Real Time Outage Detection from Utility Big Data

David Rieken, D.Sc.
Aclara Technologies
Research and Advanced Product Development
Overview

• About Aclara
• Fault Detection & Localization Product
• Example Detections
Who We Serve

- Serving 780+ Utilities - 40 of the largest in 24 countries
- 27 Million AMI and 71 Million Meter endpoints with billion+ readings per day
- 99% Customer Loyalty
- Comprehensive Solutions Suite
- 6 Million Customers Actively Engaged
Who We Serve
Aclara’s Continued Expansion

Meters
- The acquisition of GE Meters combines Aclara’s industry leading AMI technology with GE Meters' 130 years of operating experience, technology development and commercial expertise
- Enables accelerated development and delivery of advanced smart infrastructure solutions by leveraging AMI-Meter technology roadmaps

SGS
- Acquisition of Smart Grid Solutions specializing in software enabled installation and maintenance services
- Improves the safety, quality, and efficiency of customer smart grid initiatives

Lighthouse
- Expands capabilities in distribution grid monitoring

2014
An affiliate of Sun Capital Partners acquired Aclara from ESCO
Electric Utility Experience

**ComEd**
- 4.1 million meters
- 11,400 square miles of coverage
- Satellite manufacturing facility in Chicago, IL will generate local production

**Florida Power & Light**
- 5 million meters
- 1 million load control devices (2GW)
- 20+ years of partnership

**Scottish Power**
- Renewable management and load monitoring
- Accelerating Renewable Connection (ARC) IFI Project

**Puerto Rico Electric Power Authority**
- 1.5 million endpoints
- Business partner for more than 15 years
Aclara Solutions Portfolio
AMI - Unified System

- Head-end unifies Aclara’s communication technologies
  - TWACS Power Line
  - RF – Electric/Water
  - Metrum Cellular

- Providing maximum flexibility to meet Smart Grid and AMI requirements

- Migratable - accommodates evolution of AMI technology use

- Optimize a solution – the best-suited technologies for the application
Electric Smart Infrastructure

- Distribution Automation
- Energy Balance
- Active Locational Sensing/Phasor Measurement
- Locational Alerts and Troubleshooting
- Volt-VAR Optimization
- Distributed Energy Resources
- Demand Response
- Fixed Load Control
- Outage Detection
- Transformer Monitoring
- Distributed Energy Resources
Fault Detection and Localization

“Automatically display outages, determine fault locations and verify restorations in record time”
Algorithm Architecture

Analytic Engine (AE/Freya) ➔ Data ➔ Sensor array
• TWACS Meters ➔ Distribution Network

Ping Strategy ➔ state ➔ Select devices to interrogate
Network state

Sensor data are collected on nodes and edges

\[
\mathbf{X} \equiv \{x(v) \forall v \in V\}
\]

\[
\Theta \equiv \{\theta(e) \forall e \in E\}.
\]

\[
\theta : E \rightarrow \{0, 1\}
\]

\[
\theta(e) \mapsto \begin{cases} 
0 & \text{edge } e \text{ is faulted} \\
1 & \text{edge } e \text{ is not faulted.}
\end{cases}
\]

\[
x : V \rightarrow \{0, 1\}
\]

\[
x(v) \mapsto \begin{cases} 
0 & \text{node } v \text{ is not powered} \\
1 & \text{node } v \text{ is powered}
\end{cases}
\]
Sensor data

We are given data

$$D = \{d(v) : v \in V\} \cup \{d(e) : e \in E\}$$

which are independent measurements made at some or all nodes or edges. The data must satisfy

$$p(D|X, \Theta) = \prod_{e \in E} p(d(e)|\theta(e)) \prod_{v \in V} p(d(v)|x(v)).$$
Problem statement

Calculate the MMSE estimates:

\[ \hat{x}(v) = \sum_{x(v)} x(v)p(x(v)|D) = p(x(v) = 1|D) \]

\[ \hat{\theta}(e) = \sum_{\theta(e)} \theta(e)p(\theta(e)|D) = p(\theta(e) = 1|D) \]

and the MAP estimate:

\[ (\hat{X}, \hat{\Theta}) = \arg \max_{X, \Theta} p(X, \Theta|D). \]
Node/Edge Displayed State

MAP $\geq 0.5$
MMSE $\geq \epsilon$

MAP $< 0.5$
MMSE $< \epsilon$

MAP $\geq 0.5$
MMSE $\leq 0.5$

MAP $\leq 0.5$
MMSE $\leq \epsilon$

Very Likely Unpowered

Very Likely Powered

Uncertain

Applied to every node and edge independently.
## TWACS communications/TNS

<table>
<thead>
<tr>
<th></th>
<th>AMI</th>
<th>Link-level ping</th>
<th>Fast poll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inbound length</td>
<td>10-20 bytes</td>
<td>3 bytes</td>
<td>1 byte</td>
</tr>
<tr>
<td>Duration</td>
<td>~10 sec</td>
<td>1.5 seconds</td>
<td>0.5 seconds</td>
</tr>
<tr>
<td>Probability of responding when powered ($P_D$)</td>
<td>Moderate</td>
<td>High</td>
<td>Not as high as you might think!</td>
</tr>
<tr>
<td>Probability of responding when unpowered ($P_{FA}$)</td>
<td>Virtually Zero</td>
<td>Very low</td>
<td>Not as low as you might think!</td>
</tr>
</tbody>
</table>

$$
\phi = \ln \left( \frac{P_D}{P_{FA}} \right) \\
\phi = \ln \left( \frac{1 - P_D}{1 - P_{FA}} \right)
$$

Successful transactions

Unsuccessful transactions
Naïve sensor model

\[ p(d(v) = 0|x(v) = 0) = 1 - P_{FA} \]
\[ p(d(v) = 1|x(v) = 0) = P_{FA} \]
\[ p(d(v) = 0|x(v) = 1) = 1 - P_D \]
\[ p(d(v) = 1|x(v) = 1) = P_D \]

\[ \sum_{n=1}^{N} d(v_n)|x(v_n) = 1) \sim B(n, P_D) \]

<table>
<thead>
<tr>
<th>Exchanges</th>
<th>72052</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{FA})</td>
<td>N/A</td>
</tr>
<tr>
<td>(P_D)</td>
<td>0.94</td>
</tr>
</tbody>
</table>
Less naïve sensor model

Transactions within a single exchange are jointly distributed:

\[ P(d(v_1), \ldots, d(v_N)|x(v_1), \ldots, x(v_N)) = P(d(v_1), \ldots, d(v_N)|x(v_1), \ldots, x(v_N), y = 1)P_y + \]
\[ P(d(v_1), \ldots, d(v_N)|x(v_1), \ldots, x(v_N), y = 0)(1 - P_y) \]
\[ = P_y \prod_{n=1}^{N} p(d(v_n)|x(v_n), y = 1) + (1 - P_y) \prod_{n=1}^{N} p(d(v_n)|x(v_n), y = 0) \]

<table>
<thead>
<tr>
<th>if y=0</th>
<th>d(v)=0</th>
<th>d(v)=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>x(v)=0</td>
<td>1-P_{FA}</td>
<td>P_{FA}</td>
</tr>
<tr>
<td>x(v)=1</td>
<td>1-P_{D}</td>
<td>P_{D}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>if y=1</th>
<th>d(v)=0</th>
<th>d(v)=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>x(v)=0</td>
<td>1-P_{FA}</td>
<td>P_{FA}</td>
</tr>
<tr>
<td>x(v)=1</td>
<td>1-P_{e}</td>
<td>P_{e}</td>
</tr>
</tbody>
</table>
Less naïve sensor model

Successful transactions in an exchange:

\[ D \equiv \sum_{n=1}^{N} d(v_n)|x(v_n) = 1) \]

\[ \implies D \sim P_y B(n, P_D) + (1 - P_y) B(n, P_e) \]

<table>
<thead>
<tr>
<th>Exchanges</th>
<th>72052</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{FA})</td>
<td>N/A</td>
</tr>
<tr>
<td>(P_D)</td>
<td>0.99</td>
</tr>
<tr>
<td>(P_Y)</td>
<td>0.058</td>
</tr>
<tr>
<td>(P_e)</td>
<td>0.061</td>
</tr>
</tbody>
</table>
Dynamic networks

Problem: The network state is not constant. We must redefine the network state variables and data as functions of time:

\[ x : V \times \mathbb{R} \rightarrow S_x \]
\[ \theta : E \times \mathbb{R} \rightarrow S_\theta \]
\[ \mathbf{X}(t) = \{x(v, t) : v \in V\} \]
\[ \Theta(t) = \{\theta(e, t) : e \in E\} \]
\[ \Gamma(t) \equiv \mathbf{X}(t), \Theta(t) \]
\[ D(t) = \{d(v, t) : v \in V\} \cup \{d(e, t) : e \in E\} \]

The problem now is to estimate

\[ p(\Gamma(t_N), \ldots, \Gamma(t_1)|D(t_N), \ldots, D(t_1)) \]
Hidden Markov models

One approach is to model the state as a Markov random process:

\[ p(\Gamma(t_N)|\Gamma(t_{N-1}), \ldots, \Gamma(t_1)) = p(\Gamma(t_N)|\Gamma(t_{N-1})) \]

Then,

\[ p(\Gamma(t_N), \ldots, \Gamma(t_1)|D(t_N), \ldots, D(t_1)) \propto p(D(t_N), \ldots, D(t_1)|\Gamma(t_N), \ldots, \Gamma(t_1)) \]
\[ \times p(\Gamma(t_N), \ldots, \Gamma(t_1)) \]
\[ = p(\Gamma(t_1)) \prod_{n=1}^{N} p(D(t_n)|\Gamma(t_n))p(\Gamma(t_n)|\Gamma(t_{n-1})) \]
\[ = p(X(t_1), \Theta(t_1)) \prod_{n} p(X(t_n), \Theta(t_n)|X(t_{n-1}, \Theta(t_{n-1}))) \]
\[ \times \prod_{e \in E} \prod_{v \in V} p(d(e, t_n)|\theta(e, t_n))p(d(v, t_n)|x(v, t_n)) \]
Hidden Markov models

The network state term can be factored

\[ p(X(t_n), \Theta(t_n)|X(t_{n-1}), \Theta(t_{n-1})) = p(X(t_n)|\Theta(t_n), X(t_{n-1}), \Theta(t_{n-1}))p(\Theta(t_n)|X(t_{n-1}), \Theta(t_{n-1})). \]

For fault detection it is true that

\[ X(t) = f(\Theta(t)). \]

Therefore, for fault detection

\[ p(X(t_n), \Theta(t_n)|X(t_{n-1}), \Theta(t_{n-1})) = p(X(t_n)|\Theta(t_n))p(\Theta(t_n)|\Theta(t_{n-1})). \]

Thus having dynamic states introduces a new term to the factor graph.
Example: Single-variable state
Ping strategy

Henceforth, we will use the complete network state vector

\[ \Gamma \equiv \{X, \Theta\}. \]

Find a subset of nodes, \( V^O \subset V \), such that

\[ H(\Gamma | d(v) \forall v \in V^O) \]

is minimized.

\[ H(\Gamma | d(v) \forall v \in V^O) = H(\Gamma) - I(\Gamma; d(v) \forall v \in V^O) \]

Equivalently, find \( V^O \subset V \) such that

\[ I(\Gamma; d(v) \forall v \in V^O) \]

is maximized.
Ping selection
Ping selection
Ping selection
Example 1: Overnight detection
Example 2: Vacation home outage
Closing Remarks

• Product launch later this year
• Presently running 24/7 at two co-ops
• Over ten more awaiting product launch