Data Delivery Mechanisms and Issues for Wide Area Measurement Systems (WAMS)

Prof. Dave Bakken
School of Electrical Engineering and Computer Science
Washington State University
Pullman, Washington, USA

PSERC Webinar
October 4, 2011
Overview of Presentation

• Introduction
• Emerging Power Applications
• Implementation Issues for WAMS Data Delivery (WAMS-DD)
• NASPI and NASPInet
• GridStat

Lots to cover, not in full detail in every area!
Background: Applied Computer Scientist

• Work in “distributed computing”, above the network layer
  – Not a power engineer!

• Working closely with Prof. Anjan Bose for 13 years.
  – “How can distributed computing (and computer networking and real-time computing) help improve communications for the bulk power grid?”
  – Also Mani Venkatasubramanian (power), Carl Hauser (distributed computing)

• 1990s at research lab BBN working on wide-area data delivery for DARPA

• Worked for Boeing, consulted to Amazon.com, etc.
Better Communications are Needed

• Grids are getting more stressed each year
  “With the exception of the initial power equipment problems in the August 14, 2003 blackout [in North America], the on-going and cascading failures were almost exclusively due to problems in providing the right information to the right place within the right time.”
  Francis Cleveland, 2007

• Inadequate communications major contributing factor in recent major blackouts

• Other challenges for the bulk power system
  – Growth in generation and load far more than transmission capacity growth (in North America)
  – Integrating renewable sources of energy
  – Distributed control
  – Retiring operators (in North America)

• All can be mitigated by better communications
Interoperability (“universal connectivity”) is key

In order to create this new power delivery system, what is needed is a national electricity-communications superhighway .... The ultimate challenge in creating the power delivery system of the 21st century is in the development of a communications infrastructure that allows for universal connectivity.

Clark Gellings, US EPRI, 2003 (emphasis is mine)

This interoperability (“universal connectivity”) can only be achieved at the data/middleware layer, not the network layer

— See our Grid-Interop 2009 paper for more (details at end)
Overview of Presentation

• Introduction
• **Emerging Power Applications**
• Implementation Issues for WAMS Data Delivery (WAMS-DD)
• NASPI and NASPInet
• GridStat
Wide Range of QoS+ Requirements

• QoS+:
  – network/middleware “QoS” (latency, rate), availability/criticality
  – Also things an implementer/deployer of WAMS-DD needs to know: geographic scope, quantity.

• Comparing Apples and Apples:
  – Normalize each from 1 (very easy) to 5 (very hard)

• Wide ranges
  – Across application families
  – Sometimes within them (each configuration is different)
### Normalized Values of QoS+ Parameters

<table>
<thead>
<tr>
<th>Difficulty (5: hardest)</th>
<th>Latency (msec)</th>
<th>Rate (Hz)</th>
<th>Criticality</th>
<th>Quantity</th>
<th>Geography</th>
<th>Deadline (for Bulk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5–20</td>
<td>240–720+</td>
<td>Ultra</td>
<td>Very High</td>
<td>Across grid or multiple ISOs</td>
<td>&lt;5 sec.</td>
</tr>
<tr>
<td>4</td>
<td>20–50</td>
<td>120–240</td>
<td>High</td>
<td>High</td>
<td>Within an ISO/ RTO</td>
<td>1 min.</td>
</tr>
<tr>
<td>3</td>
<td>50–100</td>
<td>30–120</td>
<td>Medium</td>
<td>Medium</td>
<td>Between a few utilities</td>
<td>1 hr.</td>
</tr>
<tr>
<td>2</td>
<td>100–1000</td>
<td>1–30</td>
<td>Low</td>
<td>Low</td>
<td>Within a single utility</td>
<td>1 day</td>
</tr>
<tr>
<td>1</td>
<td>&gt;1000</td>
<td>&lt;1</td>
<td>Very Low</td>
<td>Very Low (serial)</td>
<td>Within a substation</td>
<td>&gt;1 day</td>
</tr>
</tbody>
</table>

Also what kind of msgs (both I/O): streaming, condition-based, bulk; person or computer in loop
Applications (ProciEEE Section & NASPIInet Class)

1. Traditional State Estimation (III.A)
2. Direct State Measurement (III.A & NASPIInet Class B)
3. Operator Displays (III.B & NASPIInet Class D)
4. Catch Up For Operator Displays (III.B)
5. Distributed Wide-Area Control (NASPIInet Class A)
6. Distributed SIPS (III.C & NASPIInet Class A)
7. Synchronous Distributed Control (III.C & NASPIInet Class A)
8. Renewable Generation Islanding Control
9. Transient Stability (III.C & NASPIInet Class A)
10. Ancillary Services (III.C & NASPIInet Class A)
11. Automated Contingency Drill-Down (III.D & NASPIInet Class D, sort of)
12. Post-Event Analysis (III.E & NASPIInet Class C)
13. Research Traffic (III.F & NASPIInet Class E)

Notes

- This normalized parameterization can be considered a (significant) refinement of the original NASPIInet traffic categories
- Can’t go through following tables in great detail due to time

**Bottom line: Wide range of QoS+ requirements; not “one size fits all”**
### Most Difficult Input for Each App

<table>
<thead>
<tr>
<th>App</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop Entity</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>Kind</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>Co</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>Co</td>
<td>Co</td>
<td></td>
</tr>
<tr>
<td>Lat.</td>
<td>1–2</td>
<td>1–2</td>
<td>1</td>
<td>1</td>
<td>2–4</td>
<td>4–5</td>
<td>2–4</td>
<td>2-3</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Rate</td>
<td>1–2</td>
<td>1–2</td>
<td>2–3</td>
<td>—</td>
<td>2–3</td>
<td>5</td>
<td>1-2</td>
<td>2–3</td>
<td>—</td>
<td>—</td>
<td>2–3</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Crit</td>
<td>1-5</td>
<td>1-5</td>
<td>1-5</td>
<td>1–2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4-5</td>
<td>5</td>
<td>1–3</td>
<td>5</td>
<td>1-5</td>
<td>1-5</td>
</tr>
<tr>
<td>Quan</td>
<td>3–5</td>
<td>1–2</td>
<td>3–5</td>
<td>1–2</td>
<td>3–5</td>
<td>2–4</td>
<td>1-3</td>
<td>1-3</td>
<td>1–2</td>
<td>1–5</td>
<td>3–5</td>
<td>5</td>
<td>1-5</td>
</tr>
<tr>
<td>Geog</td>
<td>5</td>
<td>1-5</td>
<td>5</td>
<td>5</td>
<td>1–5</td>
<td>1–5</td>
<td>1–5</td>
<td>2-3</td>
<td>4-5</td>
<td>3–5</td>
<td>3–4</td>
<td>3–5</td>
<td>3–5</td>
</tr>
<tr>
<td>Dline</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2–3</td>
<td>1</td>
</tr>
</tbody>
</table>

Notice: **very wide range** of parameters

- ....... And this is just for applications conceived today, let alone the 30+ year expected lifetime of NASPInet
# Most Difficult Output for Each App

<table>
<thead>
<tr>
<th>App</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loop</strong></td>
<td><strong>Entity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td><strong>Kind</strong></td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>Bu</td>
<td>Co</td>
<td>Co</td>
<td>Co</td>
<td>Co</td>
<td>Co</td>
<td>SS</td>
<td>SS</td>
<td>Bu</td>
<td>Bu</td>
</tr>
<tr>
<td>1–2</td>
<td>1–2</td>
<td>1</td>
<td>—</td>
<td>3–5</td>
<td>5</td>
<td>3–5</td>
<td>3–5</td>
<td>5</td>
<td>1–2</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td><strong>Rate</strong></td>
<td>1–2</td>
<td>1–2</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1–2</td>
<td>2–3+</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Crit</strong></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1–2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1–3</td>
<td>5</td>
<td>1–2?</td>
<td>1</td>
</tr>
<tr>
<td><strong>Quan</strong></td>
<td>3–5</td>
<td>1–2</td>
<td>1</td>
<td>2–4</td>
<td>1–2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3–5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Geog</strong></td>
<td>1–2+</td>
<td>1–3+</td>
<td>1</td>
<td>1–2+</td>
<td>1–5</td>
<td>1–5</td>
<td>1–5</td>
<td>2–3</td>
<td>3–5</td>
<td>2</td>
<td>3–4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Dline</strong></td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2–3</td>
<td>1</td>
</tr>
</tbody>
</table>

Notice: **very wide range** of parameters

- ....... And this is just for applications conceived today, let alone the 30+ year expected lifetime of NASPInet
Overview of Presentation

• Introduction
• Emerging Power Applications
• Implementation Issues for WAMS Data Delivery (WAMS-DD)
• NASPI and NASPInet
• GridStat
QoS Requirements

- **Latency**
  - 4 ms within substation, 8-12+

- **Rate** (1/minute to 250/second)

- **Availability of Data** (EPRI IntelliGrid 2004)

<table>
<thead>
<tr>
<th>Level</th>
<th>Availability (%)</th>
<th>Downtime/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra</td>
<td>99.9999</td>
<td>~ ½ second</td>
</tr>
<tr>
<td>Extremely</td>
<td>99.999</td>
<td>~5 minutes</td>
</tr>
<tr>
<td>Very</td>
<td>99.99</td>
<td>~1 hour</td>
</tr>
<tr>
<td>High</td>
<td>99.9</td>
<td>~9 hours</td>
</tr>
<tr>
<td>Medium</td>
<td>99.0</td>
<td>~3.5 days</td>
</tr>
</tbody>
</table>

- Delivered QoS **must** be tailorable per data item & changeable (in SW)
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Internet</th>
<th>NASPInet environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network size</td>
<td>10^9 interconnected hosts worldwide</td>
<td>10^5 hosts in a power grid 10^3-4 “routers”</td>
</tr>
<tr>
<td>Per-Flow state?</td>
<td>Death (RSVP)</td>
<td>Very feasible</td>
</tr>
<tr>
<td>Network design goal</td>
<td>Provide best-effort delivery for any user and purpose</td>
<td>Provide guaranteed QoS in several dimensions for specific users and purposes</td>
</tr>
<tr>
<td>Admission Cntl Perimeter</td>
<td>None</td>
<td>Complete</td>
</tr>
<tr>
<td>Fraction of Managed Traffic</td>
<td>None/Very Little</td>
<td>Almost all. All traffic subject to policing. &gt;&gt;90% periodic.</td>
</tr>
<tr>
<td>Central topology knowledge</td>
<td>Not attempted, because of large scale and dynamicity</td>
<td>Feasible, because of small scale and slow changes</td>
</tr>
<tr>
<td>Topology changes (!failure)</td>
<td>Often &amp; without warning</td>
<td>Not often &amp; virtually always with warning (except failure)</td>
</tr>
<tr>
<td>Frequency of route changes</td>
<td>Frequent; route changes computed using distributed algorithms that may converge slowly in the face of changing topology</td>
<td>Infrequent; route changes computed centrally assuming stable topology</td>
</tr>
<tr>
<td>Characteristic</td>
<td>Internet</td>
<td>EPInet</td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Latency Level Achievable</td>
<td>Slow to Medium</td>
<td>Very Fast</td>
</tr>
<tr>
<td>Latency Predictability</td>
<td>Poor</td>
<td>Very Good to Excellent</td>
</tr>
<tr>
<td>Recovery delay after dropped packet (with “reliable” delivery)</td>
<td>High (timeout waiting for data or acknowledgement)</td>
<td>Zero (redundant copy sent over disjoint path arrives virtually at the same time)</td>
</tr>
<tr>
<td><strong>DO NOT USE post-error recovery, be proactive!</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forwarding Unit</td>
<td>Uninterpreted packet</td>
<td>Update of a variable</td>
</tr>
<tr>
<td>Traffic Predictability</td>
<td>Low</td>
<td>Very High</td>
</tr>
<tr>
<td>Elasticity of QoS requirements</td>
<td>None/Low</td>
<td>Medium-High</td>
</tr>
<tr>
<td>Multicast: multiple subscribers to a single update flow</td>
<td>A small fraction of the overall traffic; does not justify significant optimization</td>
<td>The common case. Multiple subscribers to a single update flow may have different latency and reliability requirements. Significant opportunity for optimization</td>
</tr>
</tbody>
</table>
Overview of Presentation

- Introduction
- Emerging Power Applications
- Implementation Issues for WAMS Data Delivery (WAMS-DD)
- NASPI and NASPInet
- GridStat
NASPI

- Vision: “The vision of the North American SynchroPhasor Initiative (NASPI) is to improve power system reliability through wide-area measurement, monitoring and control.”
  - Synchrophasor: a sensor with a very accurate GPS clock...
  - Becoming much more deployed in US, Europe, ...

- Great need for much better data delivery services
  - Can no longer send “all data to control center at the highest rate anyone might want to”

- Very involved with spec of “NASPInet”
  - Many requirements come from GridStat research (cited)
NASPIInet Conceptual Architecture

Monitoring Center X

Apps

Phasor Gateway

Archive

Utility A

PMU

PMU

PMU

Apps

Phasor Gateway

Utility C

PMU

Historian

Utility B

Apps

Phasor Gateway

Historian

PMU

PMU

PMU

Monitoring Center Y

Phasor Gateway

Apps

Archive
Overview of Presentation

• Introduction
• Emerging Power Applications
• Implementation Issues for WAMS Data Delivery (WAMS-DD)
• NASPI and NASPInet
• GridStat
GridStat Architecture

Data Delivery Mechanisms and Issues for Wide Area Measurement Systems (WAMS)
Route Allocation to Subscriber 1

Note: GridStat, not app programmer, figures route/path
Route Allocation to Subscriber 2

Note: Sub2 may have different latency, rate, #paths than Sub1
Overview of GridStat Performance

• Forwarding Latency through one status router between 50-100 microseconds (2007 vintage mid-range PC)
  – Very little jitter
  – Scales to >100K/second in Java
  – Even much faster with “network processors”
  – In custom HW (ASIC) should scale about same as IP router

• So forwarding across an entire grid would be less than a millisecond over the speed of light
  – 8-10 hops over a wider area would be typical
  – You can afford a millisecond (IMHO; YMMV)

• You cannot buy COTS products that give you the complete required flexiblity and QoS control (including rate filtering)
Conclusions

• Better WAMS-DD can help the bulk power system
• WAMS-DD has more extreme requirements than any other; need to be careful here
• For more information (bakken@eecs.wsu.edu):