The NOvA Data Acquisition System

A highly distributed, synchronized, continuous readout system for a long baseline neutrino experiment

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for the NOvA Collaboration
NOvA Physics

- The recent measurements of a large $\theta_{13}$ have greatly changed the landscape of the measurements NOvA will make.

- With $\sin^2 2\theta_{13} = 0.095$ NOvA will not only make an independent measurement of $\theta_{13}$ through $\nu_e$ appearance but will measure both $\nu$ & anti-$\nu$ modes:
  \[ P(\nu_\mu \rightarrow \nu_e) \quad \text{and} \quad P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \]

- The measurements together provide significant information on the neutrino mass hierarchy and can establish/constrain CP violating in the neutrino sector through the phase $\delta_{\text{CP}}$.

NOvA sensitivities to neutrino mass hierarchy and CP phase. Plot shows the parametric contours in $\delta$ for normal (blue) and inverted (red) mass hierarchies. NOvA 1 and 2$\sigma$ contours for measurements corresponding to $\delta=3\pi/2$ in the normal hierarchy.
NOvA

• NOvA is a program to investigate the properties of neutrinos

• It includes:
  – Doubling of the Fermilab NuMI beam power to 700 kW
  – An 15kTon totally active surface detector, 14 mrad off axis at 810km (first oscillation max for 2GeV)
  – A 220 Ton totally active near detector

• It has been optimized as a segmented low Z calorimeter/range stack to:
  – Reconstruct EM showers
  – Measure muon track
  – Detect nuclear recoils and interaction vertices

• It presents a challenge for modern computing and data acquisition
The 3 NOvA Detectors

Far Detector
- 15kT “Totally Active”, Low Z, Range Stack/Calorimeter
- Surface Detector
- Liquid Scintillator filled PVC
- 960 alternating X-Y planes
- Optimized for EM shower reconstruction & muon tracking, $X_0 \approx 40cm$, $R_m \approx 11cm$
- Dims: 53x53x180ft
- “Largest Plastic Structure built by man”
- Began construction May 2012
- First operation est. Sep. 2012 (cosmics)

Near Detector
Identical to far detector
1:4 scale size
Underground Detector
Optimized for NuMI cavern rates
-- 4x sampling rate electronics

Near Det. Prototype
In operation 2010-Present on surface at FNAL in NuMI and Booster beam line

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- Near Detector Prototype Readout

- NOvA - FNAL E929
  - Run: 12125 / 6
  - Event: 201664 / CAL
  - UTC Sat May 7, 2011 03:20:54.108232000

- NOvA DAQ

- CHEP2012, A.Norman
Making the Core Measurements

- To make the core physics measurements NOvA needs to be able to do the following:
  1. *Send* a narrow (10μs) pulsed beam of mainly $\nu_\mu$ to a near detector (small) and far detector (massive) where the beam will interact.
  2. *Correlate* interactions in each detector with the beam
  3. *Compare* the rates of interaction to determine appearance/disappearance rates and energy spectra
The Correlation Problem

• There is no way to provide hard timing signals to the far detector 810km away.
• There is no way to “predict” the beam spill
  • NuMI spills are slotted into each accelerator super cycle but:
    – Timeline structure changes based on which experiments are running
    – Absolute [wall] time alignment of the super cycles will vary based on the timeline.
    – Unable to verify a spill until it has actually happened (i.e. kicker fired AND protons were recorded on target)
• The far detector is a surface detector
  • “Activity” base triggering won’t work
  • There is always significant activity in the detector
The Correlation Solution

• Design a system that doesn’t need a traditional trigger and can tolerate extremely long latencies in readout
• NOvA solution is continuous readout with absolute synchronization:
  1. Instrument every channel with TDC
  2. Synchronize every channel of the detector to every other channel (global sync)
  3. Readout the detectors continuously
  4. Time stamp every hit and store every hit in deep buffers
  5. Time stamp the beam spill at FNAL and send the information to the far detector (max latencies ≈ 20s baseline)†
  6. Match the hit data with the beam spills
  7. Record the data

† Baseline is 20s, actual buffer sizes allow for 60+ min
Readout Overview

• NOvA is a free running readout
  – The electronics are always live, always digitizing.
    • Every channel of the detector is being continuously digitized.
  – The whole system is completely deadtime-less.
  – The entire raw detector data stream (up to 4.3GB/s) is actively buffered in a large computing farm

• Triggering is asynchronous & decoupled from the readout
  – Trigger information packets are sent from FNAL over the internet to the far detector.
    • Average one way flight time is 11ms.
    • The system is designed to tolerate at least 20s of latency.
    • Real buffering can be much deeper (60+ minutes)
  – Buffered data that has a time overlap with a trigger window is saved to permanent storage
The Readout Cell

NOvA Detection Cell

- The base detector unit 3.9x6.6cm cell 15.7m long, filled with a mineral oil based liquid scintillator.
- Passage of MIP through the cell (longitudinal to beam) results in $dE/dx \approx 12.9$ MeV across the cell.
  - Roughly 10% of energy loss is in the PVC wall
  - Yields 10-12MeV of deposition in the scint.
- The measured light output is 30-38 p.e. from the far end of the cell into the APD readout
- Light yield gives a minimum Sig/Noise 10:1 (far end)

- Signal is amplified and shaped
- Channel is continuously sampled at 2MHz to obtain waveform
- Zero suppression is performed at (0.5-0.66) MIP (15-20 p.e.) via a dual correlated sampling (dcs) algorithm
- Results in a single cell, lower energy detection threshold of $\approx 6-8$MeV (far end)
- Fits to the shape of the waveform recover the timing and pulse height information
Data Concentrator Module

- The DCM is designed to aggregate the continuous data stream 64 front end boards (2048 detector cells) into partially time sorted data block.
- All the data in one DCM is one geographic quadrant on the detector.
- The DCM combines a large FPGA with a single board computer to build 5ms.
  - Event building performed in both the FPGA and the CPU.
- Run custom embedded Linux with support for NOvA firmware.
- Demonstrated to handle 24MB/s data rate on near detector.
Instrumented Detector
NOvA designed a custom timing system implemented on ARM/PowerPC + FPGAs which provides:

- A 56 bit timestamp counter on every device
  - Timestamp counter can operate at 64MHz
- A self-calibrating synchronization system that can set/align the timestamps
  - We use GPS to link sites with universal “wall time”
  - Align “NOvA Time” to GPS with epoch offset to establish higher resolution timing
- System uses a hierarchical topology to distribute:
  - Stable system clock (16/64MHz)
  - Timing Command Data
  - Synchronization pulses
  - Loopback calibration
Timing System Master/Slave

Master Timing Unit

Accelerator (x2), auxiliary trigger and external ref. clock inputs

GPS Antenna (outside)

Optical Link

6 DCMS Per Slave chain

15 Slave units in a backbone
For the Far Detector

64 FEBs Per dcm

FEB

Calibration Loopback

CAT6

Calibration Loopback
Timing System Master/Slave

- Master Timing Unit
- Slave units connected via CAT6
- Accelerator (x2), auxiliary trigger and external ref. clock inputs
- GPS Antenna (outside)
- 64 FEBs Per dcm
- Calibration Loopback
- Primary Backbone
- Secondary Backbone
- Calibration Loopback
Timing System Master/Slave

- **Master Timing Unit**
  - Accelerator (x2), auxiliary trigger and external ref. clock inputs
  - GPS Antenna (outside)

- **Slave**
  - CAT6
  - Optical Link

- **CAT6**
  - 64 FEBs Per dcm
  - Calibration Loopback

- **FEB**

- **Secondary Backbone**

- **Calibration Loopback**

- **NOvA Far Detector Timingsystem & teststand in production for monitoring and diagnostics of Ash River GPS**

- **NOvA DAQ**

- **CHEP2012, A.Norman**
Synchronized DAQ

When you are done you have:

<table>
<thead>
<tr>
<th>Device</th>
<th>Daughter</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master</td>
<td>1 per chain</td>
<td>3 per site</td>
</tr>
<tr>
<td>Slave</td>
<td>15 per chain</td>
<td>30 far/4 Near</td>
</tr>
<tr>
<td>DCM</td>
<td>6 per chain</td>
<td>30 chains, 180 units 14 near†</td>
</tr>
<tr>
<td>FEB</td>
<td>64 per DCM</td>
<td>11520 far 576 near</td>
</tr>
<tr>
<td>Readout Cells</td>
<td>32 per FEB</td>
<td>368,6400 far 18,432 near</td>
</tr>
</tbody>
</table>

Sync’d and counting in lockstep.
Synchronization

• How do you actually sync 386,000+ channels of readout?

You take a cue from Bell Telephone:

“At the tone the time will be...”
Sync System

Step 1

Use GPS to determine the 64bit NOvA time at the next 1s boundary (64MHz precision)

Send this time over the serial command channel.

The timing circuit loads the bytes into the “time stamp preset” registers.
Sync System

Step 2

Use the serial command channel to set the “Preset Enabled Arm” register.

This Arms the system to react when it receive the next sync pulse.

Having a specific Arm functions allows the sync line to be used for differ purposes like:

- Self Delay Calibration
- Timing Fiducially Diagnostics
- External Sync. Verification
**Sync System**

**Step 3**

Send a pulse on the dedicated SYNC line at a predetermined time BEFORE the next 1s boundary.

The pulse is buffered and retransmitted at each unit.

Each unit is calibrated to know its offset from its upstream and downstream partners in the chain.

The pulse is not actually delivered to the circuit until a calibrated number of master clock cycles have elapsed on this unit.
Step 4

Upon reception of the delayed sync, the values of the preset register are latched into the active time stamp registers.

The ARM register is cleared and the system continues counting on the next master clock cycle with the synchronized time.
Fully Synchronized Detector

DCM Readout Region
Fully Synchronized Detector

NOvA - FNAL E826
Run: 108938
Event: 314724
UTC Tue Dec 21, 2010 11:48:18.997623872

Readout Region Top-1-1
Readout Region Top-2
Readout Region Side 1-2
Readout Region Side 2-2
Readout Region Side 2-3
Readout Region Side 2-3
The data from DCMs are sent to a farm of “buffer nodes”.

Every 5ms the data stream from ALL DCMs on the detector is transmitted into a single buffer node.

This gives a complete 5ms snapshot of the detector in that buffer node.

The destination buffer node is then rotated in a round-robin pattern through the entire cluster (1s return to start with nominal 200 buffer nodes).

Projected data rates allows us to buffer up to 69min of raw, min bias readout system wide (baseline buffering 20s).
Readout Buffering

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Beam Triggering

• For the core NOvA beam related physics topics \{\theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2\} the only “triggers” you need are:
  – NuMI Beam spill
  – Calibration pulser
• These are completely open zero bias selections.

• NuMI Beam Spill Trigger
  – Centered on the GPS time of the spill at FNAL
  – Extract a window around that time to get side bands
  – For initial running we use a wide window (500\mu s) to locate and characterize the beam
  – For production running we narrow the window to 30\mu s to retain sideband information, and take additional calibration data in the off spill intervals

Nova beam trigger structure, 30\mu s trigger window corresponding to beam spill + sidebands
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NuMI Beam Trigger window from 2011/2012 near detector running. Beam appears in the detector 220μs after the MIBs $74$ signal to the extraction kicker.
Data Driven Trigger

• It’s important to note that ALL the data (≈4.3GB/s) is buffered in our buffer farm
• But only 30μs of each 2s is written out as physics beam triggers
• Being able to examine the full data stream in real time while it is in the buffers gives us the opportunity to generate “data driven triggers”
• Because the detector is 100% live these triggers have tremendous potential for accessing Non-accelerator physics, calibration:
  – Improve detector calibrations using “horizontal” muons
  – Verify detector/beam timing with contained neutrino events
  – Search for exotic phenomena in non-beam data
    (magnetic monopole, WIMP annihilation signatures)
  – Search for directional cosmic neutrino sources
  – Detect nearby supernovae
**DDT Design Overview**

- **11520 FEBs**
  - (368,460 det. channels)

- **Zero Suppressed at**
  - \( \frac{1}{2} - \frac{2}{3} \) **MIP**
  - (6-8MeV/cell)

- **Minimum Bias**
  - 0.75GB/S Stream

- **200 Buffer Nodes**
  - (3200+ Compute Cores)

**Beam Spill Indicator**
- (Async from FNAL @ .5-.9Hz)

**Calib. Pulser**
- (50-91Hz)

**Buffer Nodes**

- **DCMs**

**Shared Memory DDT event stack**

- **5ms data blocks**

**Data Buffer**

**Data Driven Triggers System**

- **Trigger Processor**
- **Trigger Processor**
- **...**

**Event builder**

- **Trigger Reception**
- **Data Slice Pointer Table**
- **Data Time Window Search**

**Data Logger**

**Global Trigger Processor**

**Data Driven Trigs. Decisions**

**Grand OR Trigger**

**Data**

**Trigger Broadcast**

**ARTDAQ-DDT**

**Data Driven Triggers System**

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- **Trigger Processor**
- **...**

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- **Trigger Reception**
- **Data Slice Pointer Table**
- **Data Time Window Search**

**Data**

**Trigger Broadcast**

**Data Logger**
• Data Driven Triggering (DDT) is implemented in NOvA using ARTDAQ
  – Event processing framework (see talk C.Green)
  – Tailored to read from shared memory event buffers which are populated directly by the NOvA event builder
  – Partitioned off from primary DAQ chain for system stability
  – Permits the shared use of algorithms between online/offline:
    • transparent simulation of triggers, efficiencies, etc...
    • Leverages work on offline reconstruction & analysis modules
    • Simplifies development, testing, validation cycles
Example: Hough DDT

- Real world track finding in X/Y calorimeter
  - Linear Hough transform
  - 2D view version is a example of $N^2$ complexity algorithm
    - Can be implemented in serial, partitioned or massive parallel processing (i.e. GPU exploration)
    - Allows for tuning of both the algorithm and framework
  - For NOVA-DDT we implemented a global hit transformation on 5ms time windows
    - 500× nominal beam spill window
    - Allows for simultaneous searches for both fast and slow ($\beta=1-10^{-4}$) track topologies
    - Hough method is expandable into dim > 2 using timing & pulse height information
Example: Hough DDT

Transform applied Globally to X/Y Views

Local track features detected

Trigger decisions are issued based on accumulations/peaks in the Hough coordinates

Extraction of tracks from long $\Delta t$ (5ms) slices
The Hough algorithm was implemented in the ARTDAQ framework to provide a data driven trigger (DDT) test.

The DDT system was run on the near detector prototype data stream
- Surface detector with zero suppression threshold set to match far detector data rates
- Total readout ≈1/30 of far detector readout
- 5ms (500x beam window) slices of data were processed as a single block (no partitioning)
- Goal was to achieve 60ms decision

Real performance without parallelization, partitioning or algorithm specific optimization:
- 98ms to decision
- 2% of processing time spent in framework overhead
- CPU utilization was 1/16th of available

Positions us well for larger scale tests and algorithm development
Things I didn’t cover...

- Predicting & Detecting correlated faults across systems (see next talk by Qiming Lu)
- Database systems for accelerator/beam information (see poster by I.Mandrichenko)
- Data handling and cataloging (see poster by A.Lyon)
- Message passing & State machine architectures for controlling 400+ independent event builders (ask me!)
The Future

- We have built the foundation for a unique free-running DAQ system
- We have solved the problem of correlation and synchronization
- We understand how to perform continuous readout and buffering
- We are exploring the power and opportunities of Data Driven Triggering