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CREATING REALISTIC POWER DISTRIBUTION NETWORKS USING INTERDEPENDENT ROAD INFRASTRUCTURE

Motivation

- ❖Lack of datasets to analyze complex interactions between interdependent networked infrastructures.
- ❖Lack of realistic distribution network test scenarios to validate state-of-the-art algorithms.
- ❖Lack of network models which accounts the role of human behavior and interactions.

Related Works:

- ❑Synthetic transmission networks [1].
- ❑Creation of synthetic distribution network based on statistical distribution of network attributes.

Bottom-up approach [2]:
- Residential loads are aggregated to a single point.
- The aggregated points are connected to create the network

Top-down approach [3]:
- A synthetic network is generated.
- The network is randomly populated with loads.

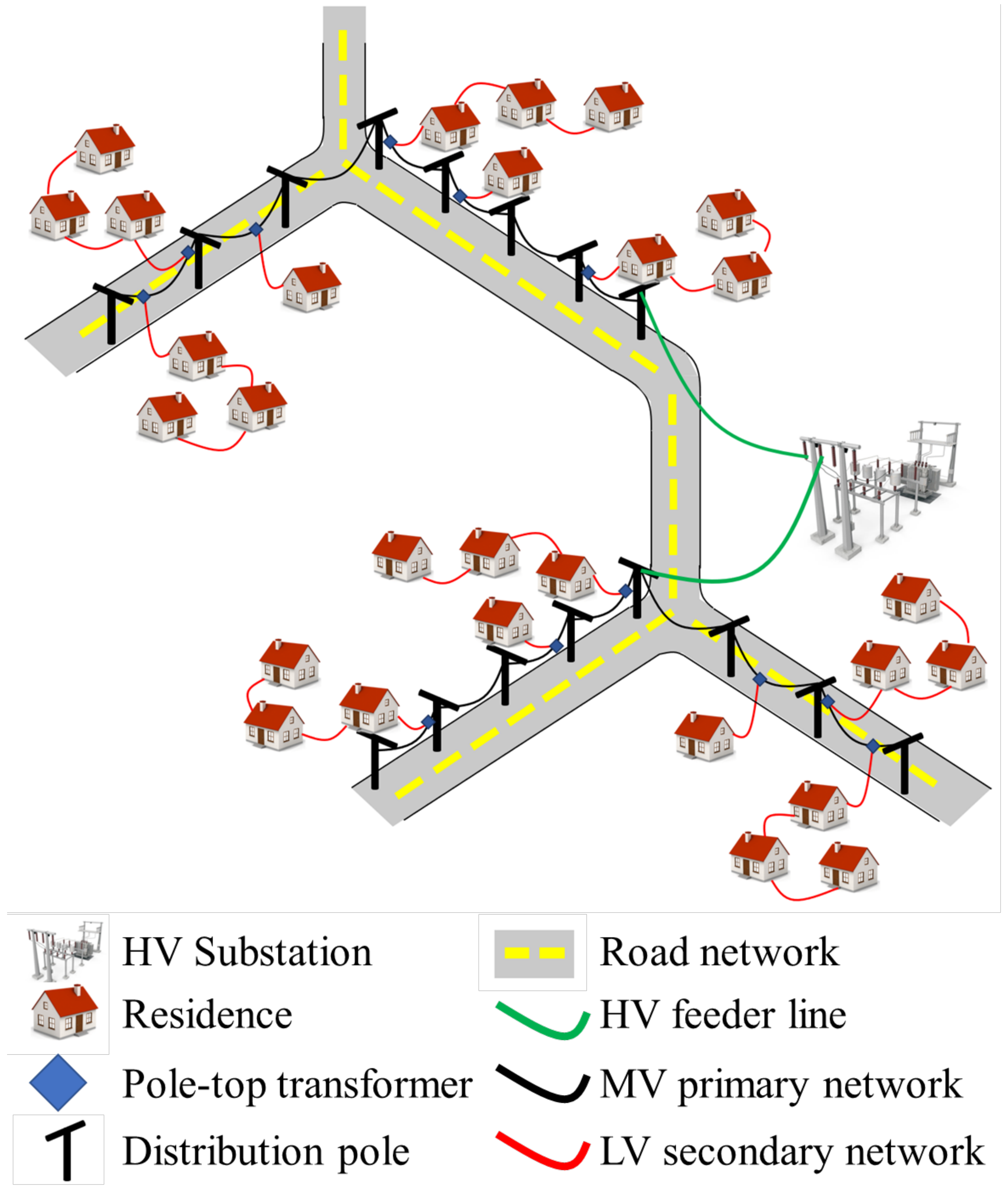
- ❑Synthetic networks do not capture the geographical aspect [2,3].
  - Similar type of networks is generated for all geographical regions.

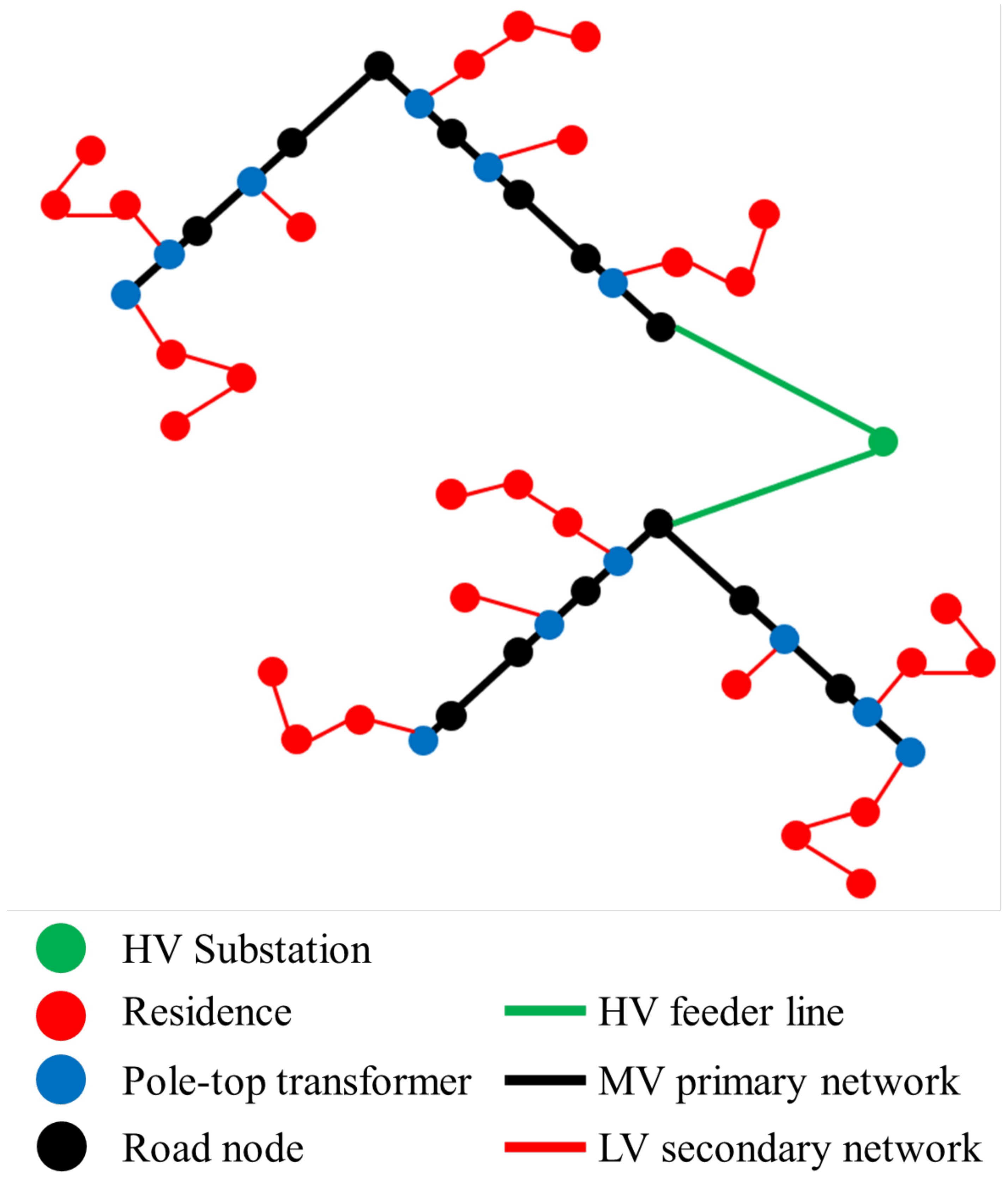
[1] B. Birchfield, K. M. Gegner, T. Xu, K. S. Shetye, and T. J. Overbye, "Statistical Considerations in the Creation of Realistic Synthetic Power Grids for Geomagnetic Disturbance Studies," IEEE Transactions on Power Systems, vol. 32, no. 2, pp. 1502--1510, Mar 2017.
[2] E. Schweitzer, A. Scaglione, A. Monti, and G. A. Pagani, "Automated Generation Algorithm for Synthetic Medium Voltage Radial Distribution Systems," IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 7, no. 2, pp. 271--284, Jun 2017.
[3] G. Pisano, N. Chowdhury, M. Coppo, N. Natale, G. Petretto, G. Soma, R. Turri, and F. Pilo, "Synthetic Models of Distribution Networks Based on Open Data and Georeferenced Information," Energies, vol. 12, no. 23, Nov 2019.

Preliminaries

Assumptions

- Power network follows the road network.
- Levels in the network
  - Low voltage secondary network
  - Medium voltage primary network
  - High voltage feeder lines
- Local transformers placed along road links.





Approach

Problem:
Given a set of residences and electric substations with their respective geographical coordinates, construct a realistic **power distribution network** connecting these points.

Approach
- Map residences to nearest road link
- Create the secondary distribution network to connect residences and local transformers.
- Create the primary distribution network to connect local transformers to substations

Dataset	Source	Attributes
Substation	Electric substation data published by US Department of Homeland Security [1].	• substation ID • longitude • latitude
Road Network	GIS and electronic navigable maps published by NAVTEQ [2].	• node ID • node longitude • node latitude • link ID • Link importance level
Residences	Synthetic population and electric load demand profiles generated by [3].	• residence ID • longitude • latitude • average hourly load demand

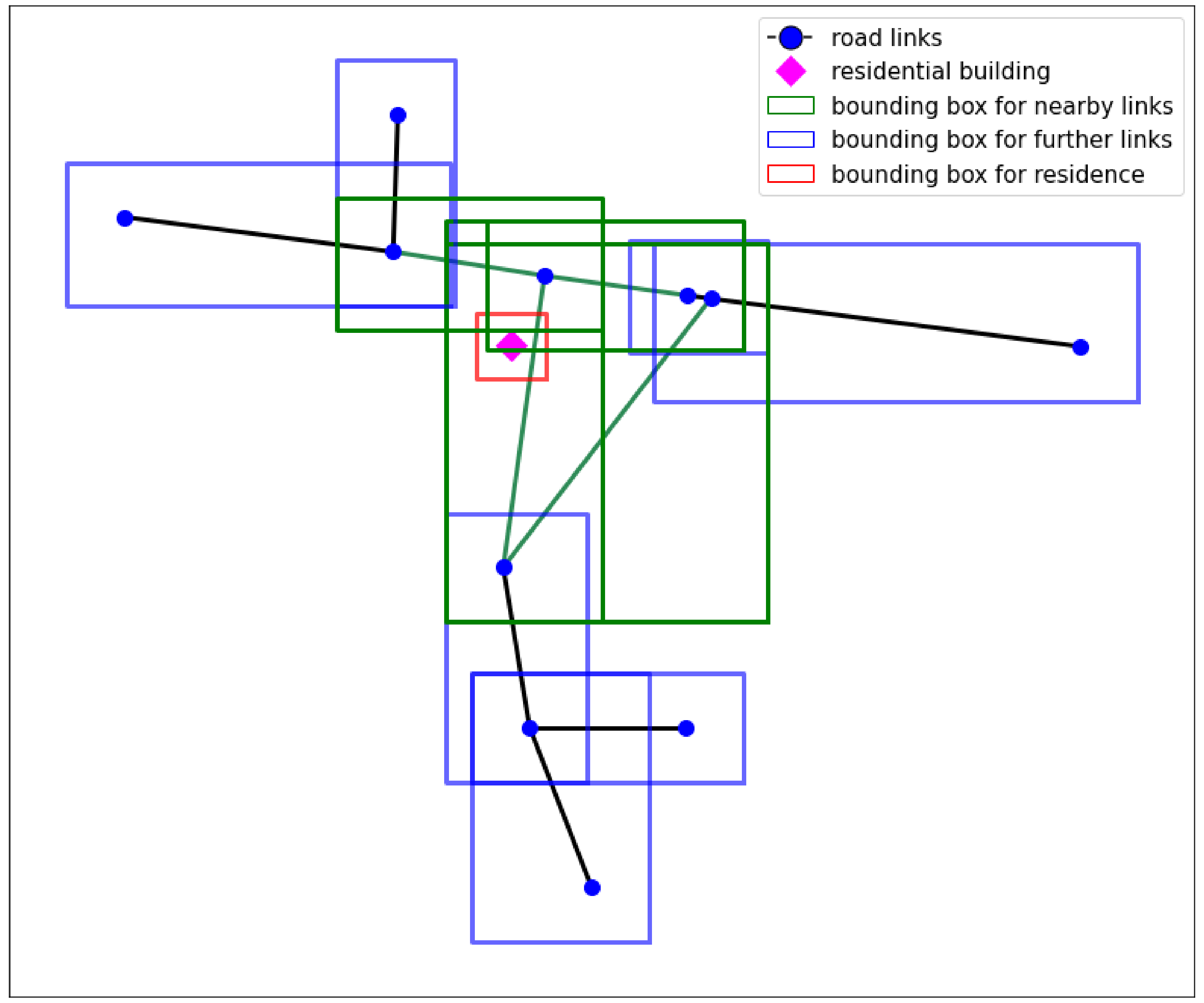
[1] "Electric Substations" 2019, last accessed 19 Oct 2019. [Online]. Available https://hid-geoplatform.opendata.arcgis.com/datasets/electric-substations.
[2] "HERE StreetMap Premium for the U.S." 2020, last accessed 13 Feb 2020. [Online]. Available: www.here.com
[3] S. Thorve, S. Swarup, A. Marathe, Y. Chungbaek, E. K. Nordberg, and M. V. Marathe, "Simulating Residential Energy Demand in Urban and Rural Areas," in 2018 Winter Simulation Conference (WSC), Dec 2018, pp. 548—559.

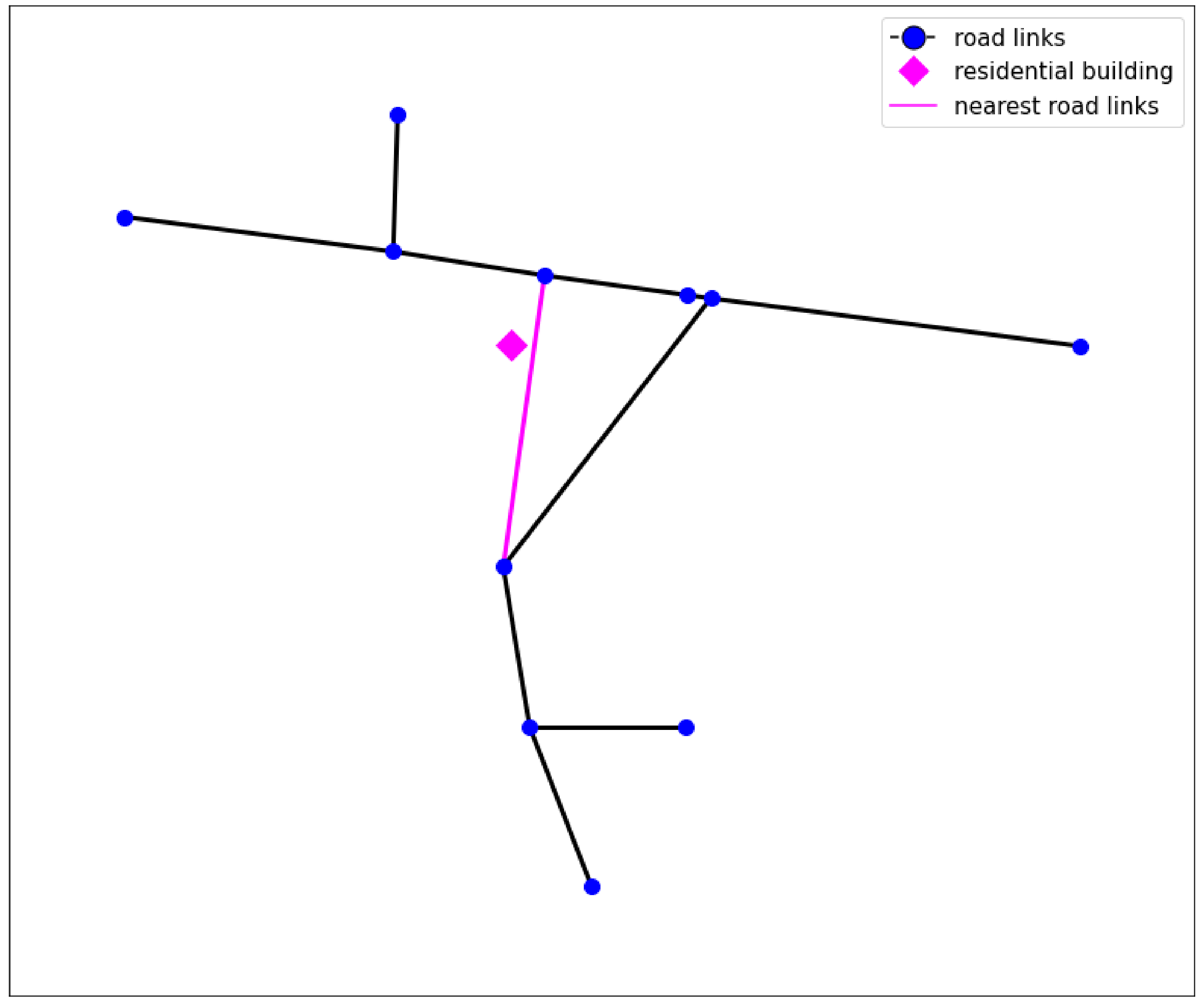
Mapping Residences to Road Links

Goal: Find the nearest road link to a residence

Approach (Quad-tree based):

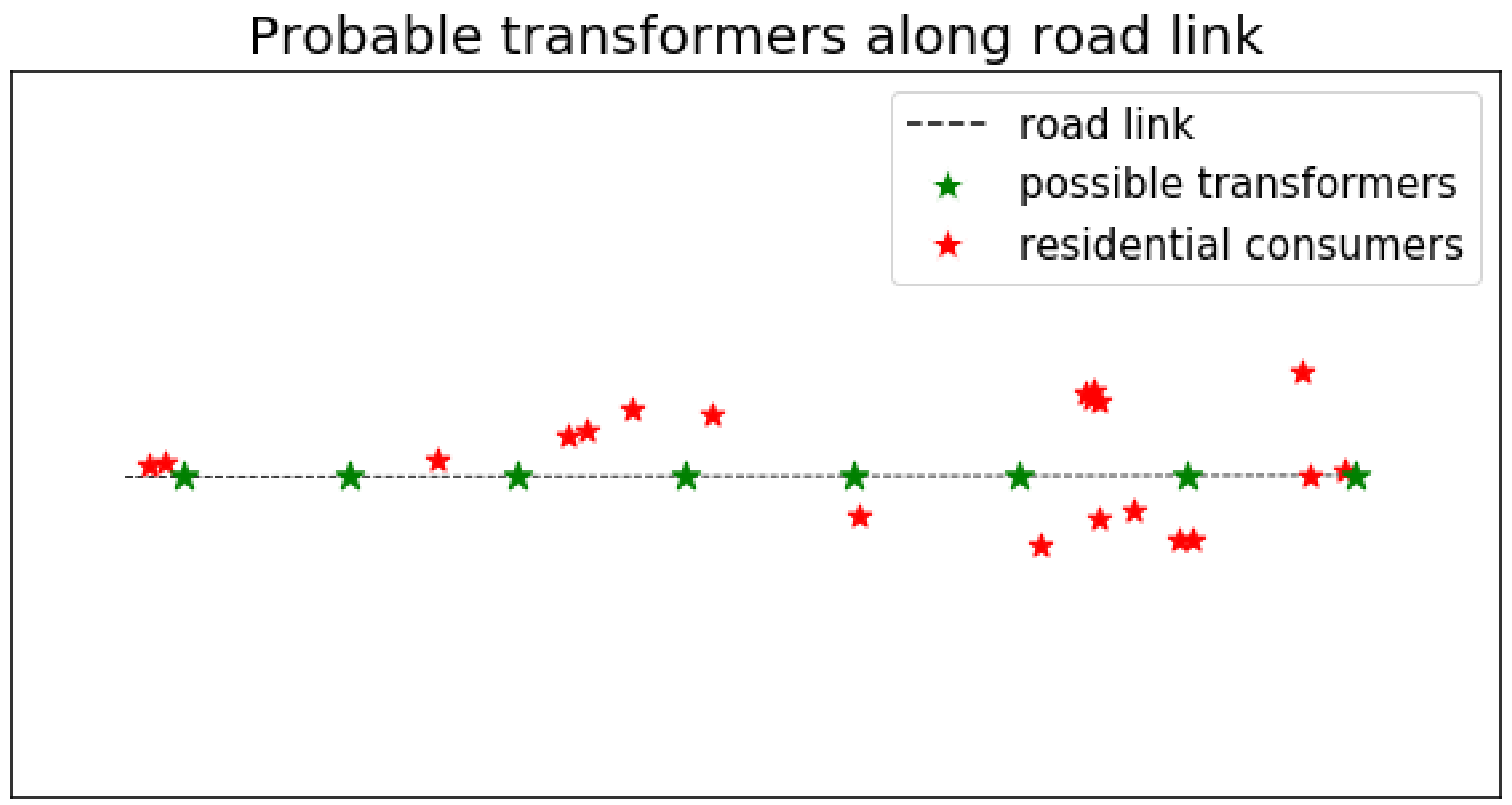
- Bounding box around each road link.
- Bounding box around residence
- Evaluate the intersections of these boxes.
- Compute the nearest link from these intersections





Next Steps

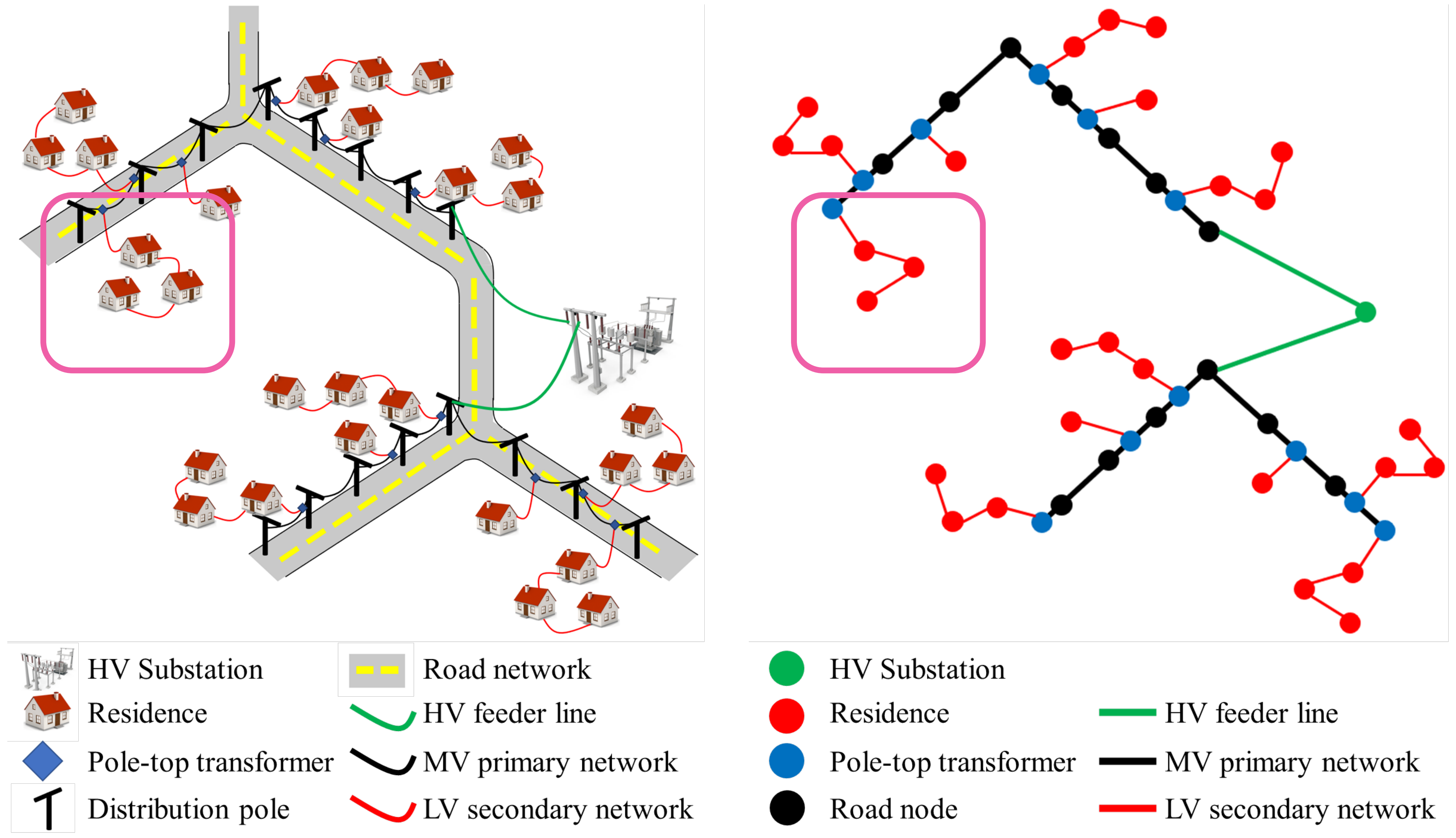
- Find residences mapped to a road link ($\mathcal{V}_H$).
- Interpolate points along link for probable local transformers ($\mathcal{V}_T$).



Secondary Network Creation

Goal: Connect residences to local transformers in a forest of star-like trees

- forest of trees configuration
- transformers are root nodes
- residences connected in chain structure



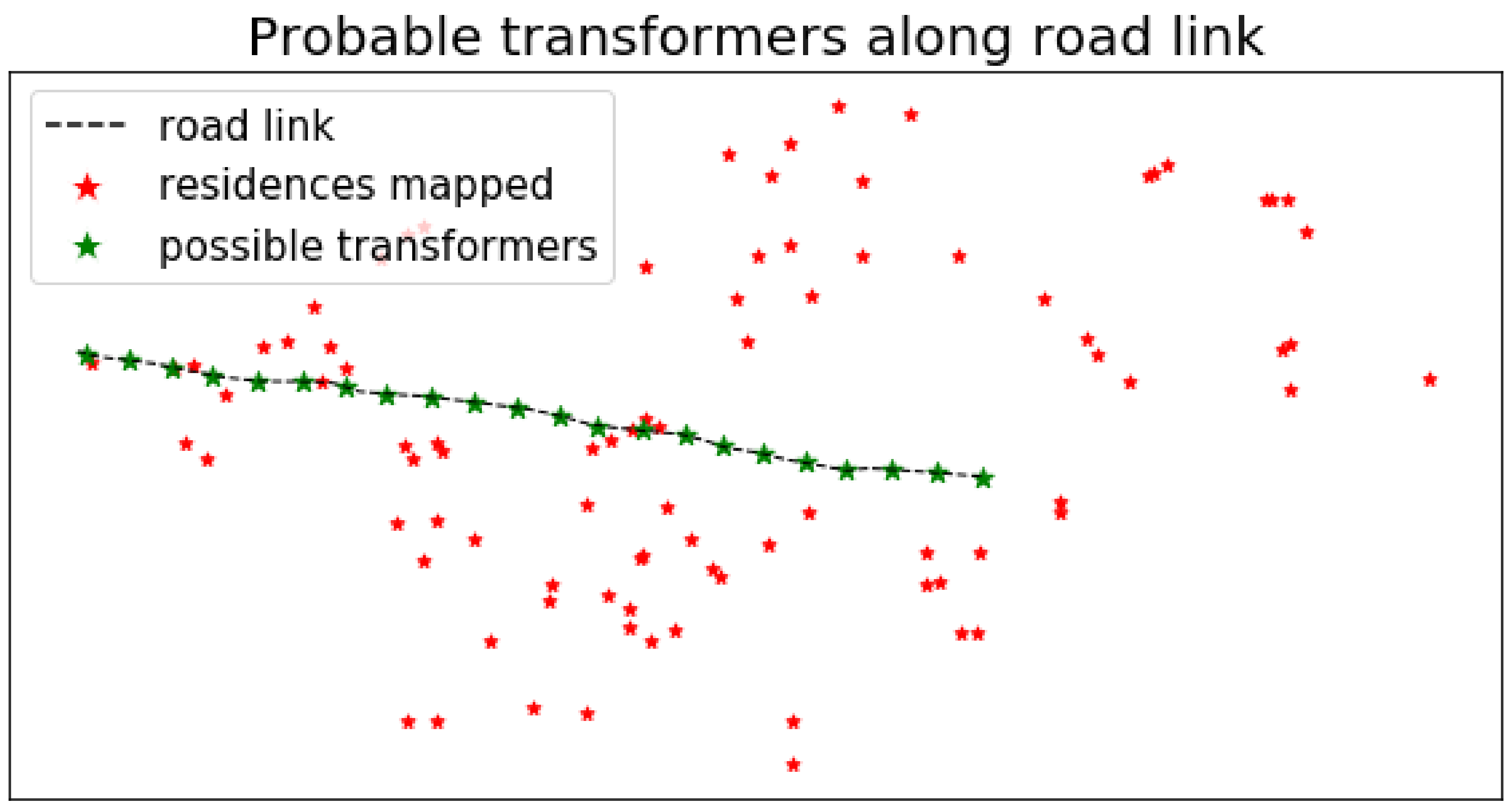
Undirected graph $\mathcal{G}_D(\mathcal{V}, \mathcal{E}_D)$

- node set: $\mathcal{V} = \mathcal{V}_H \cup \mathcal{V}_T$
- set of residences: $\mathcal{V}_H$
- probable transformers: $\mathcal{V}_T$
- candidate edge set $\mathcal{E}_D$

Optimal set $\mathcal{E}_D^* \subseteq \mathcal{E}_D$

Induced subgraph $\mathcal{G}_D^*(\mathcal{V}^*, \mathcal{E}_D^*)$

- minimum network length
- node set: $\mathcal{V}^* = \mathcal{V}_H \cup \mathcal{V}_T^*$
- actual transformers: $\mathcal{V}_T^* \subseteq \mathcal{V}_T$
- forest of $|\mathcal{V}_T^*|$ star-like trees



Secondary Network Creation

Variables

- $x_e \in \{0,1\}$: binary variable for $e \in \mathcal{E}_D$
- f_e: power flowing along edge $e \in \mathcal{E}_D$
- w_e: weight of edge $e \in \mathcal{E}_D$
- p_v: power demand at residence $v \in \mathcal{V}_H$

Constraints for $\mathcal{G}_D^*(\mathcal{V}^*, \mathcal{E}_D^*)$ to be a forest of $|\mathcal{V}_T^*|$ star-like trees

- degree of residence

  $$\deg(v) \leq 2, \forall\, v \in \mathcal{V}_H$$

- number of edges:

  $$|\mathcal{E}_D^*| = |\mathcal{V}^*| - |\mathcal{V}_T^*| = |\mathcal{V}_H|$$

- power balance constraint

  $$\sum_{e:(u,v)} f_e - \sum_{e:(v,u)} f_e = p_v, \forall\, v \in \mathcal{V}_H$$

- power flow limit

  $$-\overline{f} \leq f_e \leq \overline{f}, \forall\, e \in \mathcal{E}_D^*$$

branch-bus incidence matrix

from bus: m   to bus: n   edge (m, n)

$$\mathbf{A} = \begin{bmatrix} \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & +1 & \cdots & \cdots & 0 & -1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix}$$

Columns reordered: $\mathbf{A} = [\mathbf{A_T} \quad \mathbf{A_H}]$

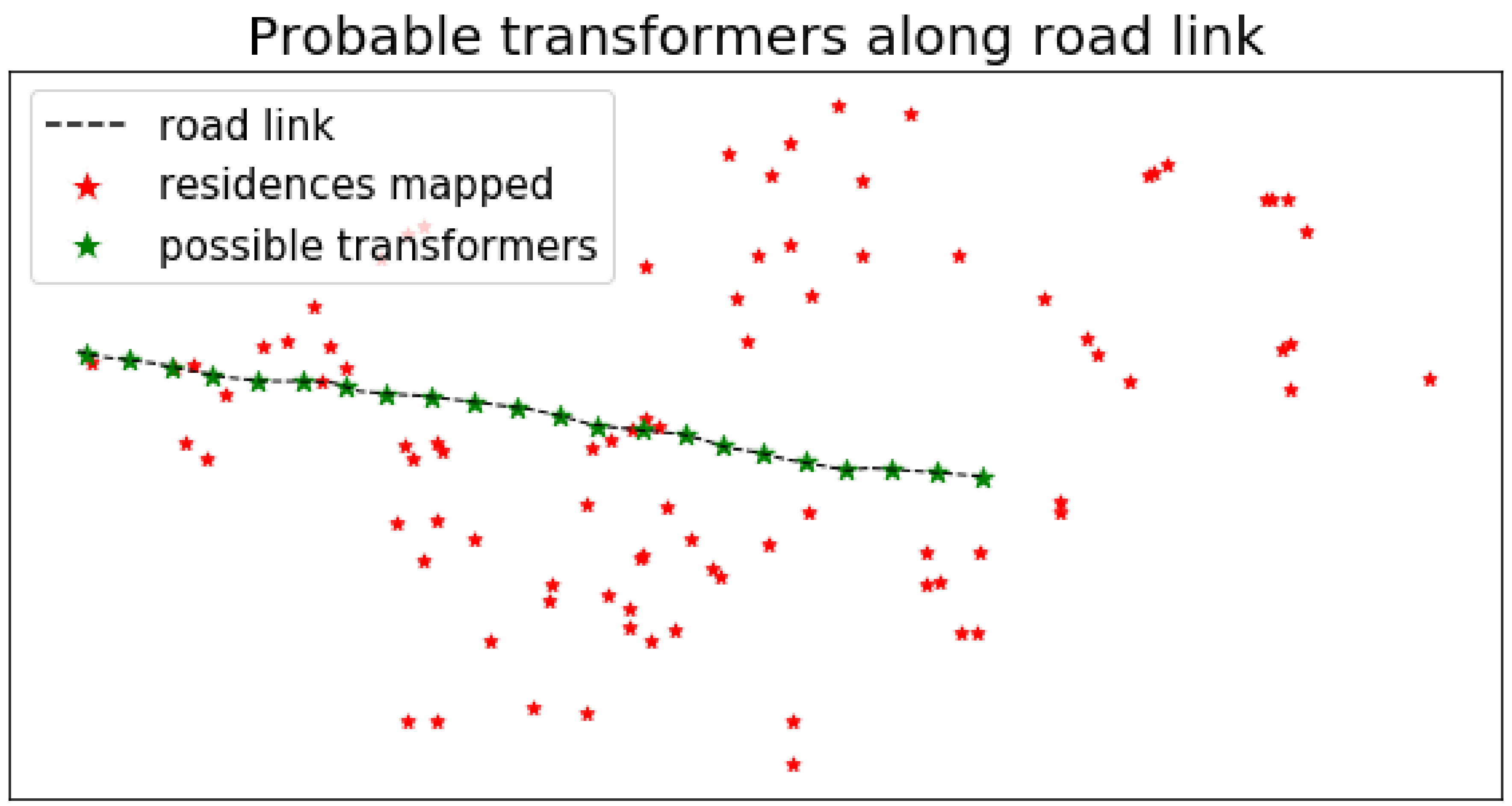
$$\begin{aligned} \min_{\mathbf{x}} \quad & \mathbf{w}^T \mathbf{x} \\ \text{s.to.} \quad & \deg(v) \leq 2, \ \forall v \in \mathcal{V}_H \\ & \mathbf{1}^T \mathbf{x} = |\mathcal{V}_H| \\ & \mathbf{A_H}^T \mathbf{f} = \mathbf{p} \\ & -\overline{f}\mathbf{x} \leq \mathbf{f} \leq \overline{f}\mathbf{x} \end{aligned}$$

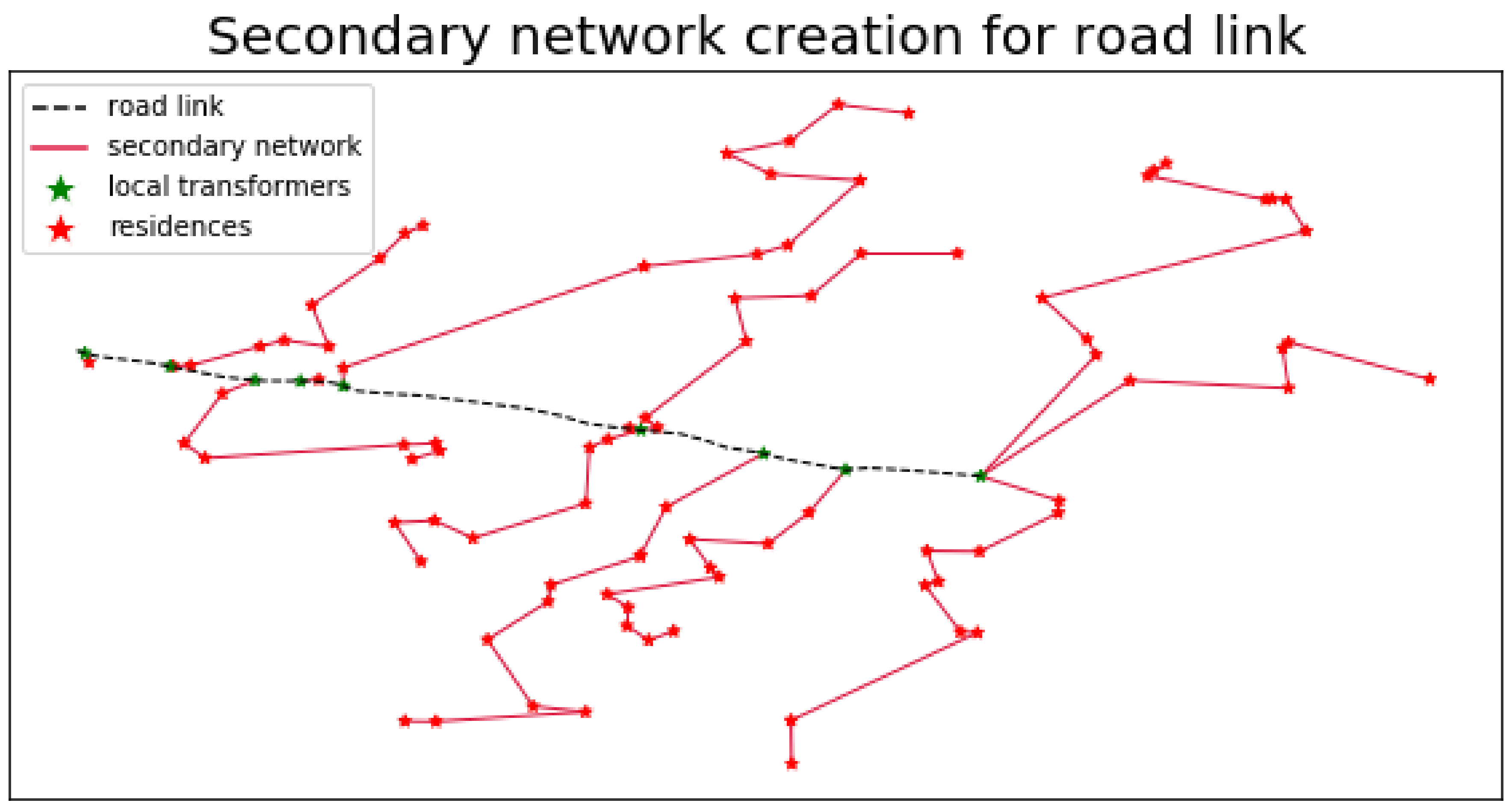
Induced graph is a forest of trees if there is no disconnected component of residence nodes

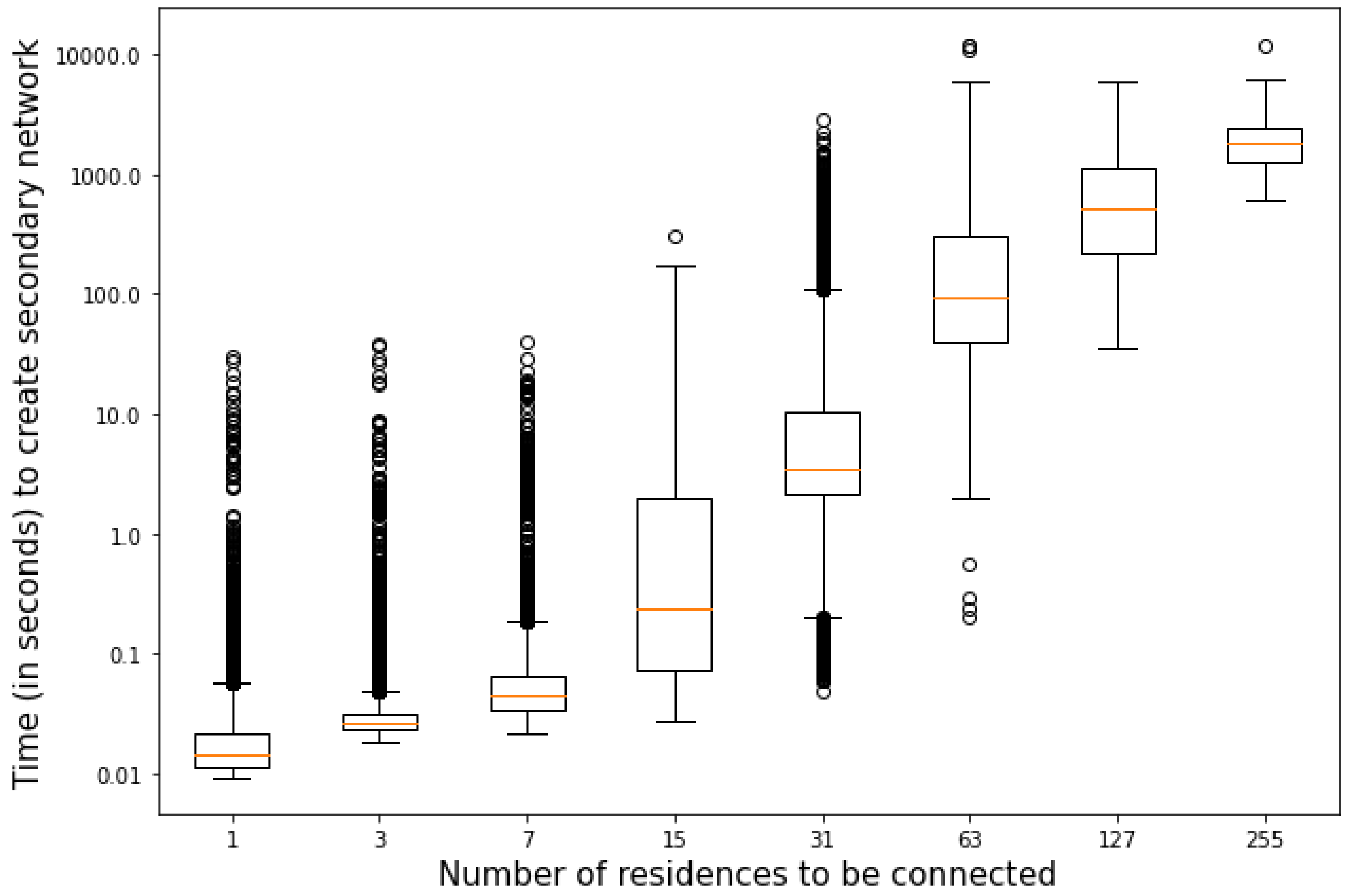
Proposition 1. *The graph $\mathcal{G}_D^\star(\mathcal{V}^\star, \mathcal{E}_D^\star)$ with reduced branch-bus incidence matrix $\mathbf{A_H}$ and node power demand vector $\mathbf{p} \in \mathbb{R}^{\mathcal{V}_H}$, with strictly positive entries, has exactly $|\mathcal{V}_T^\star|$ connected components if and only if there exists $\mathbf{f} \in \mathbb{R}^{|\mathcal{E}_D^\star|}$, such that $\mathbf{A_H}^T \mathbf{f} = \mathbf{p}$ is satisfied.*

Secondary Network Creation

Example of secondary network







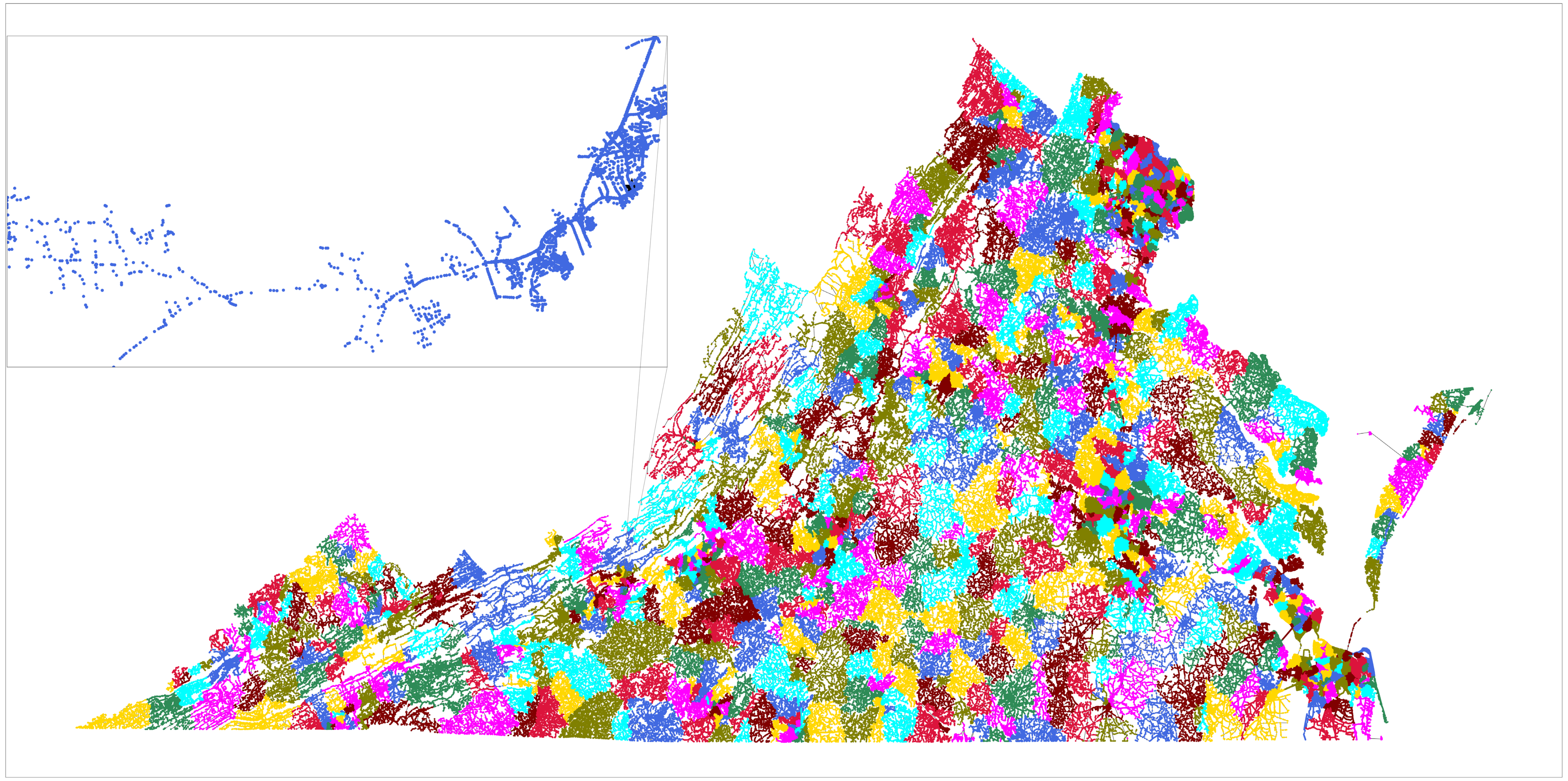
Factors affecting computation time

- Number of residences mapped to link
- Congestion of residences near link

Voronoi Partitioning

Motivation
Connect the local transformers to distribution substations using road links as proxy to construct the primary network.

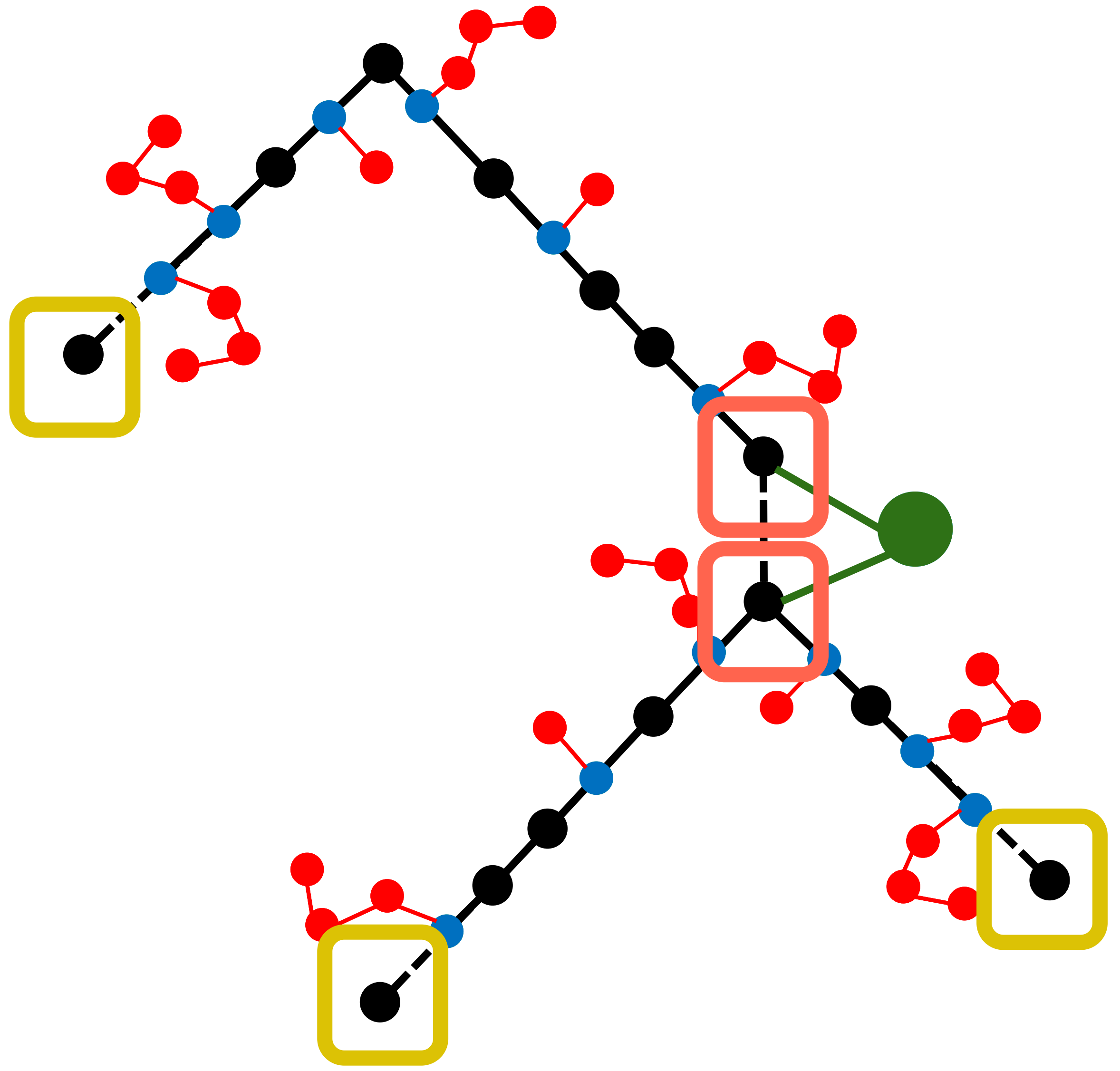
- Large number of local transformer and road nodes.
- Partition them into node groups of connected components.
- Two ways of partitioning
    - partition nodes to geographically nearest substation
    - partition nodes to nearest substation along road network

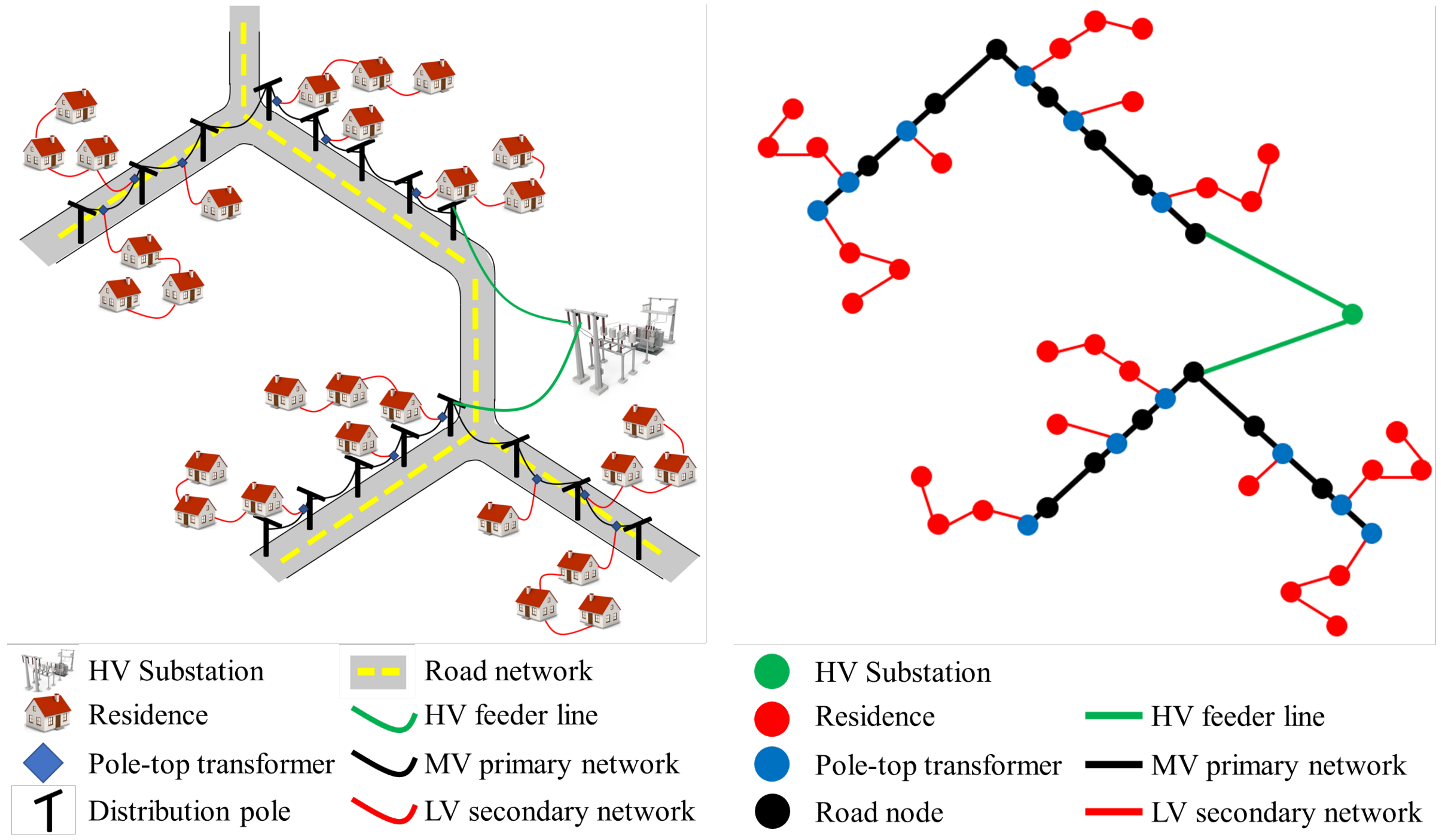


Primary Network Creation

Goal: Connect local transformers to substations

- forest of trees configuration
- minimum length network
- use road network as proxy
- some road nodes are root nodes
- road nodes cannot be leaf nodes





Undirected graph $\mathcal{G}_R(\mathcal{V}, \mathcal{E}_R)$

- node set: $\mathcal{V} = \mathcal{V}_R \cup \mathcal{V}_T$
- set of road nodes: $\mathcal{V}_R$
- probable transformers: $\mathcal{V}_T$
- candidate edge set $\mathcal{E}_R$

Optimal set

$\mathcal{E}_R^* \subseteq \mathcal{E}_R$

Induced subgraph $\mathcal{G}_R^*(\mathcal{V}^*, \mathcal{E}_R^*)$

- minimum network length
- node set: $\mathcal{V}^* = \mathcal{V}_T \cup \mathcal{V}_R^*$
- root nodes: $\mathcal{V}_{sR} \subseteq \mathcal{V}_R^* \subseteq \mathcal{V}_R$

Primary Network Creation

Variables

- $x_e \in \{0,1\}$: binary variable for $e \in \mathcal{E}_R$
- f_e: power flowing along edge $e \in \mathcal{E}_R$
- w_e: weight of edge $e \in \mathcal{E}_R$
- $y_r \in \{0,1\}$: binary variable for $r \in \mathcal{V}_R$
  - 0: road node not selected
  - 1: road node is selected
- $z_r \in \{0,1\}$: binary variable for $r \in \mathcal{V}_R$
  - 0: road node is root node
  - 1: road node is not root node
- p_v: power demand at node $v \in \mathcal{V}$
- v_v: voltage at node $v \in \mathcal{V}$
- d_r: distance of node $r \in \mathcal{V}_R$ from substation

Structural constraints

- unselected road node is not root ($y_r = 0, z_r = 1$).
- unselected road node ($y_r = 0$) has zero degree.
- selected non root road node ($y_r = 1, z_r = 1$) has degree of at least 2
- selected road node which is root ($y_r = 1, z_r = 1$) has positive degree.

$$1 - z_r \leq y_r$$

$$\sum_{e:(r,j)} x_e \leq |\mathcal{E}_R| y_r$$

$$\sum_{e:(r,j)} x_e \geq y_r$$

$$\sum_{e:(r,j)} x_e \geq 2(y_r + z_r - 1)$$

Power balance constraints

$$\mathbf{A_T}^T \mathbf{f} = \mathbf{p}$$

$$-\overline{s}(1 - \mathbf{z}) \leq \mathbf{A_R}^T \mathbf{f} \leq \overline{s}(1 - \mathbf{z})$$

$$-\overline{f}\mathbf{x} \leq \mathbf{f} \leq \overline{f}\mathbf{x}$$

Voltage constraints

$$(1 - v_r) \leq z_r \ \forall r \in \mathcal{V}_R$$

$$\underline{v}\mathbf{1} \leq \mathbf{v} \leq \overline{v}\mathbf{1}$$

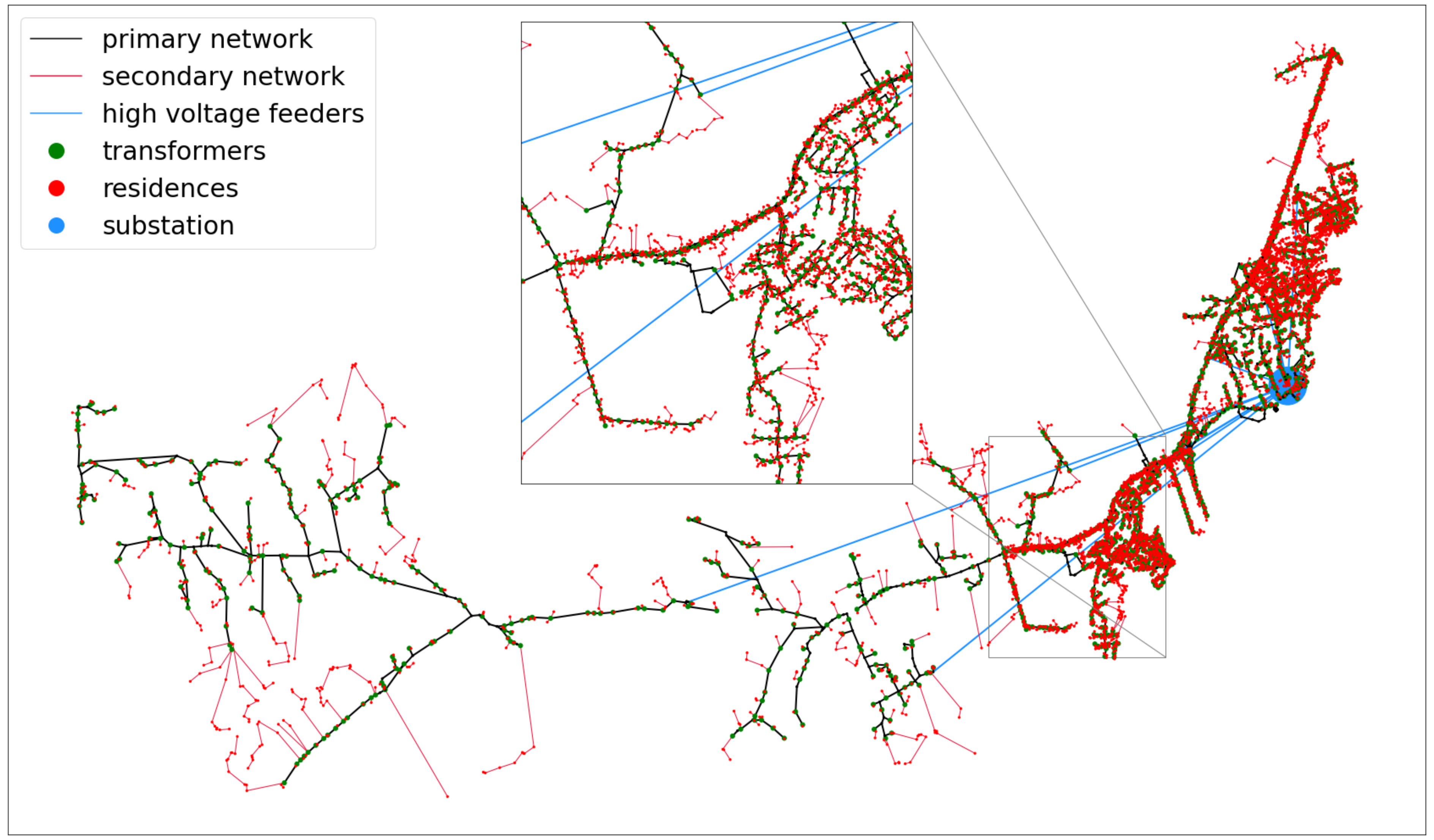
$$x_e(v_i - v_j - r_e f_e) = 0, \ \forall e \in \mathcal{E}_R$$

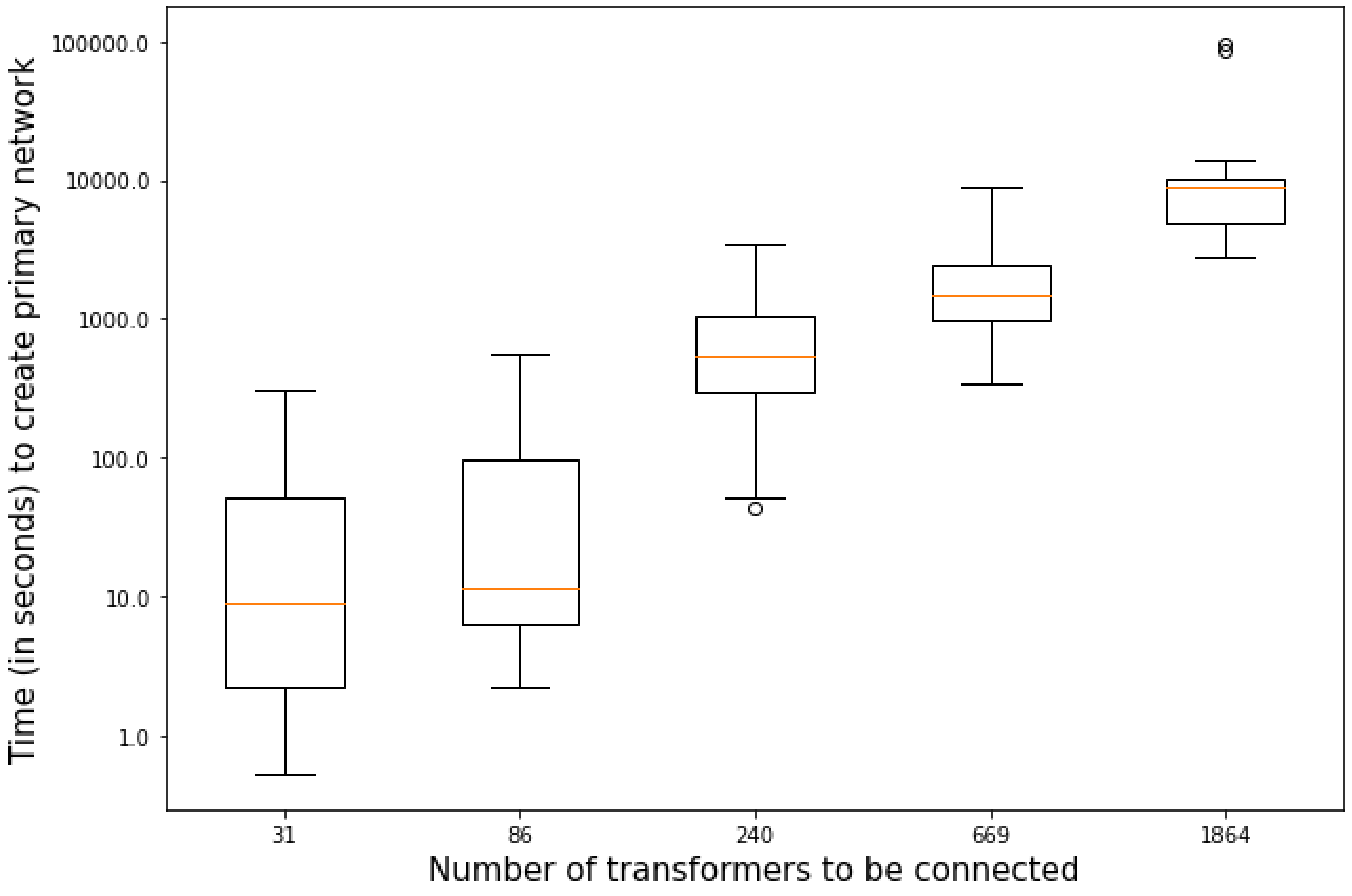
Forest of trees

$$\sum_{e \in \mathcal{E}_R} x_e = |\mathcal{V}_T| + \sum_{r \in \mathcal{V}_R} y_r - \sum_{r \in \mathcal{V}_R} (1 - z_r)$$

Objective function $\min_{\mathbf{x},\mathbf{y},\mathbf{z}} \sum_{e \in \mathcal{E}_R} x_e w_e + \sum_{e \in \mathcal{V}_R} (1 - z_r) d_r$

Primary Network Creation

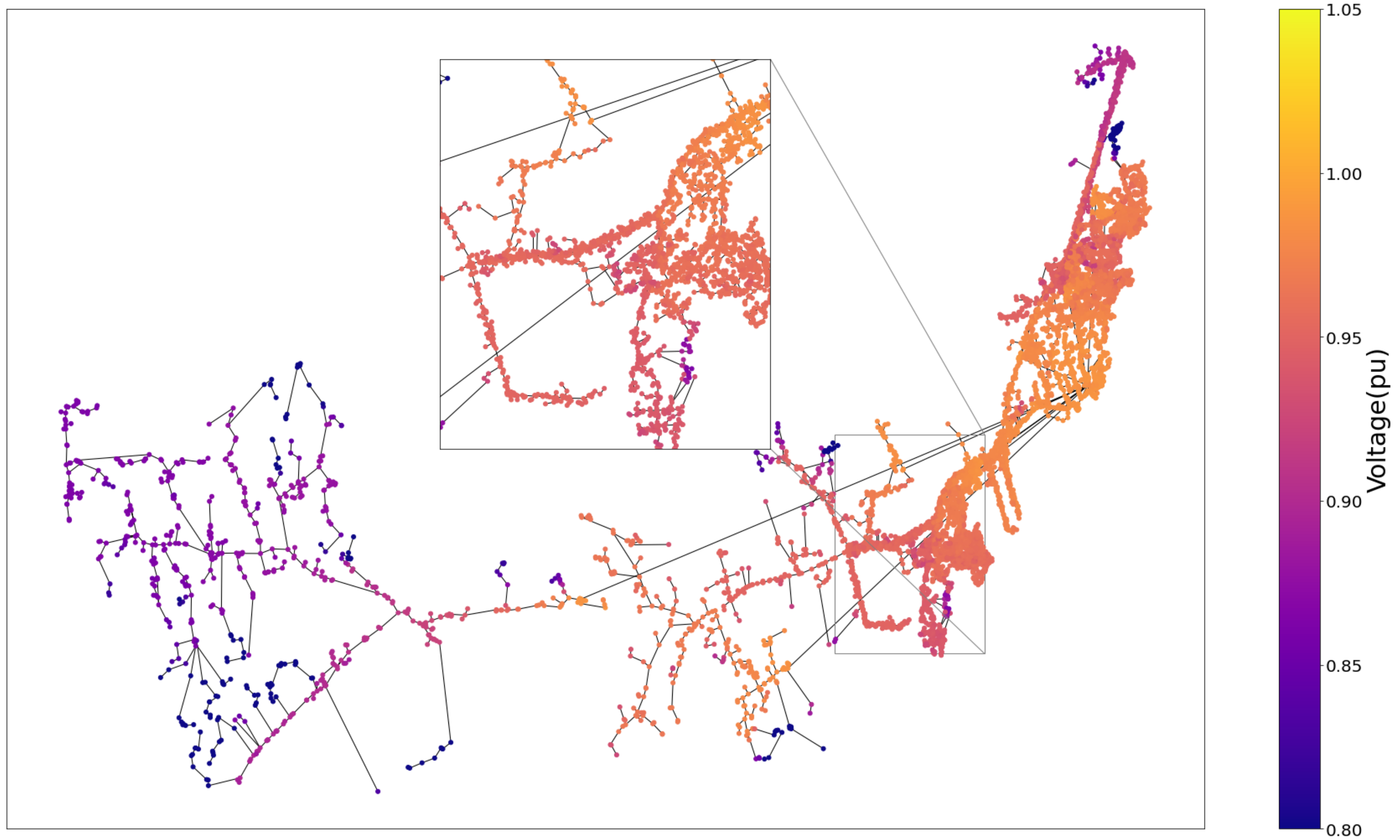


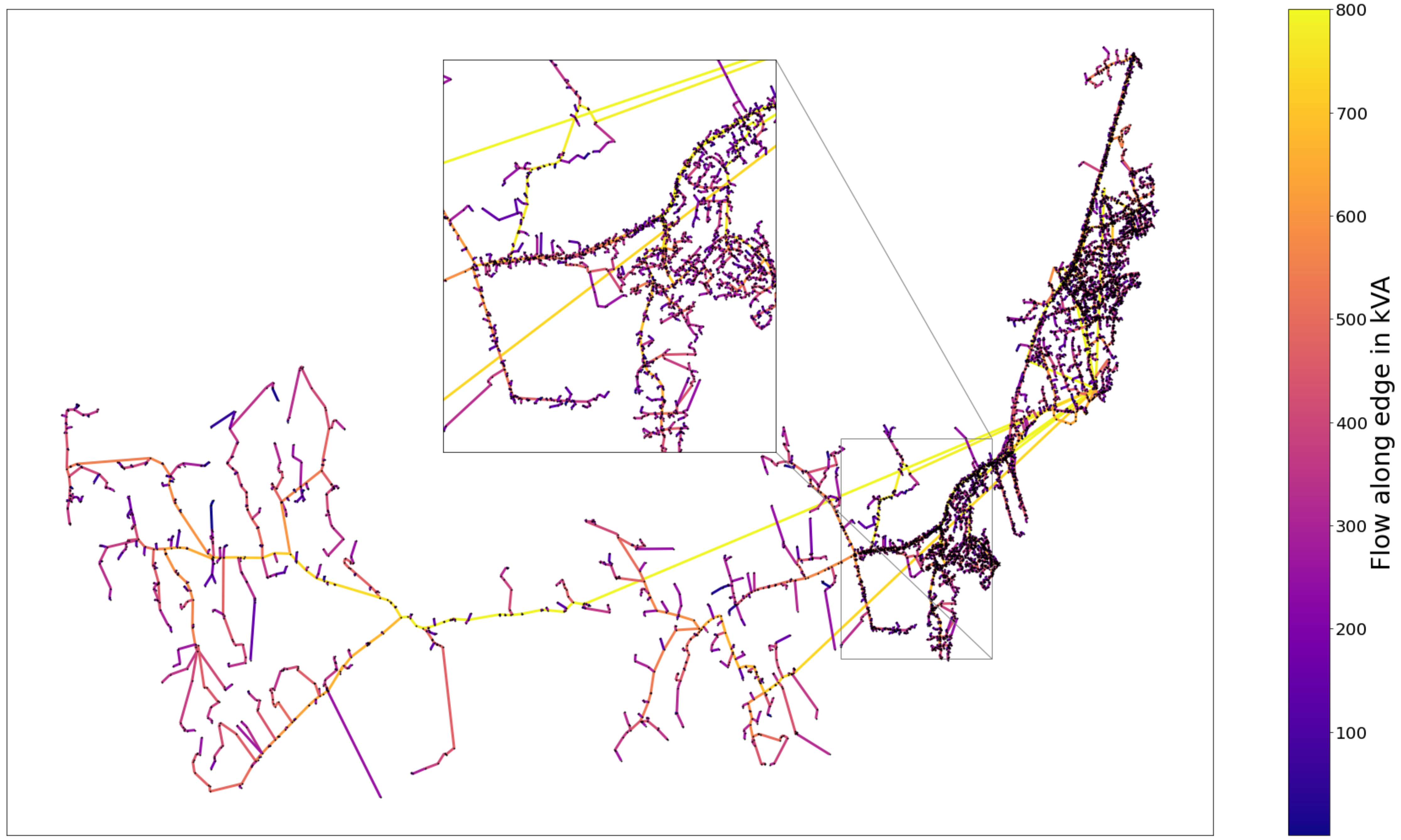


Factors affecting computation time

- Number of transformers in partition
- Feeder rating constraints

Validation and Verification

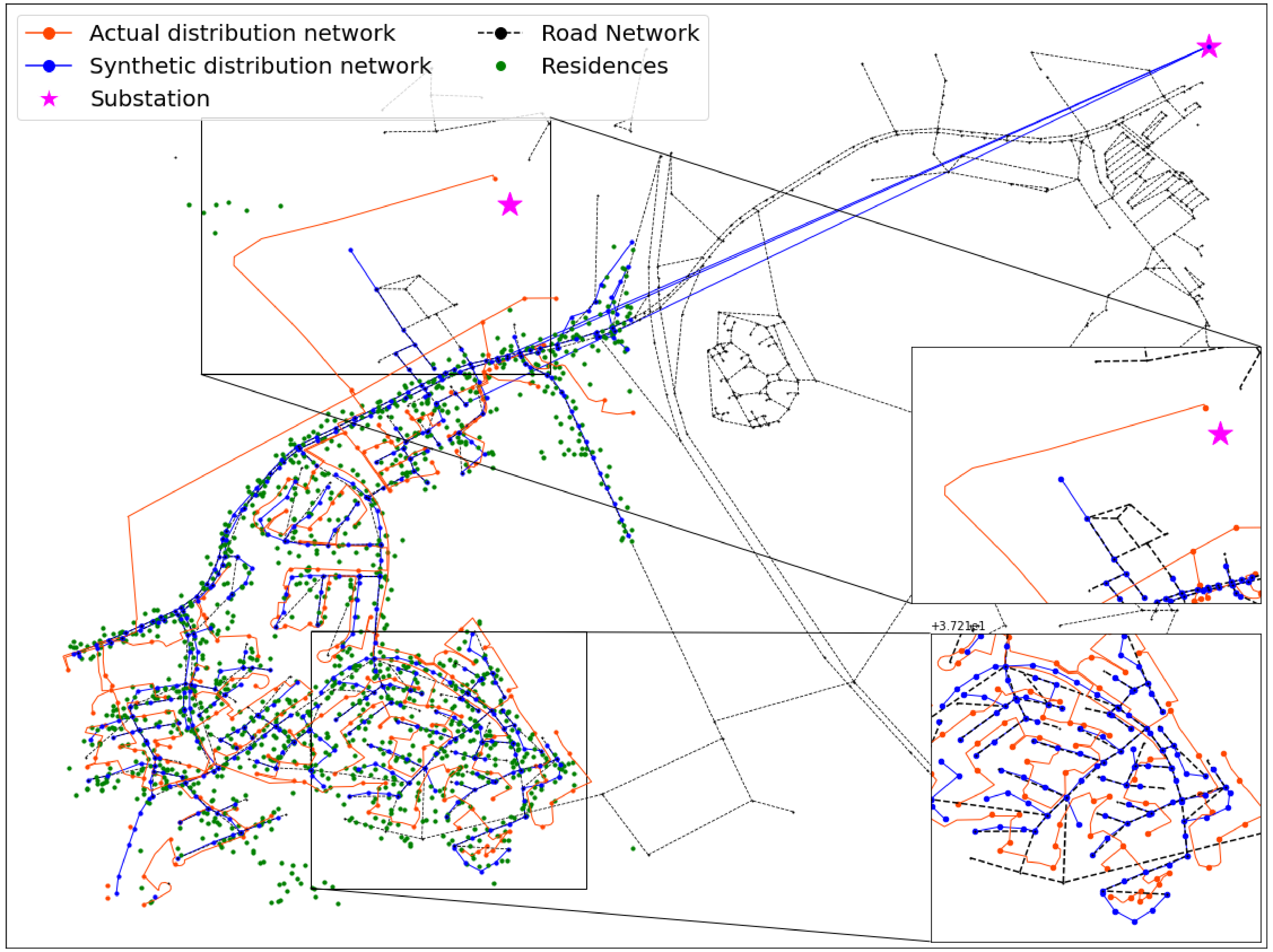


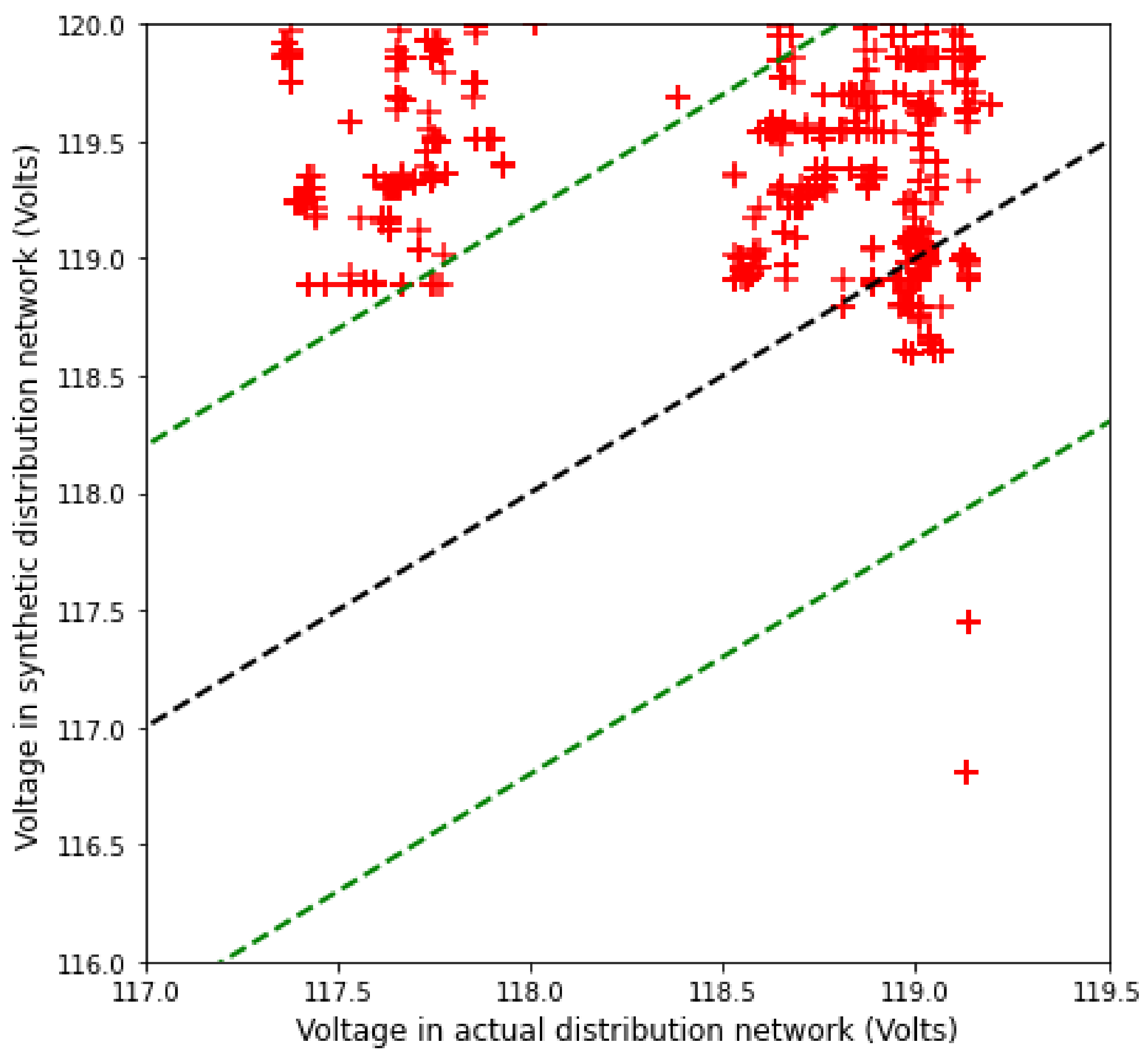


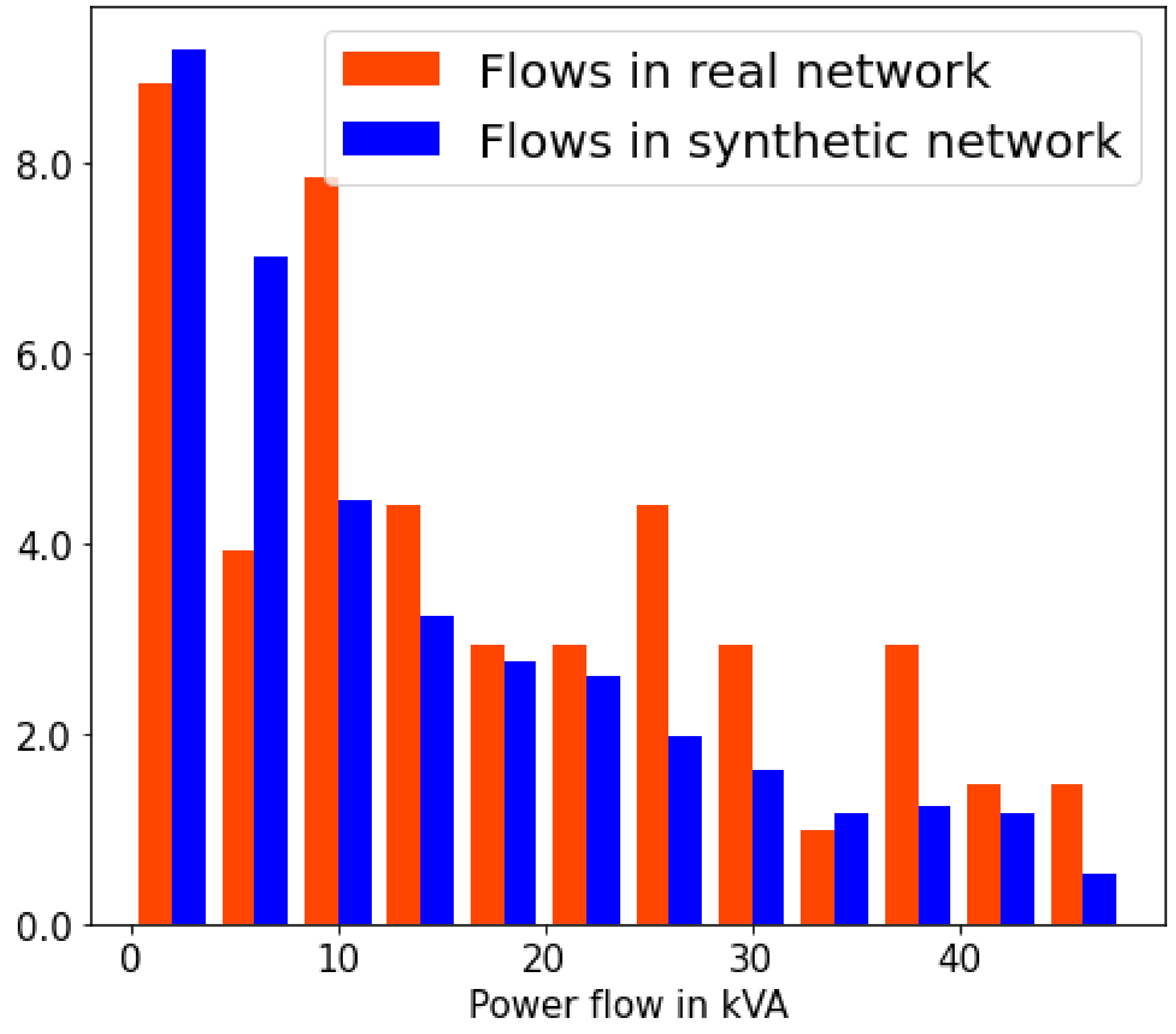
Operational Validation

- Node voltages are shown in per unit.
- Voltages at nodes are within ANSI C84.1 standards.
- Voltages at leaf nodes can be improved by capacitor installments.
- Flows near the residences are small and for feeders are high.

Validation and Verification







Structural comparison

- Both the networks follow the road network.
- Geographically nearest substation feeds actual network.
- Nearest substation along road network feeds synthetic network.

Comparison with actual network

- Node voltages are almost similar and within ANSI C84.1 standards of $\pm 5\%$ voltage regulation.
- Flow distribution in actual and synthetic networks are almost similar.

Conclusion

Summary

- Realistic distribution network of a given geographic region is generated.
- The generated network is specific to the geography of the region.
- Individual residences are connected in the created synthetic network.

Future Work

- Generate ensemble of synthetic networks.
- Create redundancies by introducing tie switches and sectionalizers.
- Use additional open-source information to create more realistic networks.
  - Building data
  - Electrified/unelectrified area data
  - Land usage data
  - Original network data

QUESTIONS?