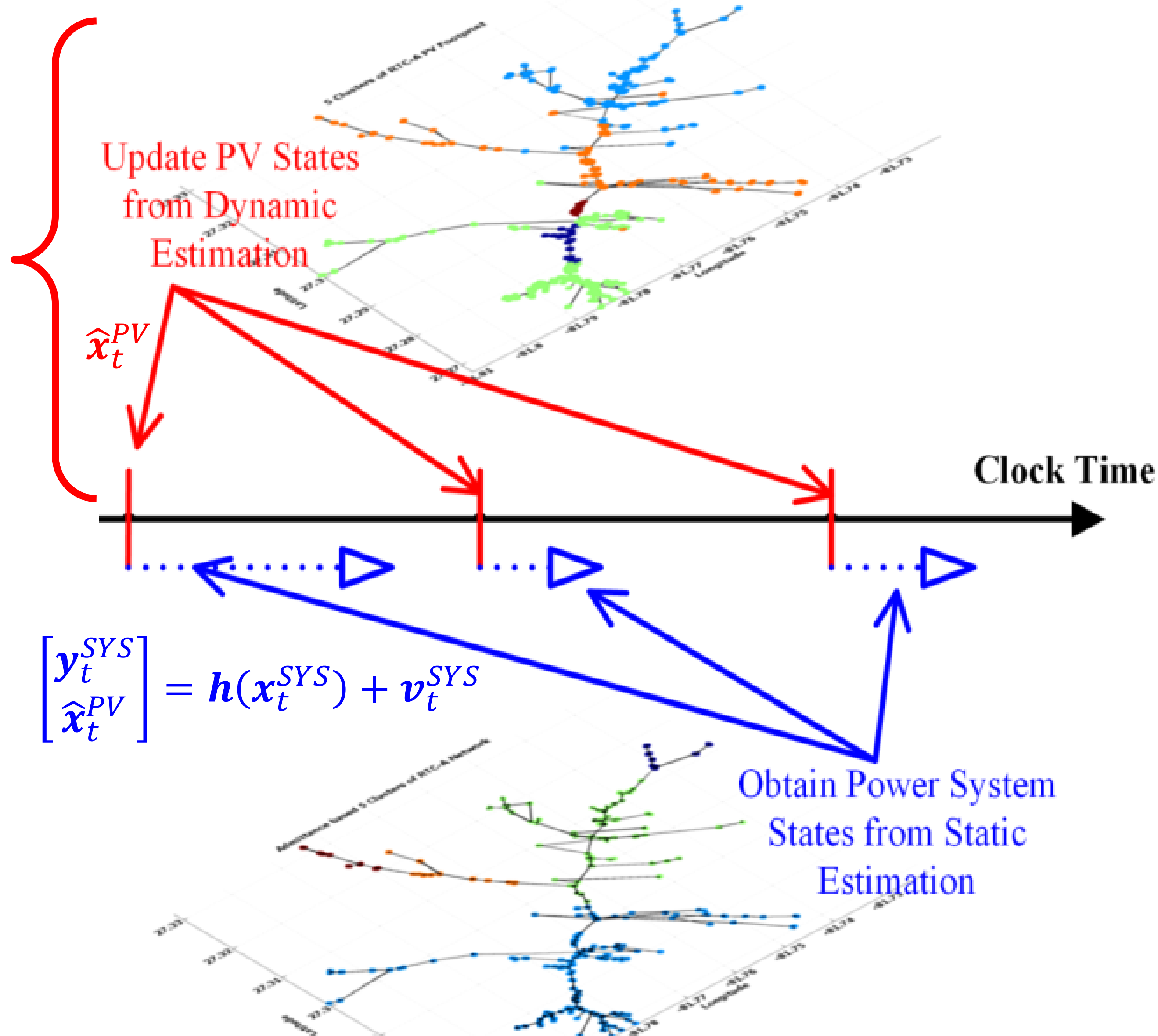


Synchronous Integration of PV and Power System States

Perform
ADMM [2] based
Information
Exchange among
neighboring clusters

Perform
Kalman Kriging in
each cluster

Distributed State
Estimation for
Distribution System



[2] V. Kekatos, and G.B. Giannakis, "Distributed Robust Power System State Estimation", *IEEE Transactions on Power Systems*, 2013.

Summary

- Distributed estimation of PV states
- Distributed distribution system state estimation
- Integration of the two to produce actionable information for DSOs/TSOs

Thank You!
Questions and Discussion

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Appendices

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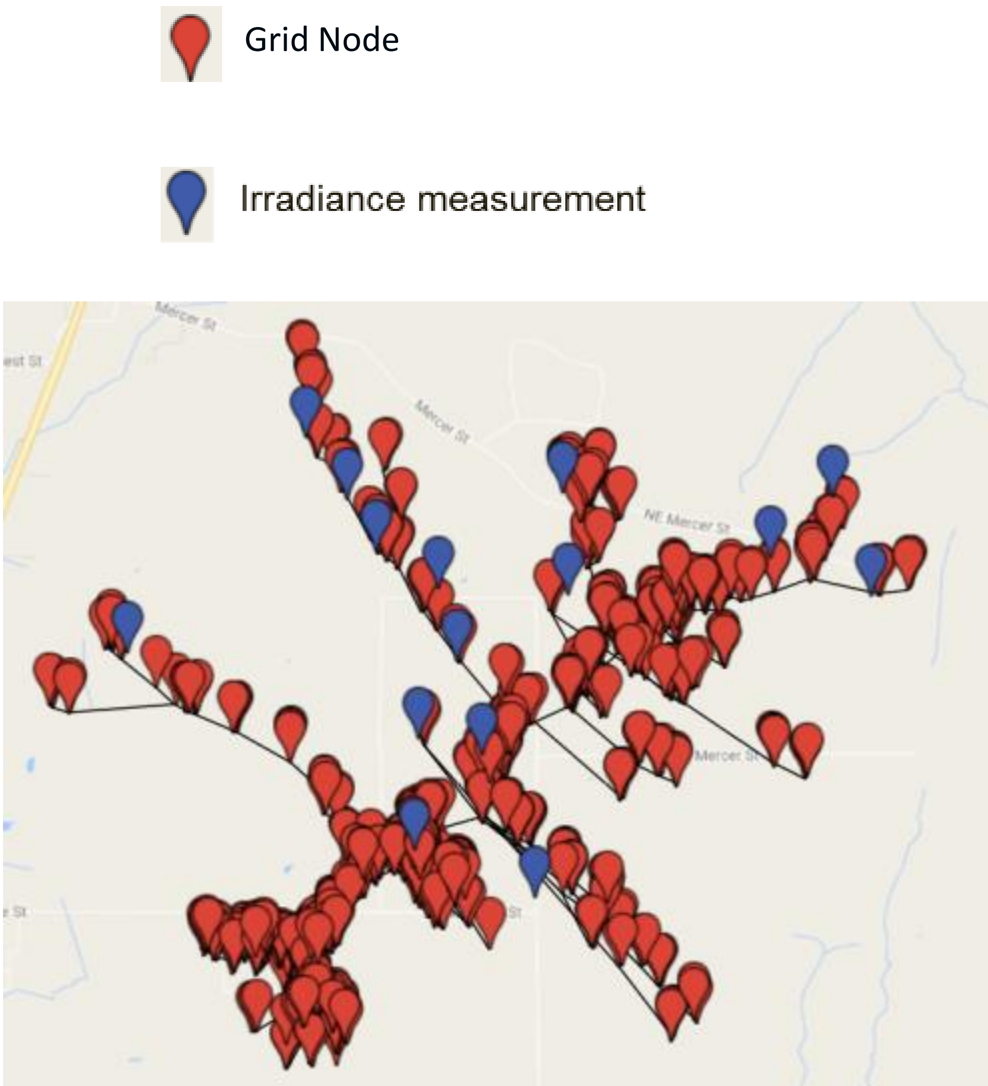
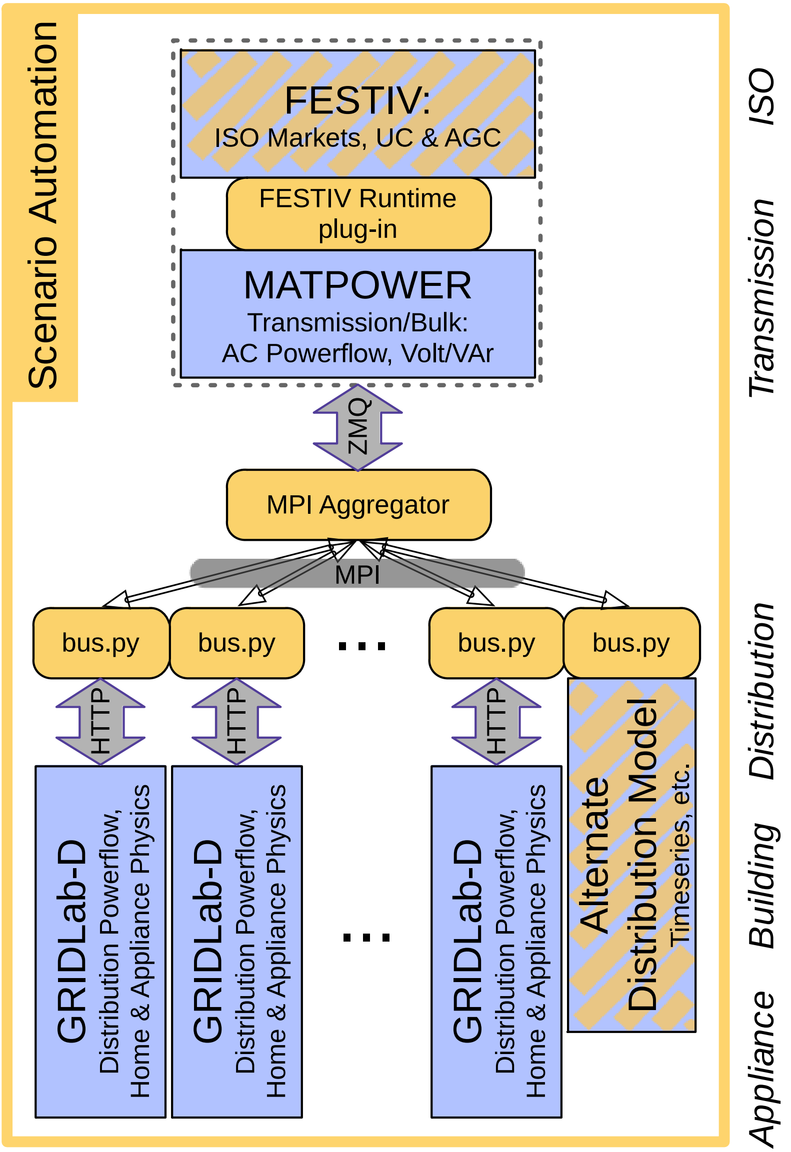
Reference Test Case A (RTC-A)



- Taxonomy feeder R2-25.00-1 from DOE's Modern Grid Initiative representing moderate urban environment
- System of 1080 nodes on a distribution feeder
- 10 percent penetration of solar panels
- Fifteen 1-sec irradiance measurements from ground stations (Desoto)
- Power system data determined by the Integrated Grid Modelling System (IGMS)

Integrated Grid Modeling System (IGMS)

- Data collected at 1-min (Trans.) and 6-sec (Dist.) resolution
  - Real and Reactive power
  - Voltage magnitude and phase angle
  - Miscellaneous variables /parameters for sanity checks
- Reference Test Case A current focus for communications development, i.e. as input only
- Future T+D+C simulation environment for ongoing GMLC projects



B. Palmintier et al., "**IGMS**: An Integrated ISO-to-Appliance Scale Grid Modeling System", in *IEEE Trans. Smart Grid*, 2016.

Opportunistic Hybrid Communication System

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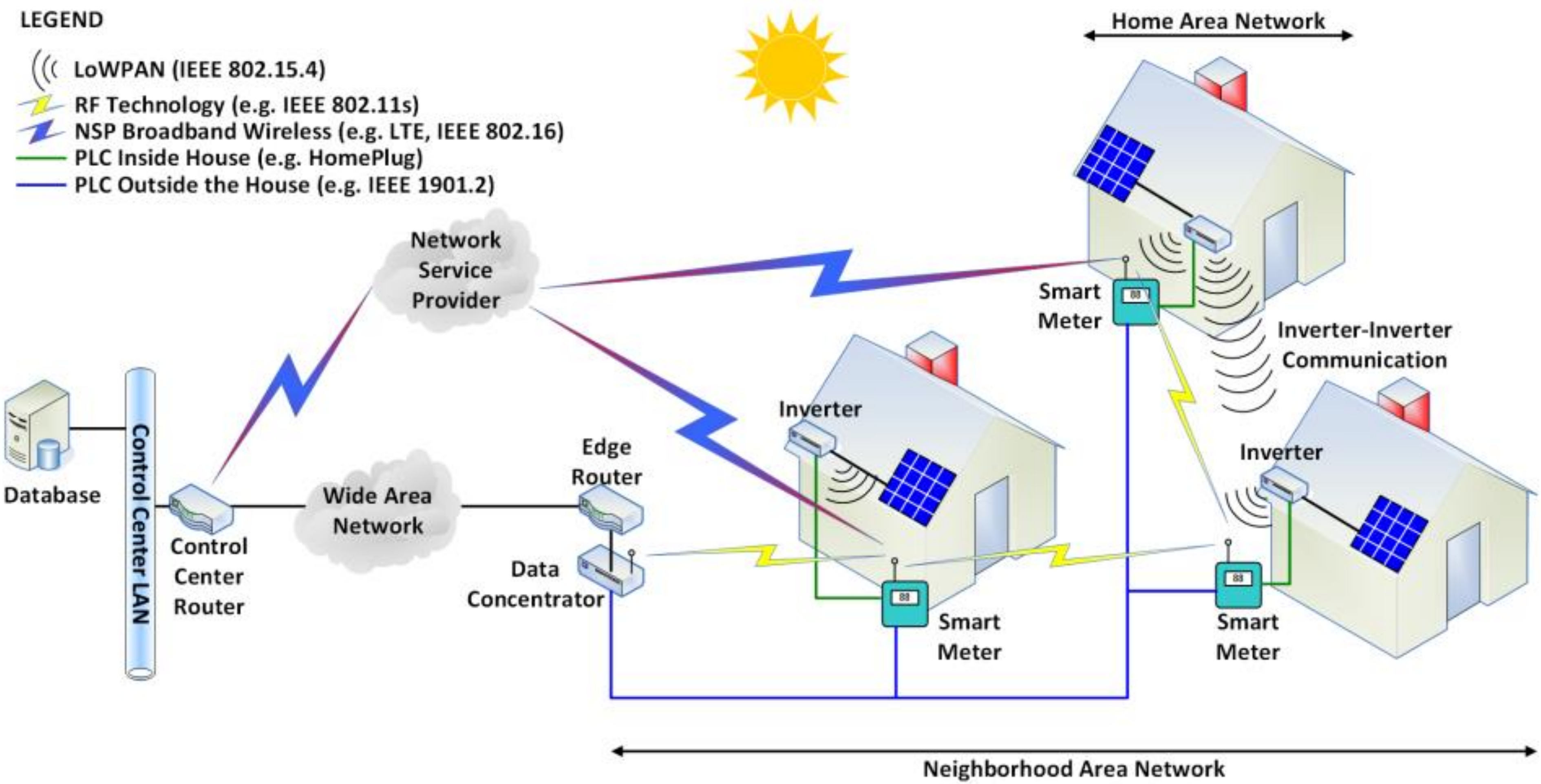
Smart Grid Communication System Overview



Expected features of Opportunistic Hybrid Networks

- **Feasibility:** Extensively use existing infrastructure, minimize new hardware to reduce cost.
- **Interoperability:** Use multiple mixed standardized communication technologies.
- **Scalability**: Accommodate high penetration of distributed PV.

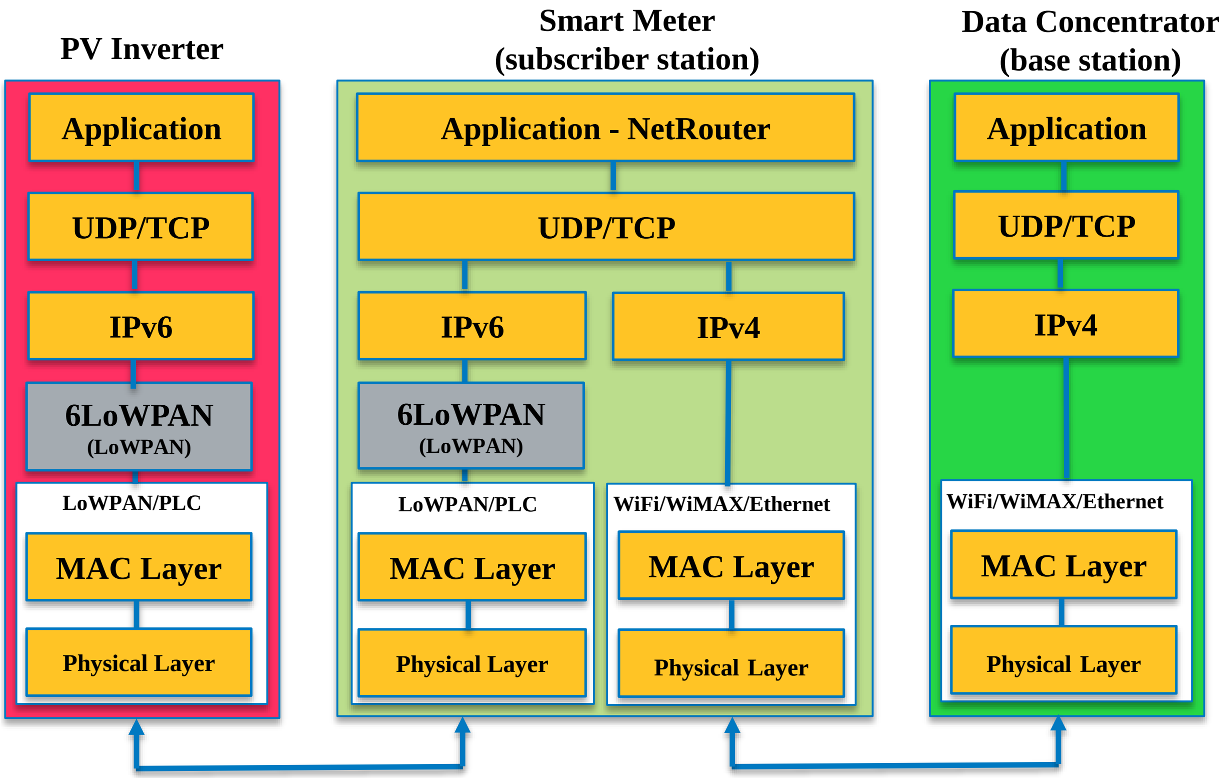
Alternative Hybrid Networks for NS3 Simulation

Hybrid Type	*Home Area Network*	*Neighborhood Area Network*
Hybrid-1	LoWPAN	Ethernet Cable
Hybrid-2	LoWPAN	WiFi
Hybrid-3	LoWPAN	WiMax
Hybrid-4	PLC	Ethernet Cable
Hybrid-5	PLC	WiFi
Hybrid-6	PLC	WiMax

Note: Reason of LoWPAN instead of well-known Zigbee is Zigbee model can not cooperate with other technologies in NS-3.

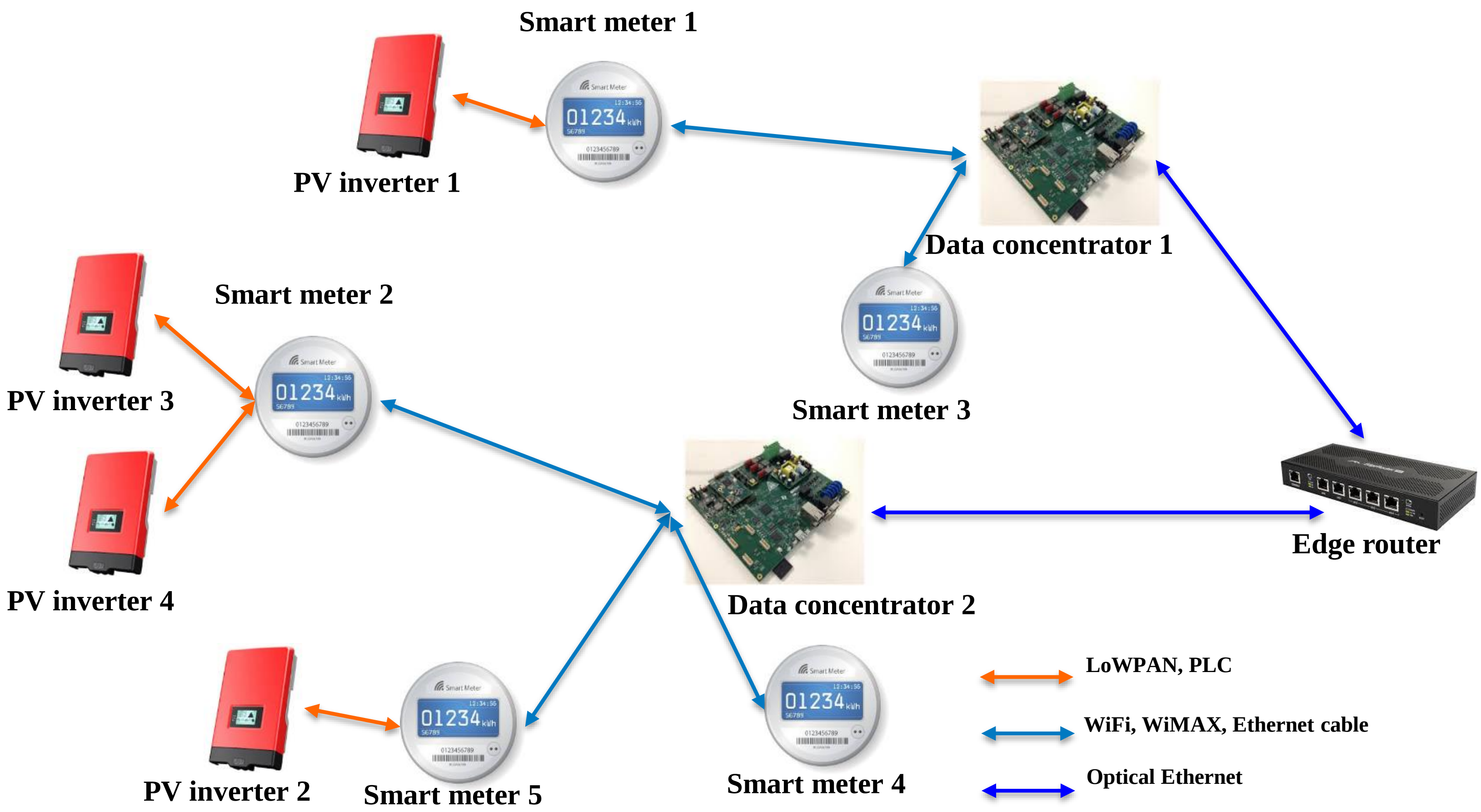
NS3 based Hybrid Simulation Networks

Main Challenge:
Integrate different technologies
and IP address mechanisms
into a simulation network.



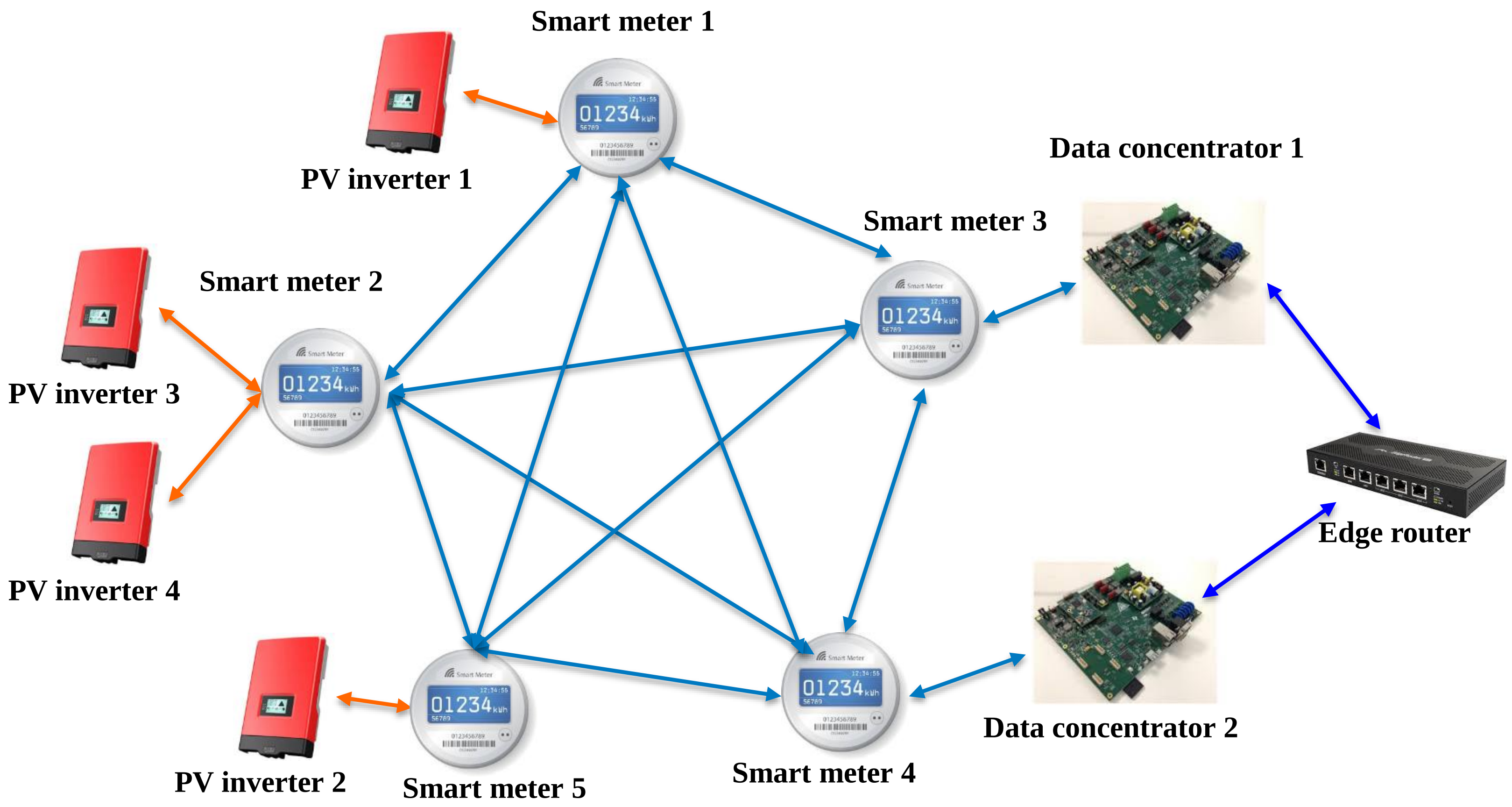
- Different technology characterized by Phy & MAC layers.
- 6LoWPAN model works as an agent between MAC layer and Network layer, and only supports IPv6. While WiFi mesh and WiMAX only support IPv4.
- Smart meter node is configured with two net devices of two technologies.
- NetRouter app is designed to function as IPv6 to IPv4 tunneling and enable IPv6&4 in a network.
- Customized Client app and Server app are developed for specific smart grid

Tree Topology Hybrid Simulation Model



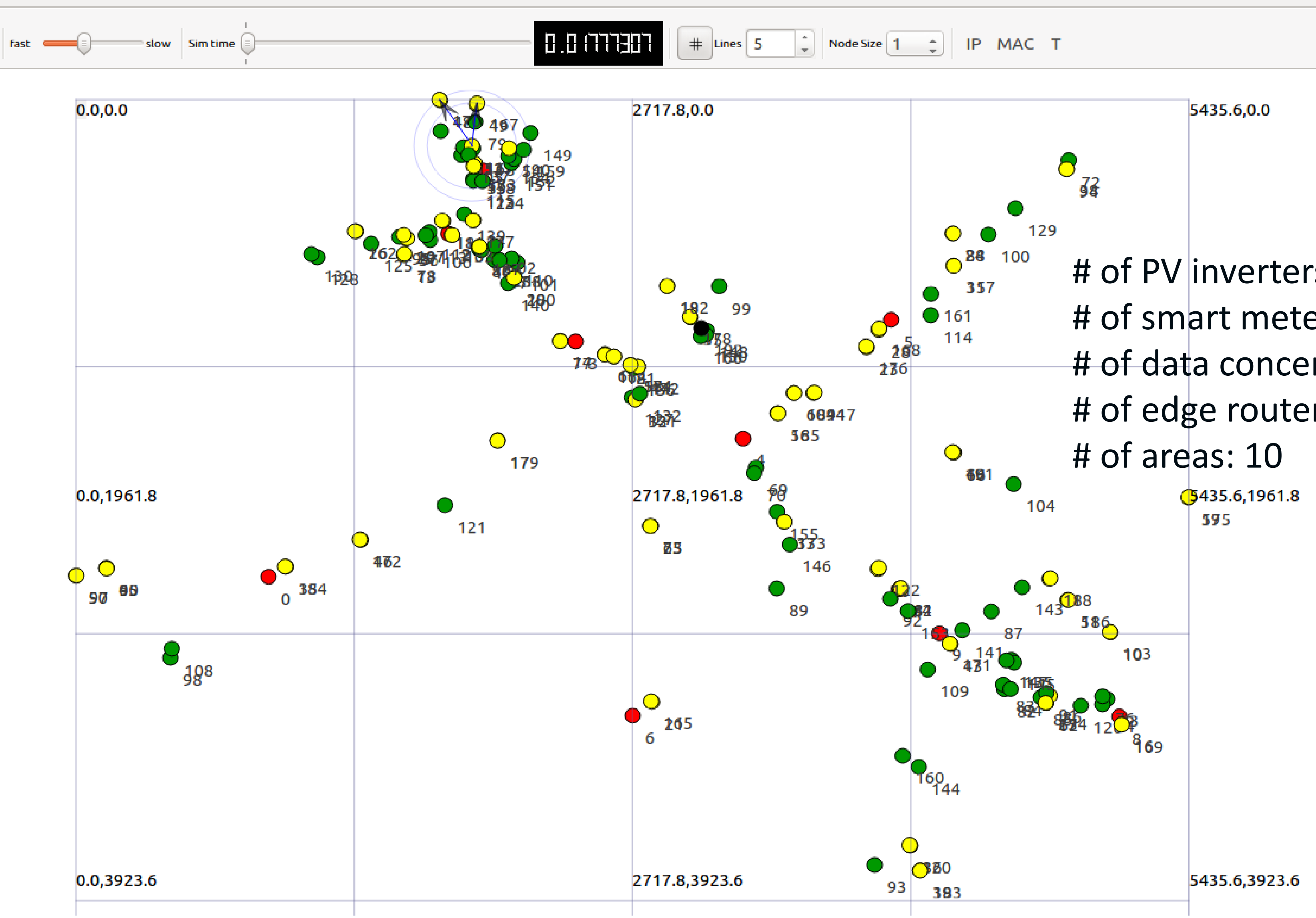
Note: Unlimited range of Ethernet causes to Tree topology intuitively;
For WiMAX, range of 50km can cover up to 10km of NAN (Neighborhood Area Network) with PMP (Point-to-Multiple points) topology.

WiFi based Mesh Topology



Note: With range of 30m-1km, WiFi has to be designed as Mesh topology to cover up to 10km of Neighborhood Area Network (NAN).

Hybrid Communication Network: RTC-A Perspective



# of PV inverters: 52

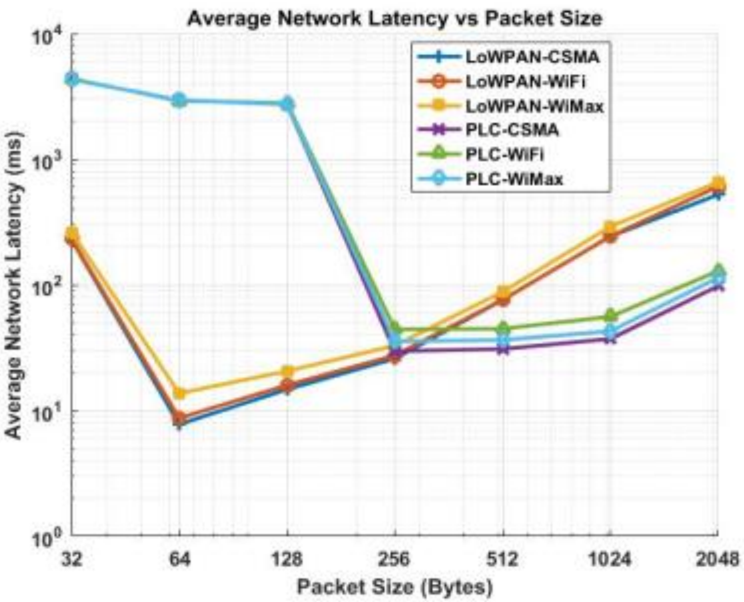
# of smart meters: 126

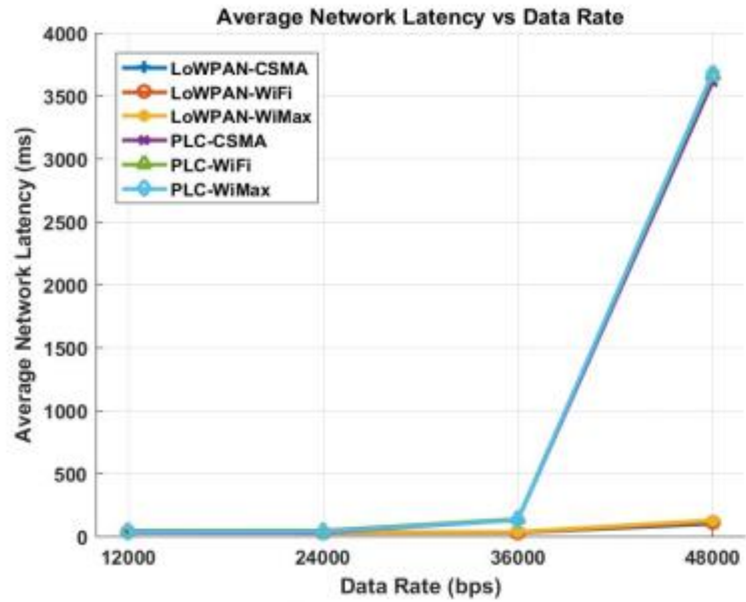
# of data concentrators: 10

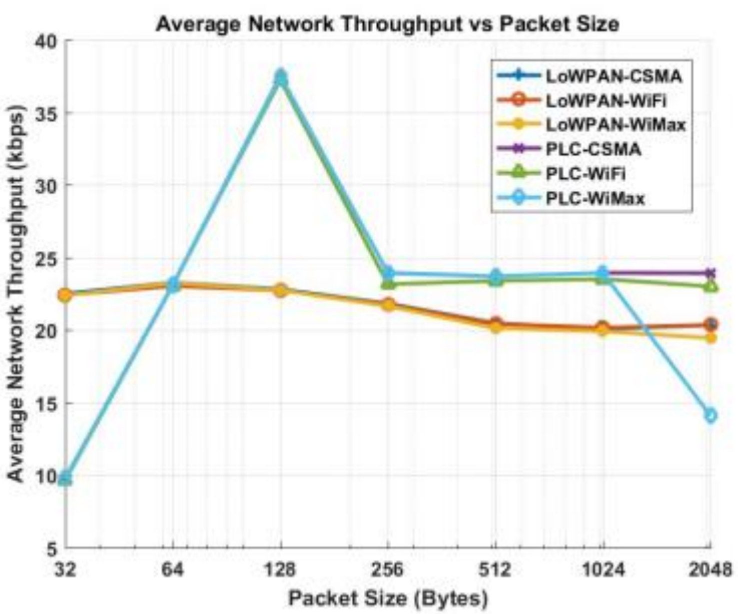
# of edge router: 1

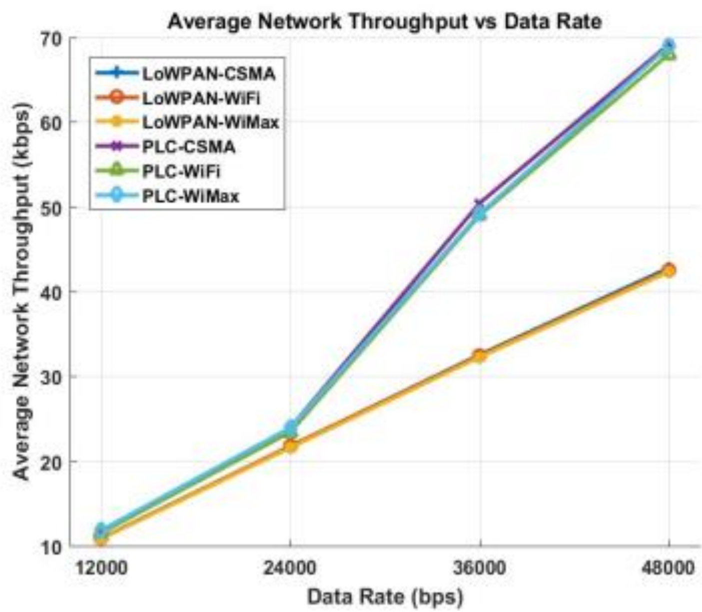
# of areas: 10

Hybrid Communication Performance

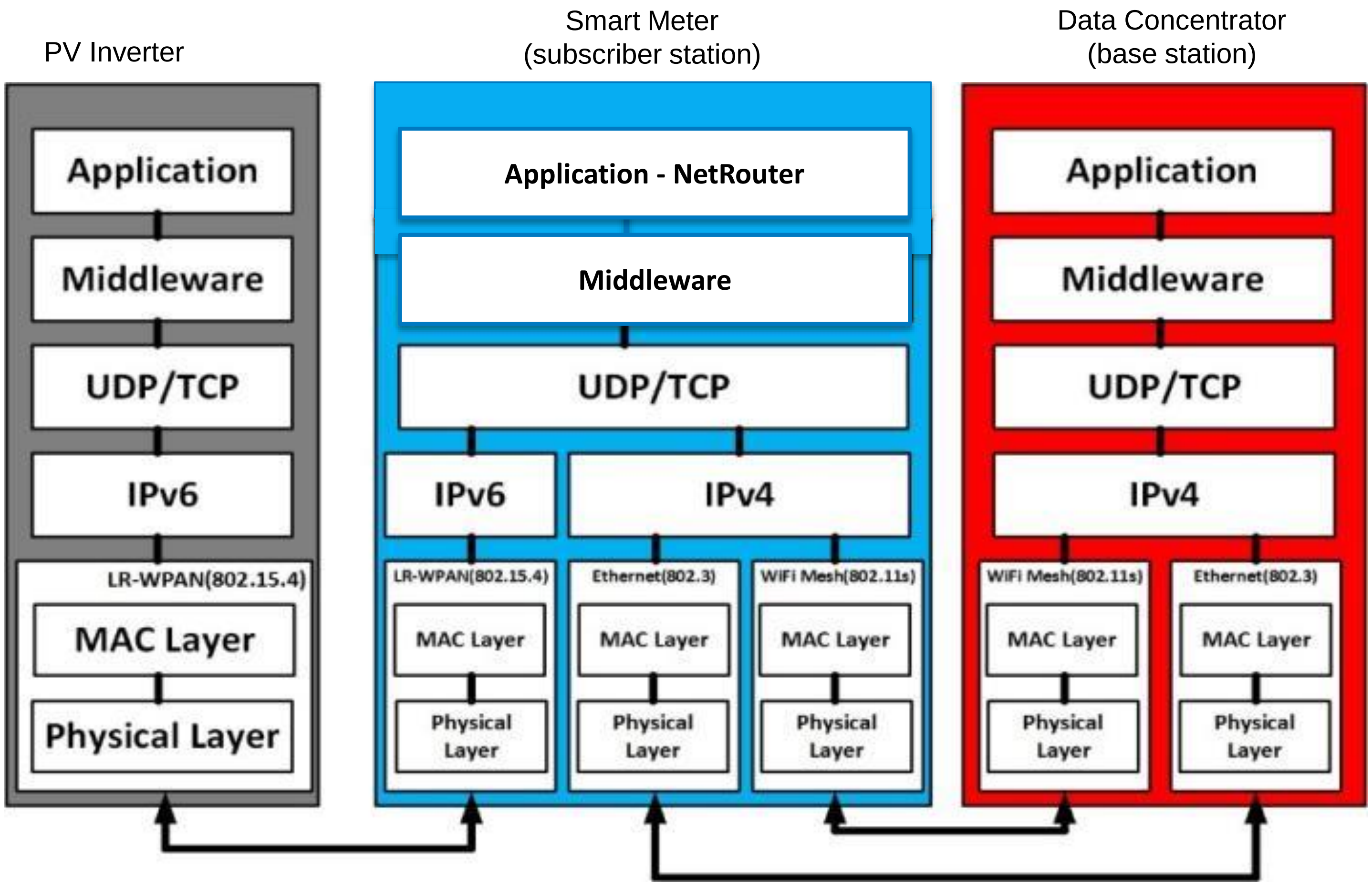






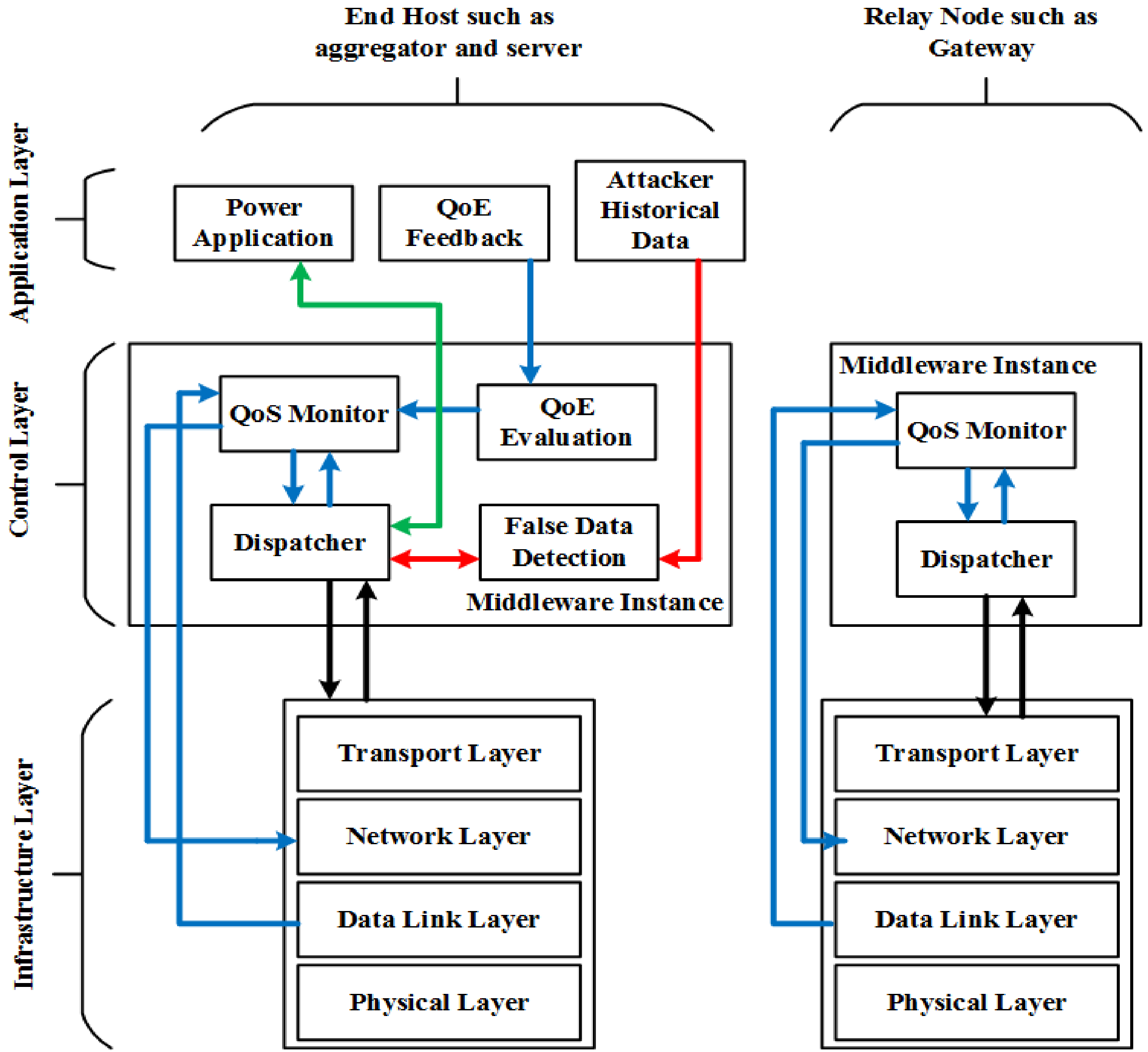


Middleware Framework



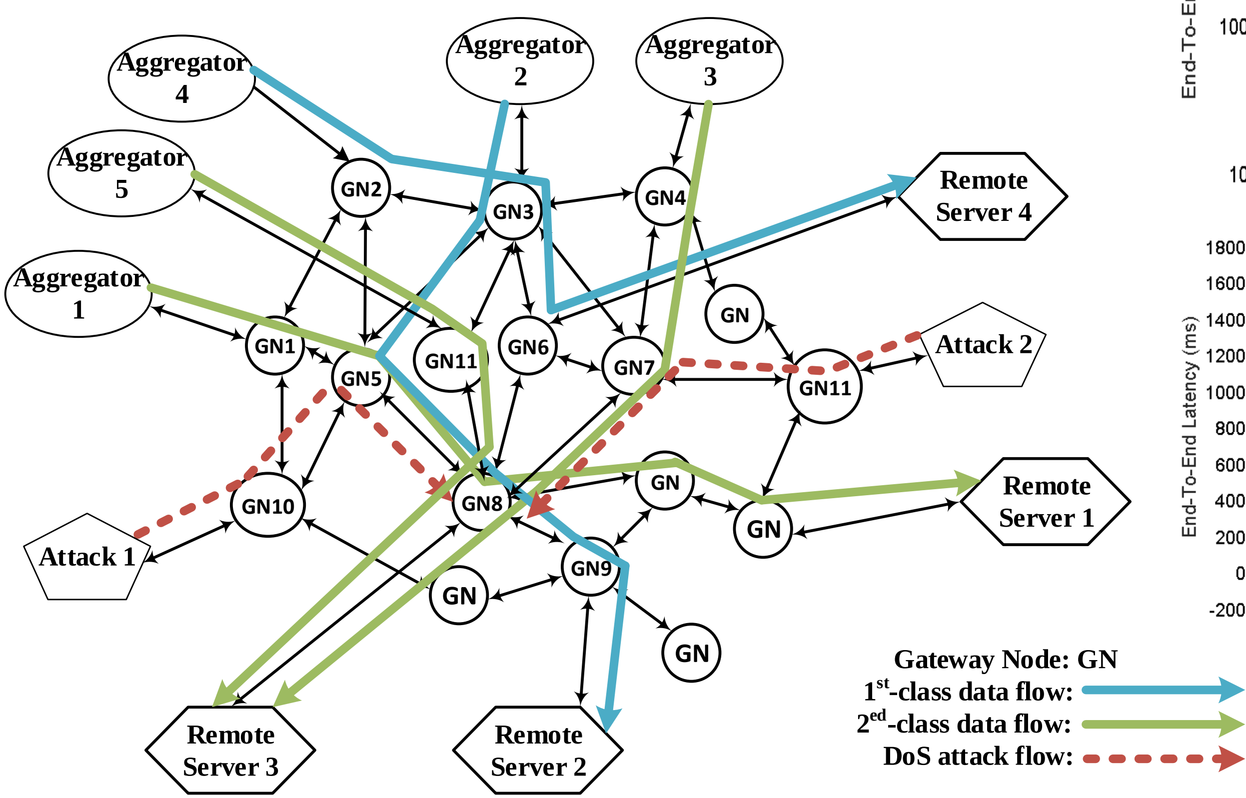
- Allows the communication node to adaptively and automatically distribute the data flow to the available links based on their real-time status.
- Not only enhance the QoS of each traffic but also efficiently utilize the existing multiple network resources.

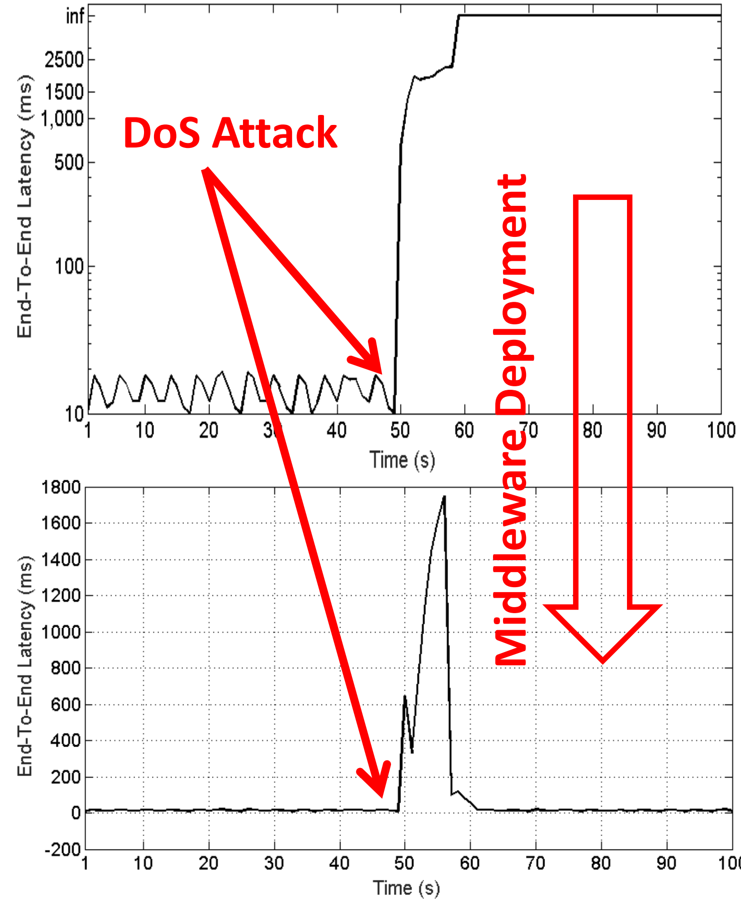
Middleware based Opportunistic Communication



DoS Mitigation through Middleware

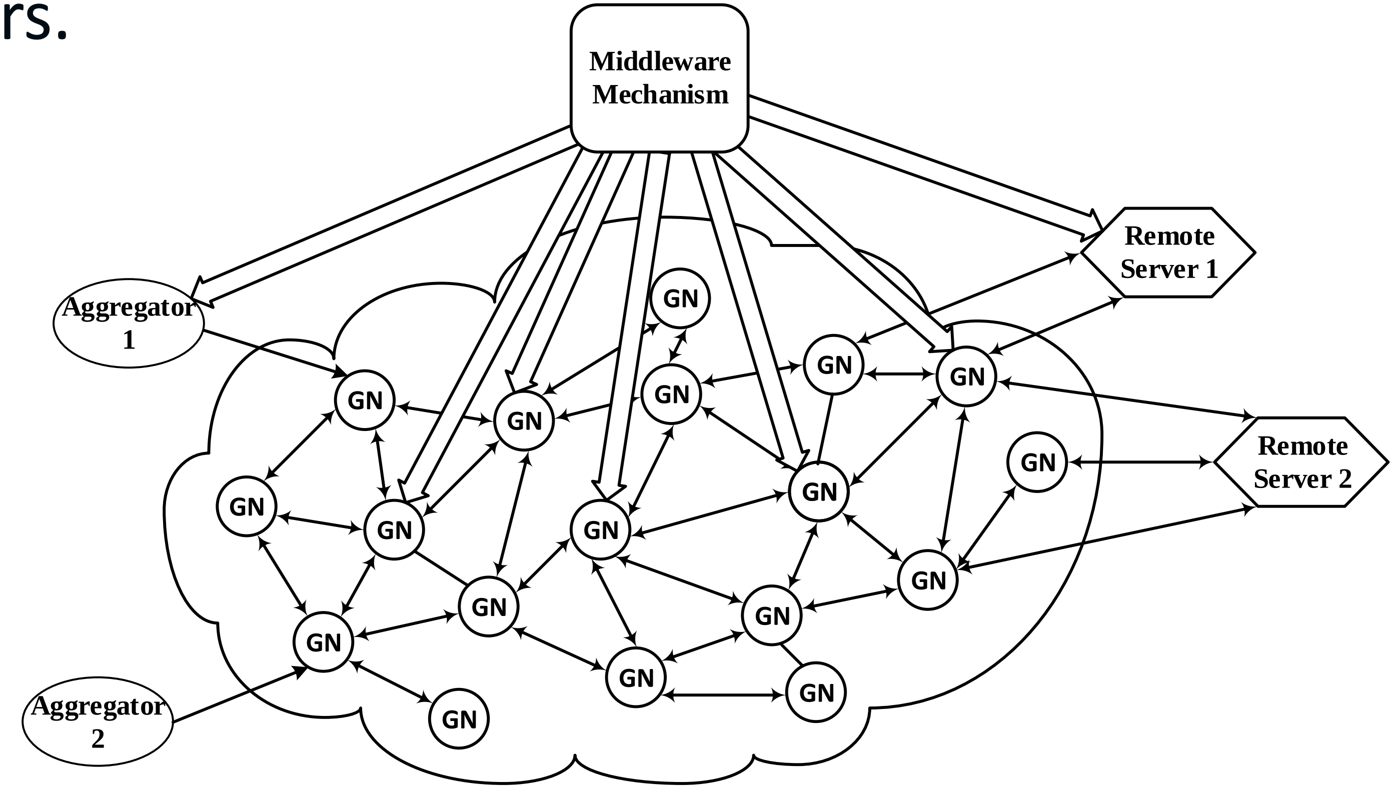
Aggregator ⇔ Smart Meter
Remote Server ⇔ Data Concentrator



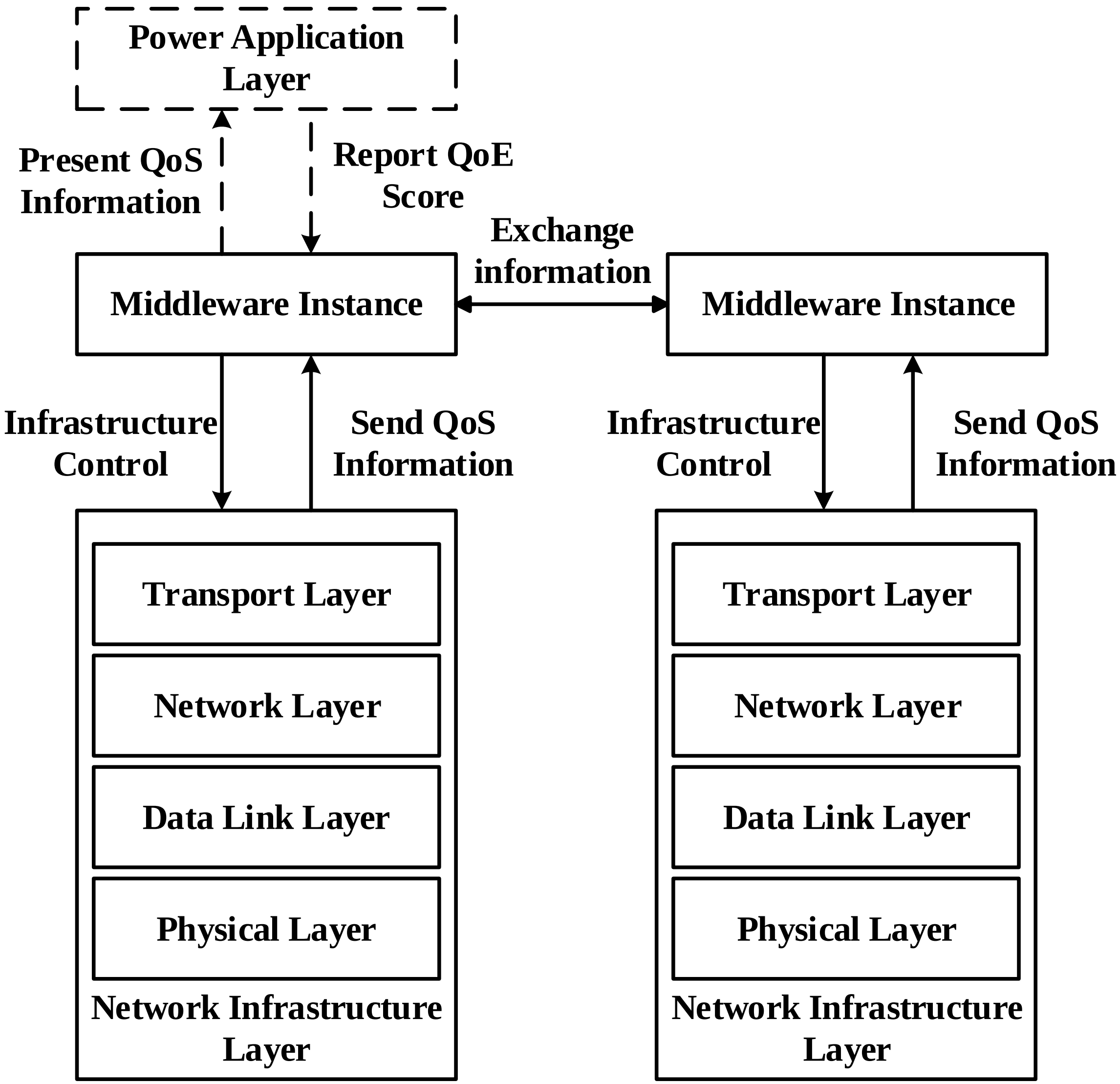


Middleware Framework Contd.

Middleware instances are installed in both aggregators and the gateway nodes of the mesh network between the aggregators and the remote servers.

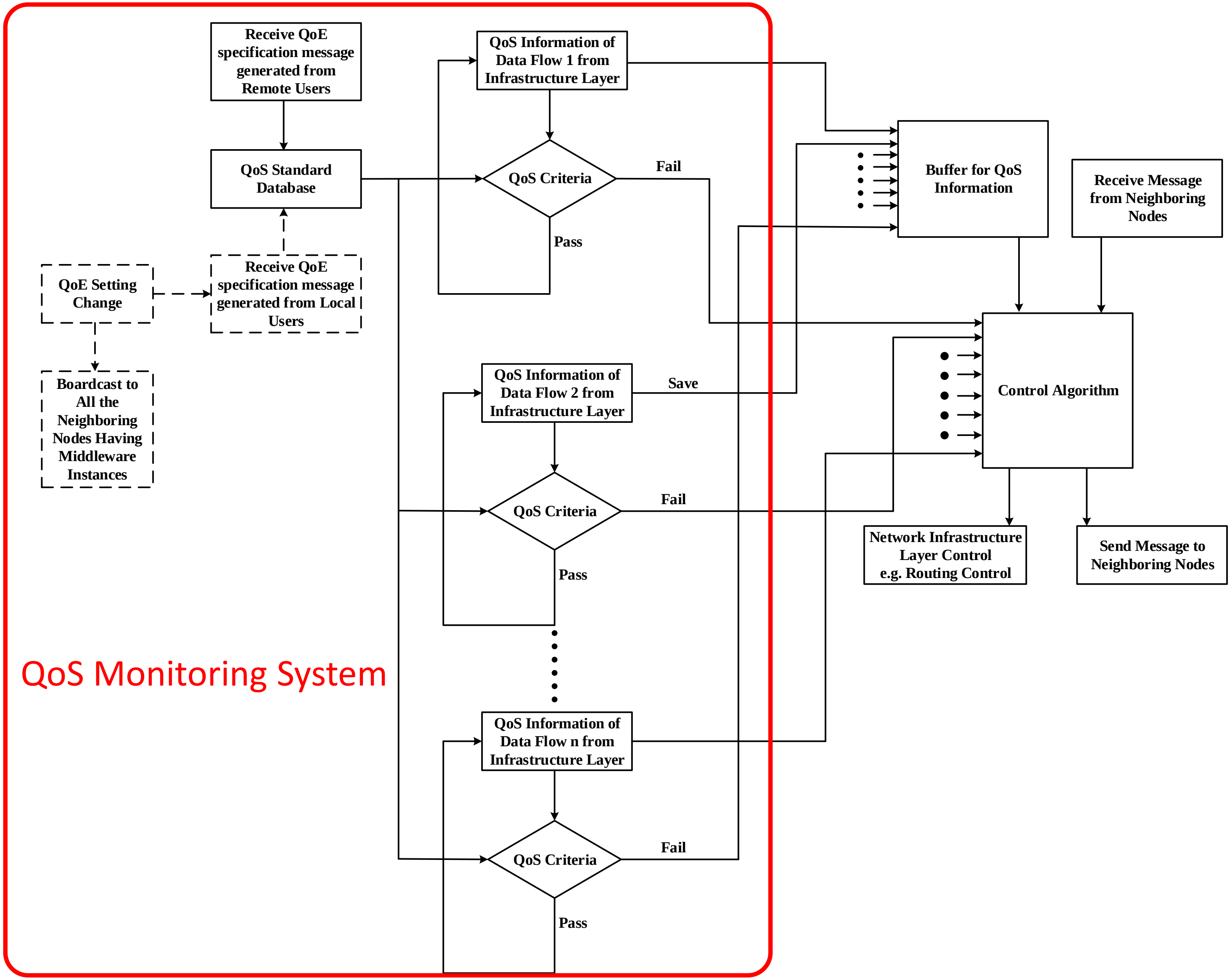


Middleware Development



- The real-time distributed middleware instances are able to manage data flows of different smart grid application services by exploiting the collaboration of different OSI layers.
- The middleware instances belonging to different network devices are able to communicate its neighboring nodes.
- The middleware instances have the same structure and functions and the only difference is that the middleware instance installed in end host has an Application Program Interface (API) that can send control commands to the middleware instances installed in the individual gateway nodes in real time.

Middleware Mechanism



State-Space Model from AR(p)

- AR(p) Model

$$x_t + [a_1 \quad a_2 \dots a_{p-1} \quad a_p] \begin{bmatrix} x_{t-1} \\ x_{t-2} \\ \vdots \\ x_{t-p} \end{bmatrix} = w_t; \; w_t \sim \mathcal{N}(0, \sigma_w^2)$$

- Define

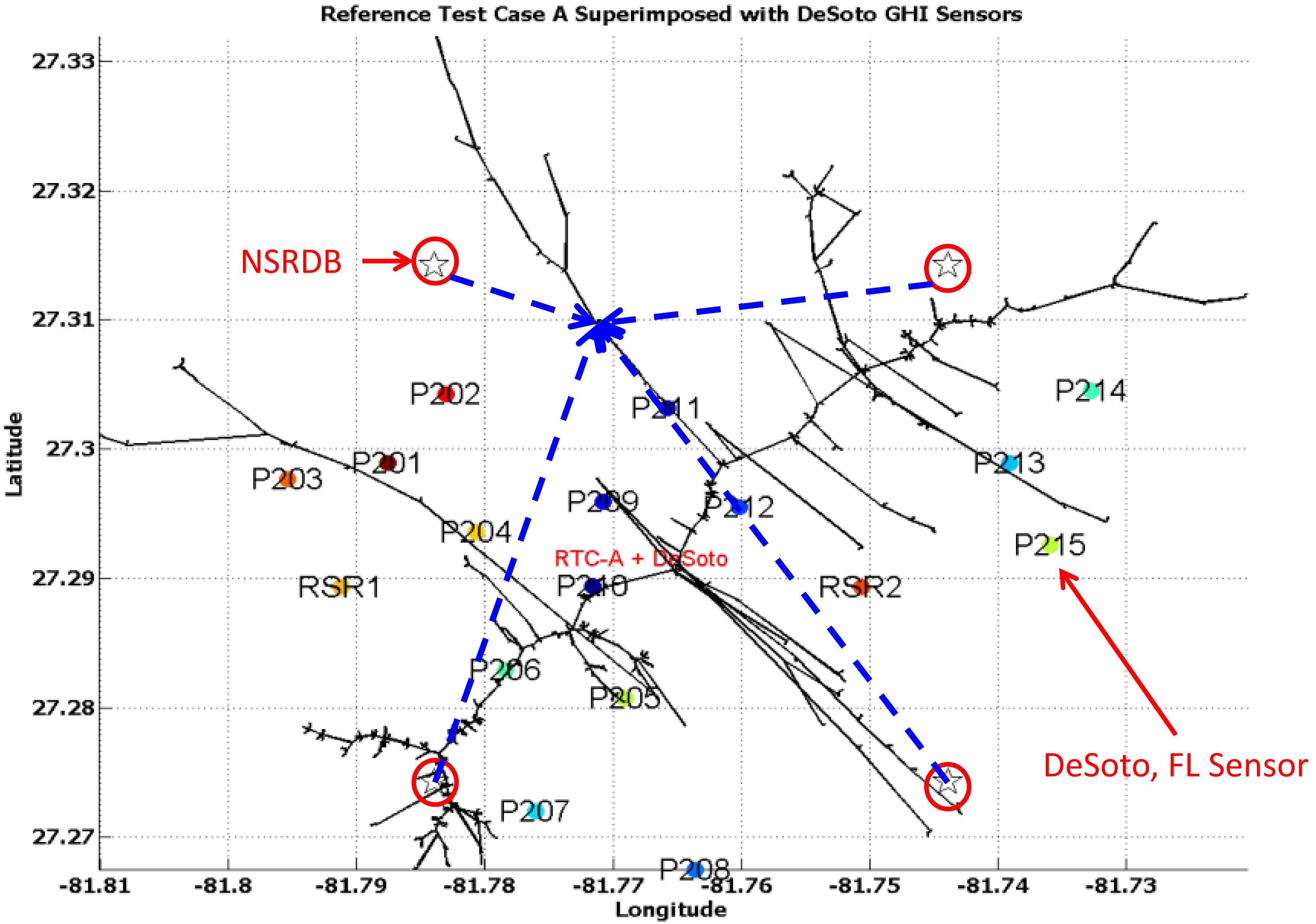
$$\boldsymbol{w}_t = \begin{bmatrix} w_t \\ 0 \\ \vdots \\ 0 \end{bmatrix}; \; \boldsymbol{x}_t = \begin{bmatrix} x_t \\ x_{t-1} \\ \vdots \\ x_{t-p+1} \end{bmatrix}$$

- State-Space Model

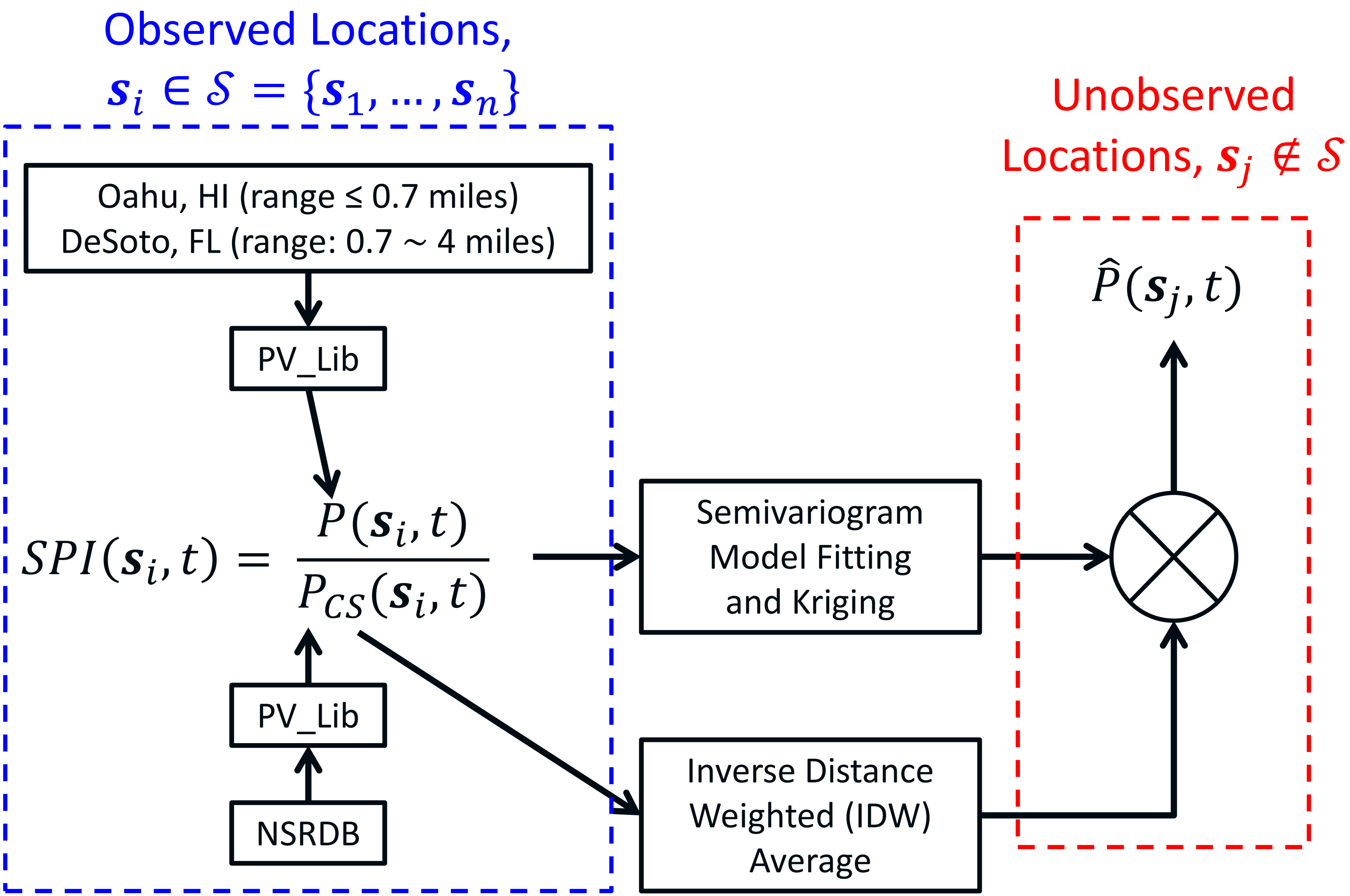
$$\boldsymbol{x}_t = \begin{bmatrix} -a_1 & -a_2 & -a_3 & \cdots & -a_p \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 1 & 0 \end{bmatrix} \boldsymbol{x}_{t-1} + \boldsymbol{w}_t = \boldsymbol{F}\boldsymbol{x}_{t-1} + \boldsymbol{w}_t$$

$$y_t = [1 \quad 0 \quad \dots \quad 0]\boldsymbol{x}_t = \boldsymbol{h}^T \boldsymbol{x}_t + v_t; \; v_t \sim \mathcal{N}(0, \sigma_v^2)$$

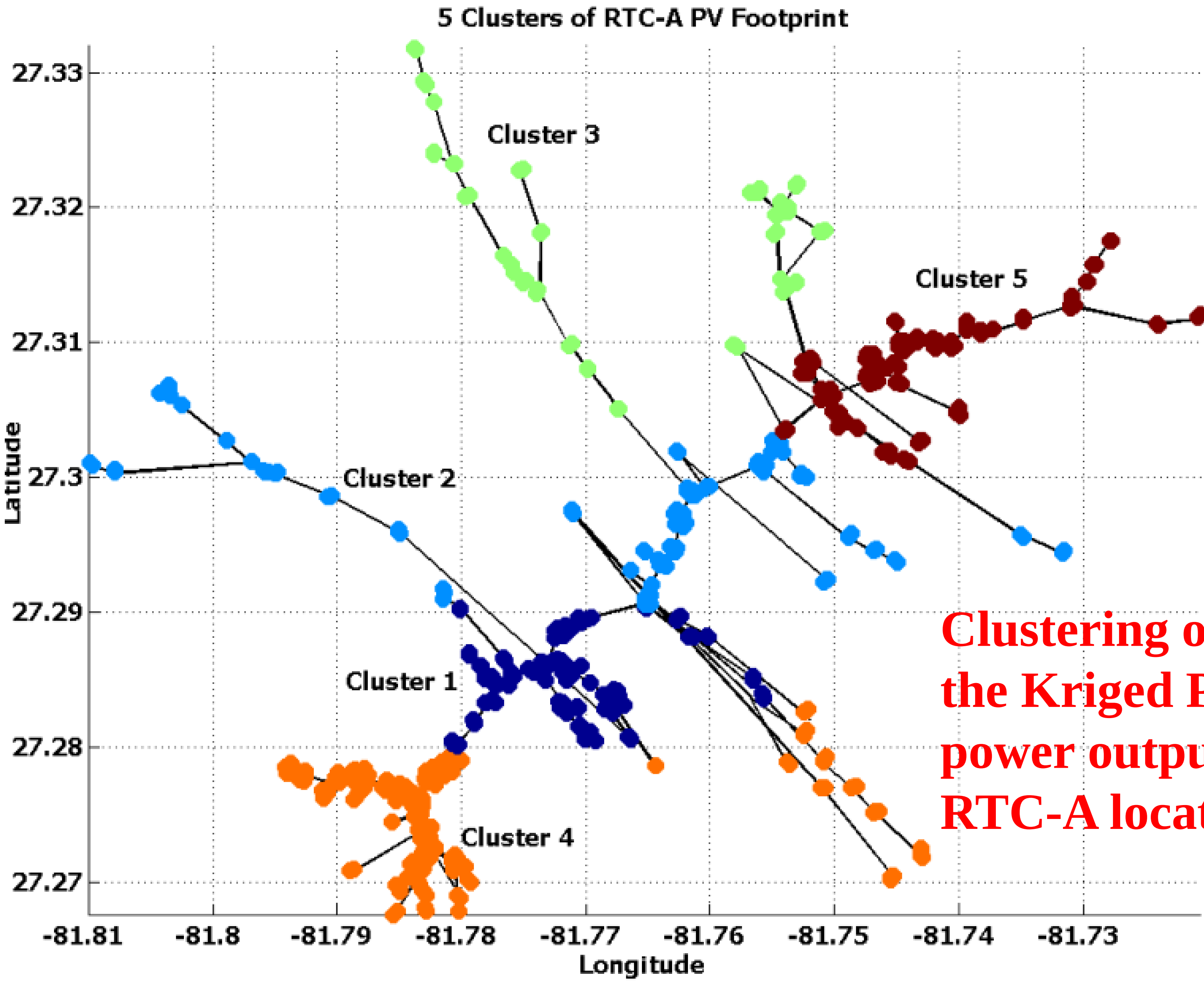
PV Power Output Profile for RTC-A



IDW and Kriging based Spatial Estimation

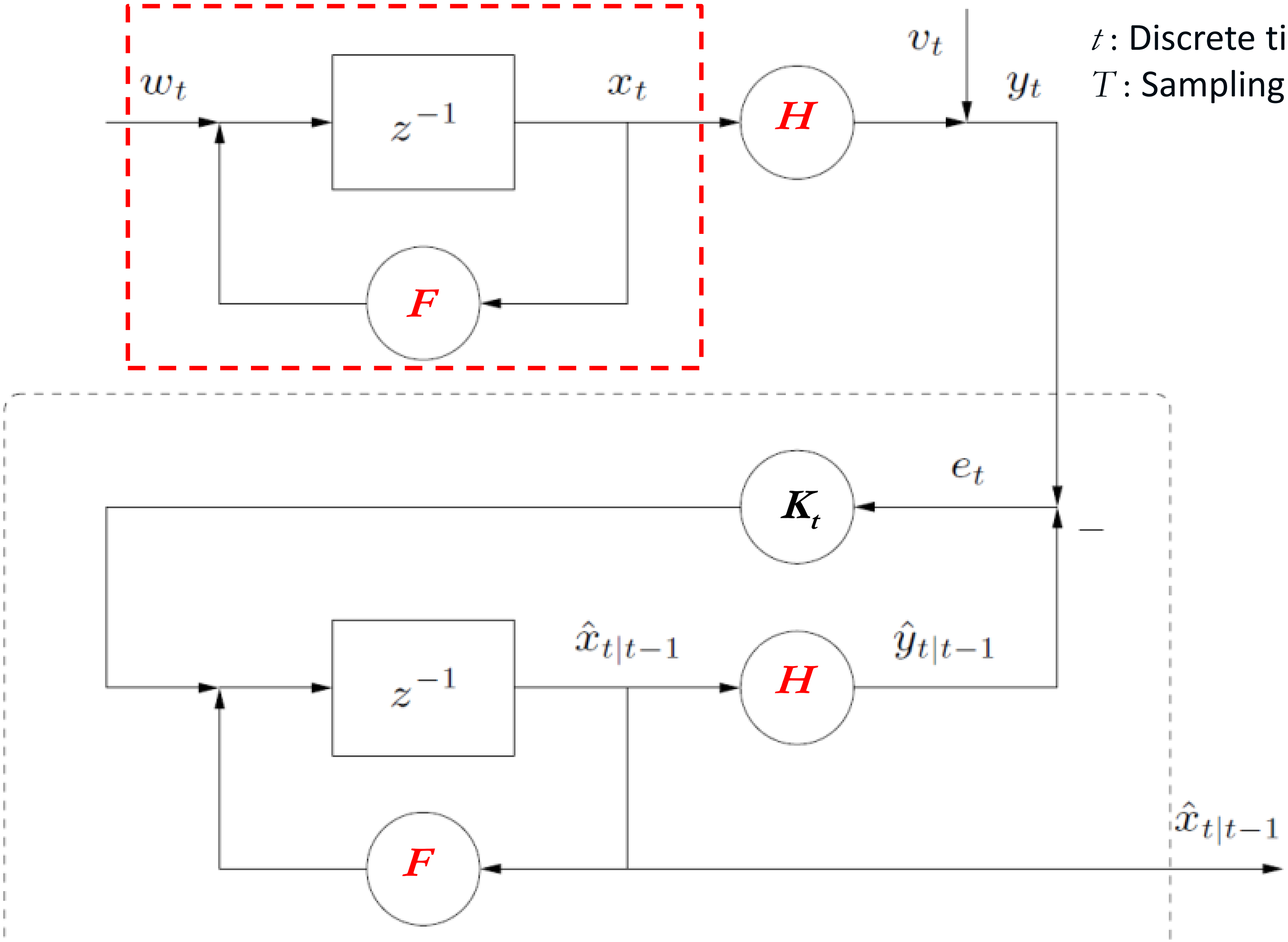


5 Clusters of Wide Area PV Footprint



Clustering over the Kriged PV power output at RTC-A locations

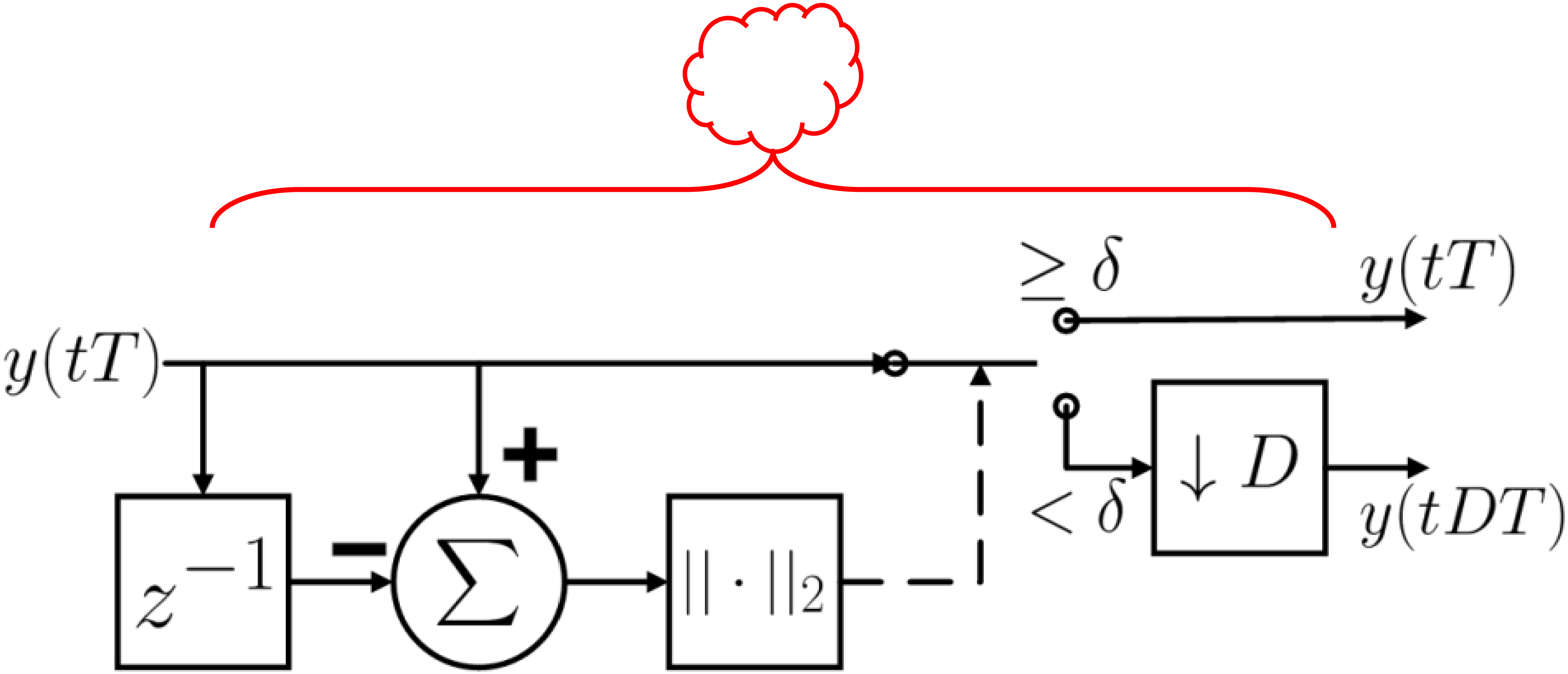
Kalman Filter



t : Discrete time instance
T : Sampling interval

[1] Adapted from Stephen Boyd, "EE 363 (Winter 2008-09) Lecture 8"

Multi-rate and Event Driven Sampling



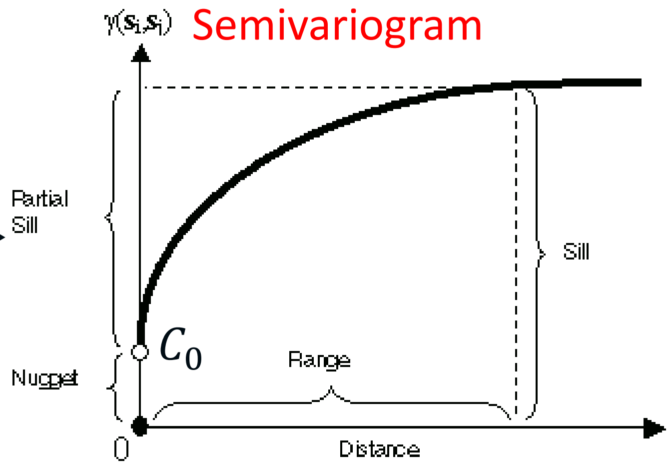
t : Discrete time instance

T : Sampling interval

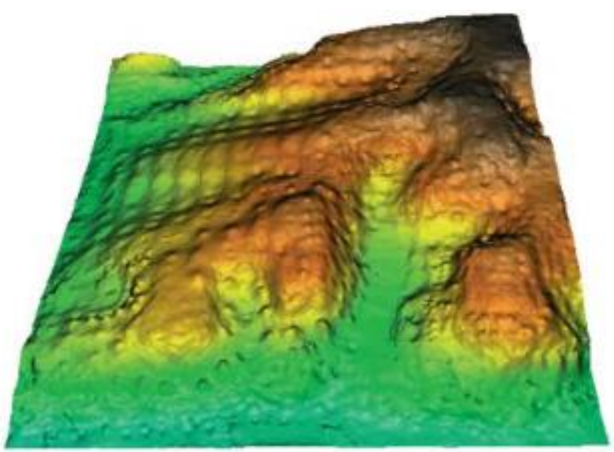
D: Decimation factor

δ: Threshold

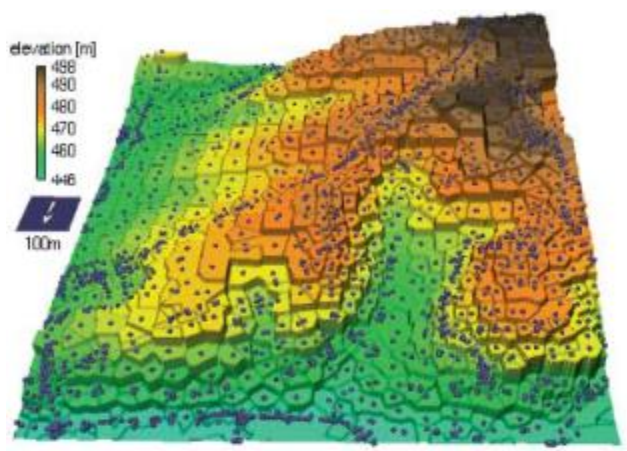
Kriging

Historical spatial observation →  → LMMSE estimate at unobserved locations

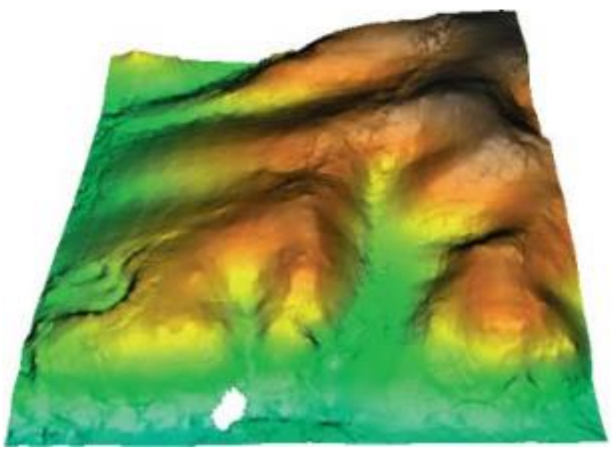
$$\gamma(\boldsymbol{s}_i, \boldsymbol{s}_j) = 0.5 \times Var\{y(\boldsymbol{s}_i) \sim y(\boldsymbol{s}_j)\}$$



Inverse Distance Weighted Average (IDW)



Given Data



Kriging

[2] Adapted from Mitas et al, "Ch 34: Spatial Interpolation" in GIS Vol.1, 1999.

Kriging Cntd.

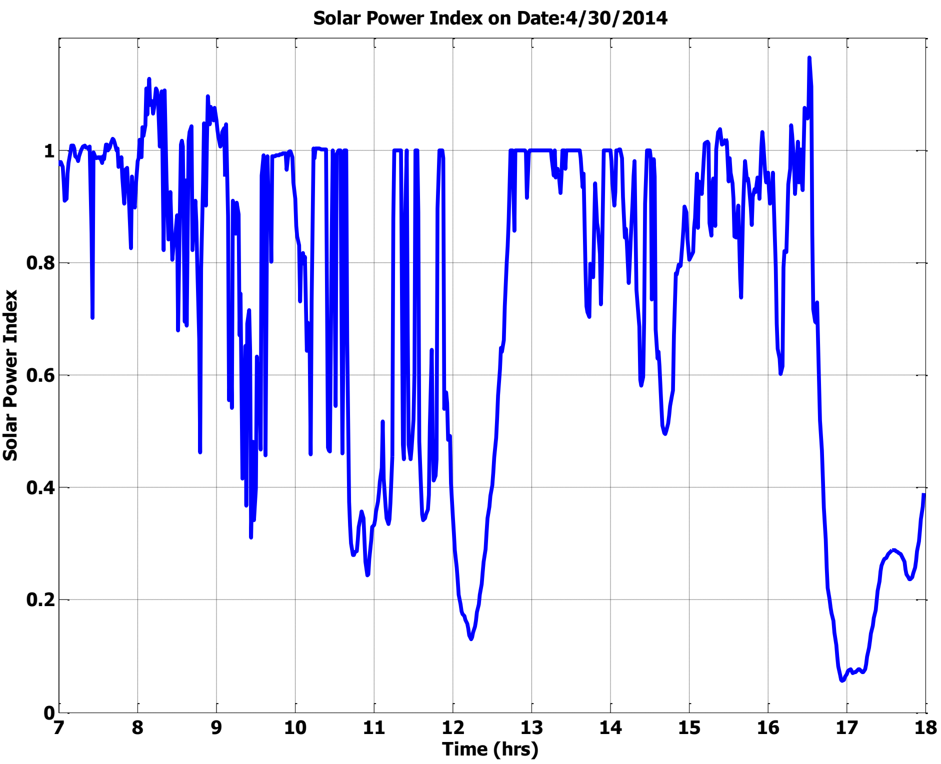
- Spatial covariance, $C_{ij} = sill - \gamma(\boldsymbol{s}_i, \boldsymbol{s}_j)$
- Solve for weights λ_k,

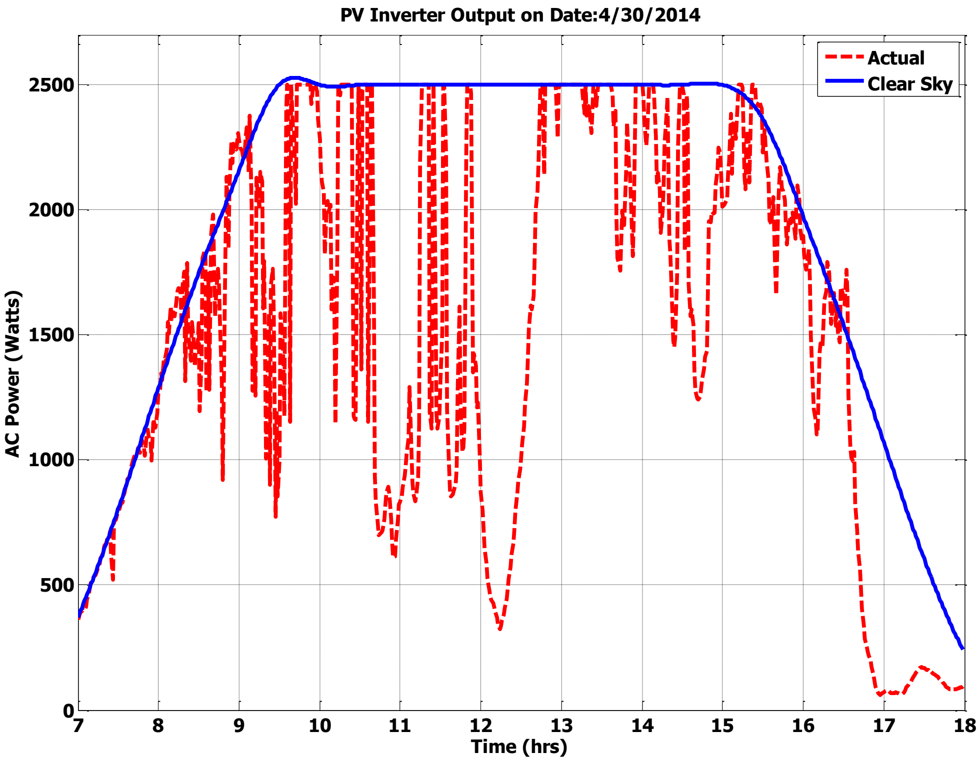
$$\begin{bmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ \mu \end{bmatrix} = \begin{bmatrix} C_{11} & \cdots & C_{1n} & 1 \\ \vdots & \ddots & \vdots & \vdots \\ C_{n1} & \cdots & C_{nn} & 1 \\ 1 & \cdots & 1 & 0 \end{bmatrix}^{-1} \begin{bmatrix} C_{10} \\ \vdots \\ C_{n0} \\ 1 \end{bmatrix}$$

- Kriged estimate at location $\boldsymbol{s}_0$, $\hat{y}(\boldsymbol{s}_0) = \sum_{k \neq 0} \lambda_k y(\boldsymbol{s}_k)$
- Kriging variance,

$$\hat{\sigma}^2(\boldsymbol{s}_0) = C(0) - \begin{bmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ \mu \end{bmatrix} \times \begin{bmatrix} C_{10} \\ \vdots \\ C_{n0} \\ 1 \end{bmatrix}$$

Step 1: Solar Power Index (SPI), DeSoto, Fl





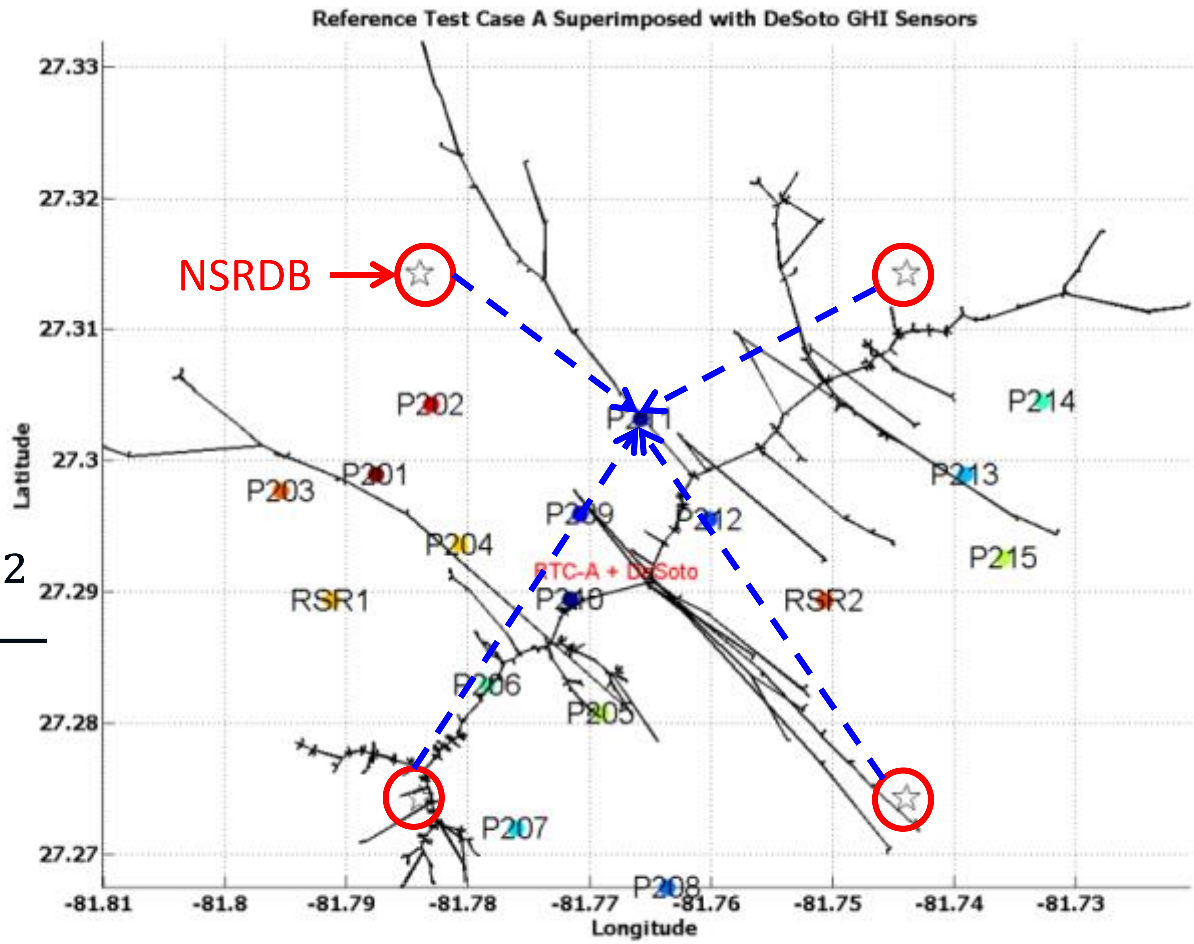
- Irradiance and weather data are fed to PV_Lib toolbox [1] assuming 2.5kW capacity
- Sampling interval, T = 1 min
- Inverter loading ratio = 1.48

[1] PV_Lib Toolbox, Sandia Natioanl Lab, Online: https://pvpmc.sandia.gov/applications/pv_lib-toolbox/

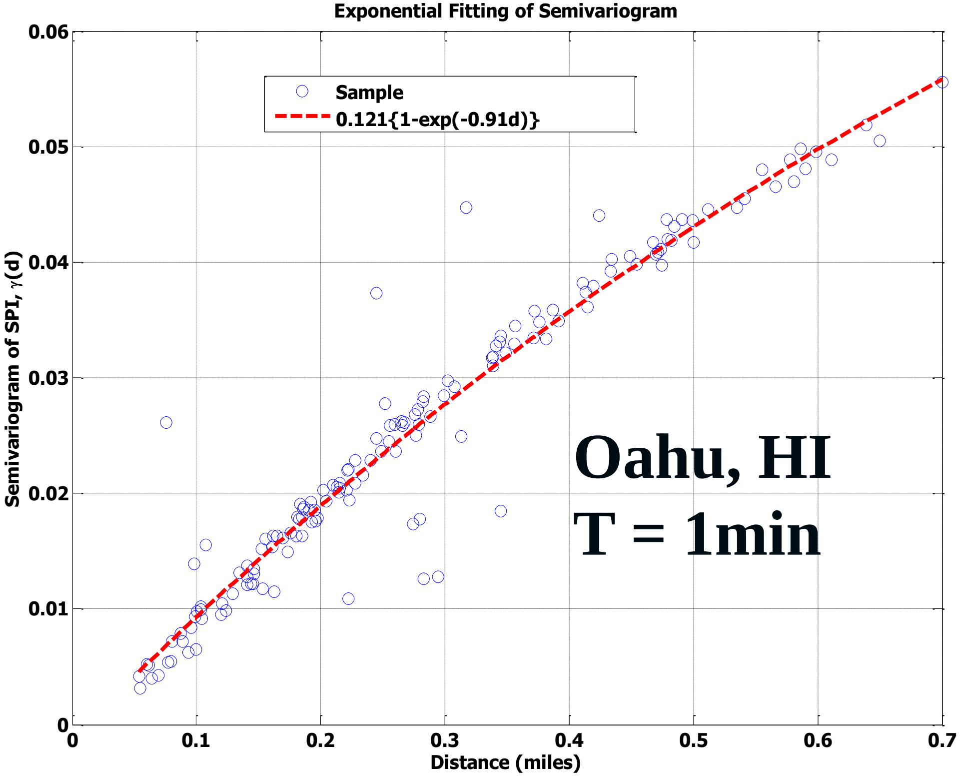
Step 2: IDW based Clear Sky AC Power

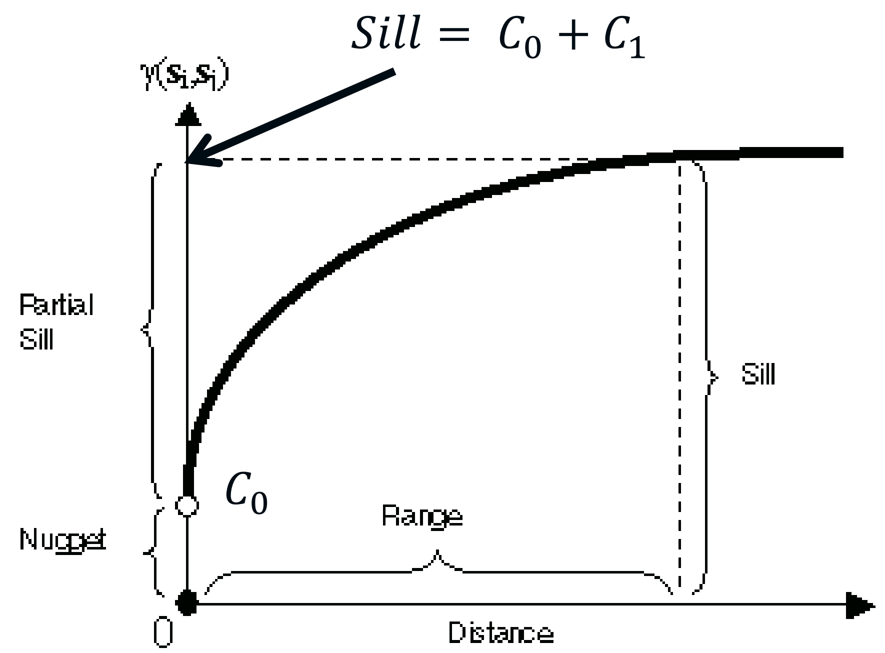
$$P_{cs}(\boldsymbol{s}_0, t)$$

$$= \frac{\sum_{i=1}^{4} P_{cs}(\boldsymbol{s}_i, t)/|\boldsymbol{s}_0 - \boldsymbol{s}_i|^2}{\sum_{i=1}^{n} 1/|\boldsymbol{s}_0 - \boldsymbol{s}_i|^2}$$



Step 3: Exponential Semivariogram Model Fitting





Exponential model

$$\gamma(d) = \begin{cases} 0, & d = 0 \\ C_0 + C_1\{1 - \exp(C_2 d)\}, & d \neq 0 \end{cases}$$

$$\gamma(\boldsymbol{s}_i, \boldsymbol{s}_j) = 0.5 \times Var\{y(\boldsymbol{s}_i) \sim y(\boldsymbol{s}_j)\}$$

Spatial covariance, $C_{ij} = sill - \gamma(\boldsymbol{s}_i, \boldsymbol{s}_j)$

State-Space Model from AR(p)

- AR(p) Model

$$x_t + [a_1 \quad a_2 \ldots a_{p-1} \quad a_p] \begin{bmatrix} x_{t-1} \\ x_{t-2} \\ \vdots \\ x_{t-p} \end{bmatrix} = w_t;\; w_t \sim \mathcal{N}(0, \sigma_w^2)$$

- Define

$$\boldsymbol{w}_t = \begin{bmatrix} w_t \\ 0 \\ \vdots \\ 0 \end{bmatrix};\; \boldsymbol{x}_t = \begin{bmatrix} x_t \\ x_{t-1} \\ \vdots \\ x_{t-p+1} \end{bmatrix}$$

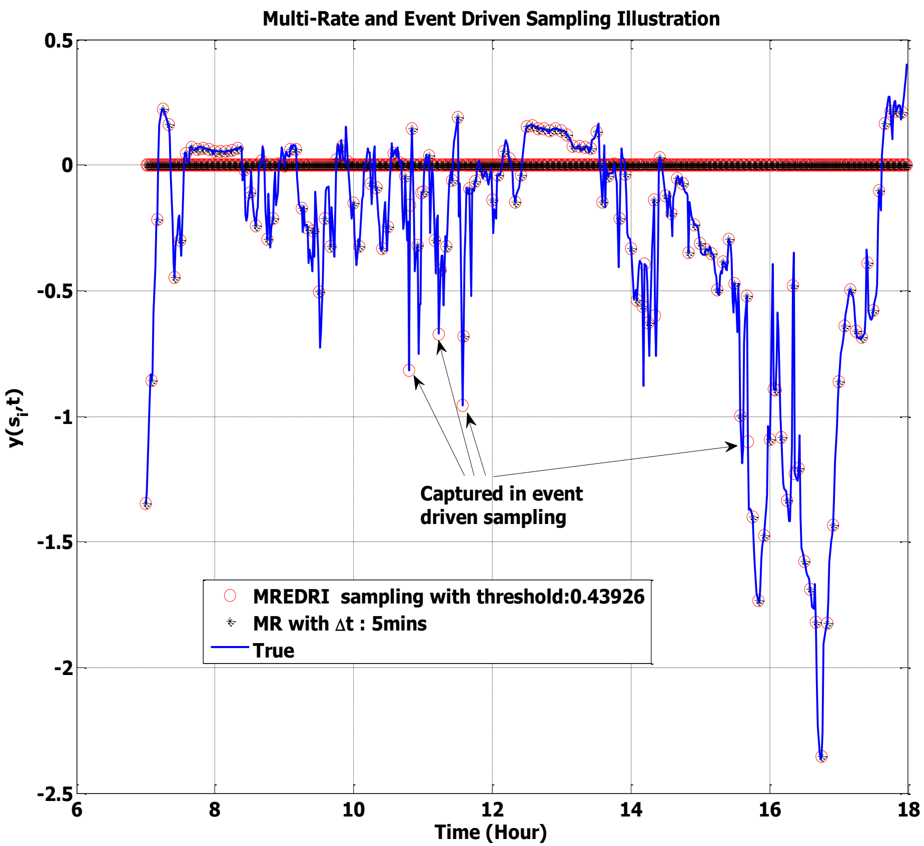
- State-Space Model

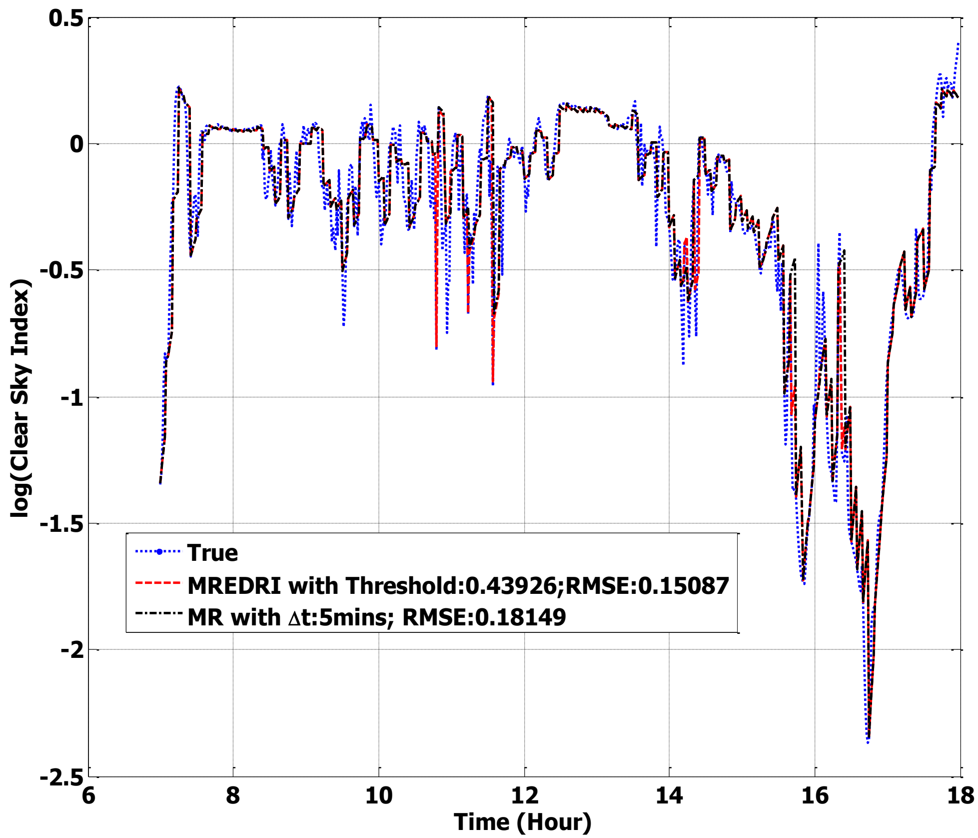
$$\boldsymbol{x}_t = \begin{bmatrix} -a_1 & -a_2 & -a_3 & \cdots & -a_p \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \ldots & 1 & 0 \end{bmatrix} \boldsymbol{x}_{t-1} + \boldsymbol{w}_t = \boldsymbol{F}\boldsymbol{x}_{t-1} + \boldsymbol{w}_t$$

$$y_t = [1 \quad 0 \quad \ldots \quad 0]\boldsymbol{x}_t = \boldsymbol{h}^T\boldsymbol{x}_t + v_t;\; v_t \sim \mathcal{N}(0, \sigma_v^2)$$

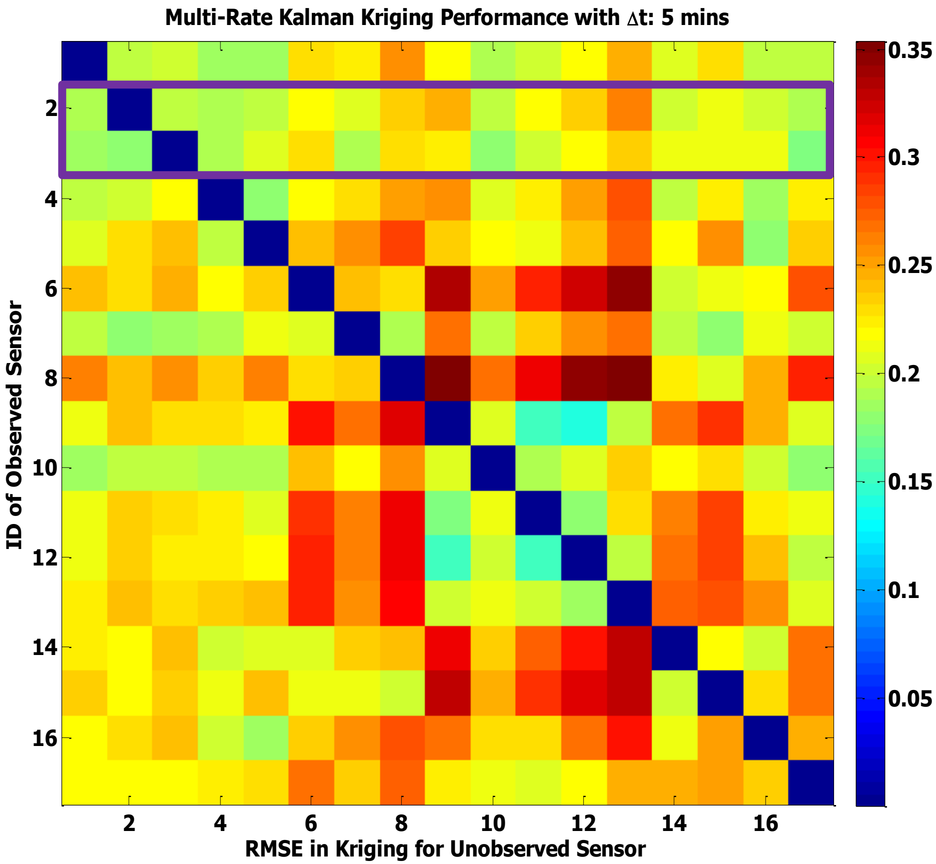
Event Driven (EDRI) Kalman Filter Performance

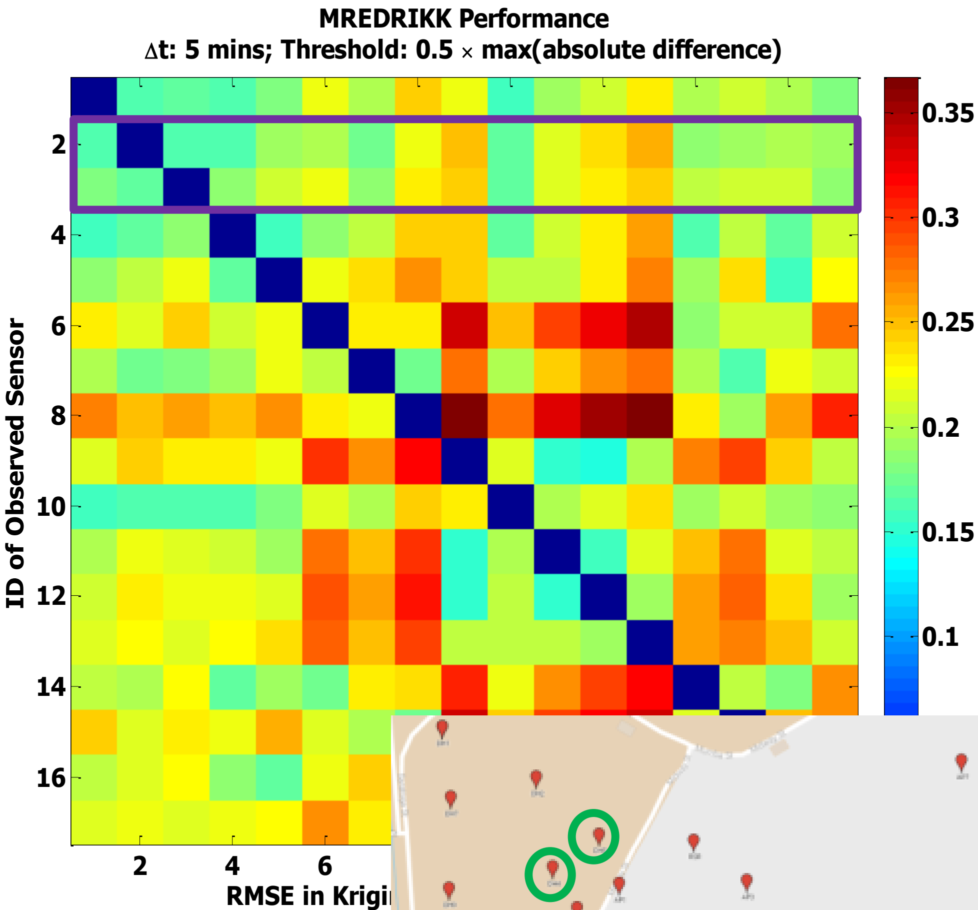
- Utilize $\boldsymbol{y}_t$ for Kalman filter if $\|\boldsymbol{y}_t - \boldsymbol{y}_{t-1}\| \geq \delta$
- Else follow the multi-rate measurement update.

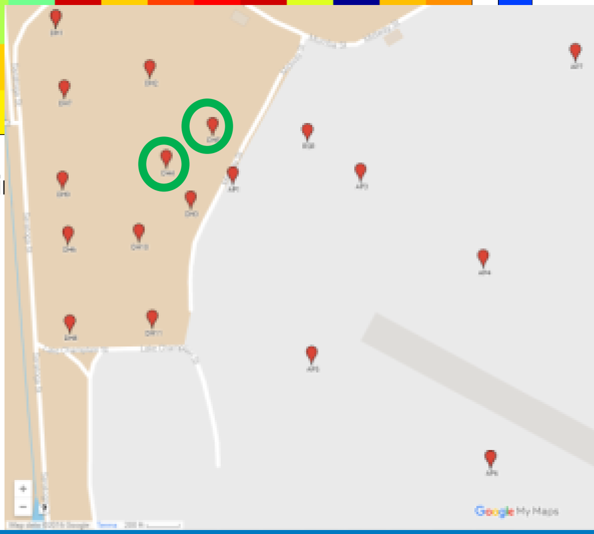




Candidate Sensor Selection in Local Neighborhood







Candidate Sensors for Observation: Sensors 2 (DH4) and 3 (DH5)

Automatic Regionalization

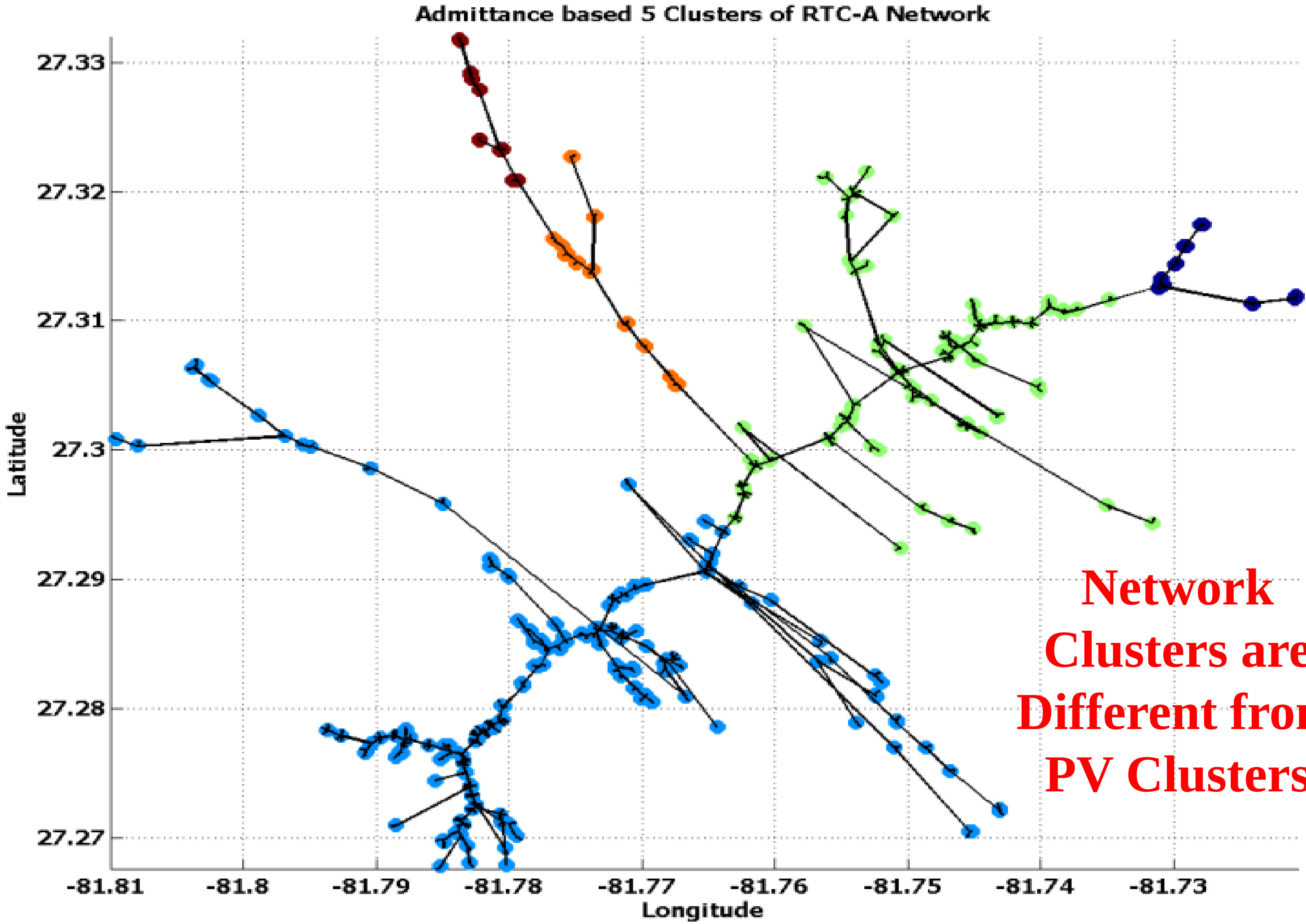
- Weighted adjacency matrix design (nodes i and j)
  - Topology Based Similarity (TBS) $w_{ij} = \begin{cases} 1, Nodes\ i\ and\ j\ are\ connected \\ 0, otherwise \end{cases}$
  - Measurement Based Similarity (MBS)

$$w_{ij} = \begin{cases} 1, Measurements\ are\ available\ for\ i\ and\ j \\ 0, otherwise \end{cases}$$

  - Weighted Measurement Based Similarity (WMBS)

$$w_{ij} = \begin{cases} \sum_{p \in \mathcal{P}} c_p, \mathcal{P} = \left\{ p \middle| \frac{\partial z_p}{\partial x_i} \neq 0\ and\ \frac{\partial z_p}{\partial x_j} \neq 0 \right\} \neq \emptyset \\ 0, otherwise \end{cases}$$

5 Clusters of RTC-A Network



Network Clusters are Different from PV Clusters

D. Wang et al., “Automatic Regionalization Algorithm for Distributed State Estimation in Power Systems”, in *IEEE Global Conference on Signal and Information Processing*, pp. 1-6, 2016

PV Statistics Integration

PV Inverter

Irradiance Sensor

Electrically Regionalized

Local Spatial PV footprint(Correlation Coefficient >80%)

(MREDRIKK + ADMM)

+

DLIA