**Introduction**

- Modern sensors that deliver fine-grained data are becoming increasingly available to assist power engineering applications.
- Power outage detection and estimation, arguably the most critical application, can benefit from insights drawn from such data.
- The grid is a highly complex system where several cyber-physical features define an exponentially large number of grid states for which there might not be data available to learn all possible outage scenarios.

**Detection Problem**

- **GOAL**: Identify and localize power line failures (edge disconnections) using PMU data collected at power buses (nodes).
- No direct edge status is available.
- Not all possible failures have been seen in the past.
- Learning all possible failures would be too expensive.
- Normal operations data lie on a low-dimensional subspace.
- Under a specific failure scenario data points also lie in a low-dimensional space.
- Failure subspaces are formed using historical data.
- Using $V^T$ subspaces are: $S^0 \subseteq \mathcal{E} \setminus \mathcal{L}_j$
- In a graph $\mathcal{P}(X, \mathcal{E})$ we learn $|\mathcal{E}|$ single-line failure scenarios, i.e. edge subspaces, with $|\mathcal{E}| \ll 2^{|\mathcal{E}|}$
- Using edge subspaces we create node subspaces.
- Node subspaces represent "any" failure.

**Methodology**

- Normal operations data lie on a low-dimensional subspace:

\[ X = U \Sigma V^T \]

- Learn subspaces
- Redefine subspaces
- According to event sources
- According to data sources

- Data-driven detection adds another cyber-physical dependability
- Data can be missing due to:
  - Equipment malfunction
  - Cyber attacks
  - Communication issues

**What about missing data?**

- "Separate" data sources according to their detection performance, identify critical nodes.
- Recommend data redundancy for critical nodes.
- For a data cluster $C$ (with nodes $i \in C$):
  - $D_C(C)$ \rightarrow detection nodes $k$, for $C$, belong to $C$.
  - $D_C(C)$ \rightarrow detection nodes $k$, for $C$, don’t belong to $C$.
- Detection nodes: using $p_i$ for all $i \in C$

**Discussion and Future work**

- Based on distances to (node) subspaces "any" failure can potentially be detected, as more complex failures lie on the union of a subset of the $|\mathcal{E}|$ single-line failure scenarios.

<table>
<thead>
<tr>
<th>Method</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log Reg (OVR) (Simple)</td>
<td>98.4%</td>
</tr>
<tr>
<td>Log Reg (OVR) (Multiple)</td>
<td>23.6%</td>
</tr>
<tr>
<td>Subspace (Single)</td>
<td>97.5%</td>
</tr>
<tr>
<td>Subspace (Multiple)</td>
<td>73.8%</td>
</tr>
<tr>
<td>Subspace (Geo-Correlated)</td>
<td>87.3%</td>
</tr>
</tbody>
</table>

Using a subset of data sources high detection accuracy can be achieved (under realistic data failures). Extreme cases of missing data lead to higher detection errors.