NOνA Event Building, Buffering and Data-Driven Triggering From Within the DAQ System

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NOνA Event Building, Buffering and Data-Driven Triggering From Within the DAQ System

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Abstract. The NOνA experiment is a long baseline neutrino experiment design to make precision probes of the structure of neutrino mixing. The experiment features a unique deadtimeless data acquisition system that is capable acquiring and building an event data stream from the continuous readout of the more than 360,000 far detector channels. In order to achieve its physics goals the experiment must be able to buffer, correlate and extract the data in this stream with the beam-spills that occur that Fermilab. In addition the NOνA experiment seeks to enhance its data collection efficiencies for rare class of event topologies that are valuable for calibration through the use of data driven triggering.

The NOνA-DDT is a prototype Data-Driven Triggering system. NOνA-DDT has been developed using the Fermilab **artdaq** generic DAQ/Event-building toolkit. This toolkit provides the advantages of sharing online software infrastructure with other Intensity Frontier experiments, and of being able to use any offline analysis module–unchanged–as a component of the online triggering decisions. We have measured the performance and overhead of NOνA-DDT framework using a Hough transform based trigger decision module developed for the NOνA detector to identify cosmic rays. The results of these tests which were run on the NOνA prototype near detector, yielded a mean processing time of 98 ms per event, while consuming only 1/16th of the available processing capacity. These results provide a proof of concept that a NOνA-DDT based processing system is a viable strategy for data acquisition and triggering for the NOνA far detector.

1. Introduction

The NOνA experiment[1] is a program to investigate the properties of neutrinos and probe the flavor structure of the neutrino sector. The experiment is designed to measure the transition probabilities for the $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\mu$ as well as the anti-neutrino modes, $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$. The combinations of these transition rates will allow NOνA to highly constrain or determine the neutrino mass hierarchy and probe for CP violation in the neutrino sector through mesurement of the CP violating phase δ_{CP}. The NOνA measurements will also provide precision measurements of the mixing angle θ_{13} which are complimentary to the Daya Bay and Reno reactor measurements, yet probe directly through the ν_e and $\bar{\nu}_e$ appearance channels. The experiment will also make a precision measurement of the atmospheric mixing angle which may be able to determine whether θ_{23} is non-maximal.

To meet the science goals of the NOνA experiment, the NOνA project includes not only the construction of the detectors but significant upgrades to the Fermilab accelerator complex to support running at higher beam intensities. Formally the NOνA project includes:

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- Doubling of the Fermilab NuMI (Neutrinos at the Main Injector) beam power from its current power of 320kW to an upgraded beam power 700 kW, as well as providing new target systems that can support the higher beam intensities.
- A 15,000 ton totally active surface detector, positioned 14 mrad off of the beam axis, at a baseline of 810 km. This choice of siting provides a narrow-banded beam peaked at 2 GeV that is at a distance which corresponds to the first oscillation maximum.
- A 220 ton totally active near detector, sited at Fermilab in the NuMI cavern complex at the same off-axis angle, to provide a similar beam spectrum.

In this design the detectors have been optimized as highly segmented, low Z, calorimeter/range stacks which are specifically tuned for reconstructing EM showers and measuring muon tracks in the 1–2 GeV energy range. The detectors are also capable of measuring low energy event signatures in the 10–100 MeV range. This permits the detector to identify Michel electrons, nuclear recoils and interaction vertices.

One of the unique features of the NOνA detectors are that they operate in a "free-running", trigger-less readout mode. In this readout mode each cell of the detector is continously digitized and the entire raw data stream for the detector is transmitted to and actively buffered in a large online computing farm. The depth of the buffers are sized to allow for 20 s or more of raw, unsupressed data to be held while information on the Fermilab beam lines is collected and transmitted to the far detector site. When the beam information is received, the data buffers are searched for all hits which overlap with the time windows defined by the NuMI beam spills. The identified hits are then transmitted and assembled into the final "event" format before being saved to permanent storage.

The extremely large data volume from the continous readout of more than 368,000 channels of the far detector must be processed in real-time, transmitted between DAQ systems, and deeply buffered to perform asynchronous triggering. This processing presents a challenge for modern computing, networking and data acquistion systems. NOνA has overcome these challenges through the use of a highly distributed DAQ readout chain that performs data aggregation, event building and time sorting in a four-level hierarchical array, which Maps the more than 368,000 channels down to a single final-stage event builder.

One of the offshoots of this approach is that at the intermediate buffering stage, all of the data from the detector is held in the buffer node farm while beam spill timing information is being received. The system can buffer at least 20 s of data. This provides an opportunity to examine the data and search for interesting events not associated with the beam pulses. This Data Driven Triggering (DDT) approach has the potential to greatly enhance the data samples collected for detector calibration, and also provide independent detection of beam neutrino events. The DDT system also permits NOνA to expand its physics scope by allowing searches for and measurements of non-accelerator-related physics phenomena such as the neutrino bursts from core-collapse supernovae and exotica such as magnetic monopoles.

Performing real-time analysis and triggering using a DDT system has the potential for introducing risks into the DAQ system. A DDT system for the NOνA experiment must be capable of maintaining a degree of separation between the primary acquistion path that feeds the event building systems and the trigger analysis framework which is analyzing and reconstructing the raw data stream. We were able to achieve this level of isolation between the primary DAQ system and the DDT/Analysis system using the NOνA-**artdaq** framework which is a specialized realtime versionof the more generic **art** event processing framework. Using the NOνA-**artdaq** framework we were able to demonstrate its compatiblity with the NOνA DAQ and readout systems and measure its performance and overhead using realistic reconstruction algorithms for muon identification in the NOνA detector.

1.1. NOνA Beam Triggering

The more than 368,000 channels in the NOνA far detector are continually digitized. The data are read out and accumulated through a multi-tiered readout chain into a large farm of high-speed computers. This results in a data stream that is comprised of the continuous waveform digitizations of each channel at an effective sampling rate of 2 MHz, with only a simple zero suppression of samples that fall within the baseline noise envelope of the channel's electronics. The full data rate of the far detector under this readout mode is limited by the front-end electronics to a maximum sustained rated of 4.3GB/s. This input data flow rate is too large to allow for any practical scheme of retaining all the data for offline analysis. Instead, some form of filtering of the data into interesting time windows is required. The overall volume of detector data that is logged to disk/tape is thus reduced to a flow that both meets the physics needs of the analysis programs and can also be handled by modern storage technologies.

To make the core physics measurements, the raw NOνA data stream that is acquired at the far detector needs to be correlated with information on the extraction of protons in the NuMI beam line and at the Fermilab target, with a separation of 810 km. The correlation of the beam spill information with the raw data stream allows for the identification of well-defined time windows. The windows correspond to the times at which the neutrinos generated at Fermilab on the NuMI beam line traverse the NOνA detectors.

The data from these windows are reconstructed to identify neutrino interactions corresponding the the ν_μ and ν_e fluxes. The comparisons of the observed fluxes between the near and far detectors allow for the determination of both the appearance and disappearance transition probabilities $P(\nu_\mu \to \nu_e)$ and $P(\nu_\mu \to \nu_\mu)$. The NOνA beam configurations also permit running in an "anti-neutrino" mode which allows for the determination of $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$. The combined measurements of these probabilities allow for NOνA to access information on the core neutrino mixing parameters and the structure of the neutrino sector, including precision measurements of θ_{13} and θ_{23}, as well as possible resolution of the sign of Δm^2_{13} and probing for CP violation in the neutrino sector through the value of PMNS phase δ_{CP}.

At the DAQ triggering level, the core measurements rely only on beam trigger derived from the FNAL accelerator systems to acquire the physics data, along with a set of calibration pulser triggers that are used to obtain minimum bias data for performing detector calibration and determining backgrounds. They do not require that the streamed hit data from the front-end systems be examined in any way prior to filtering and logging to disk.

Currently the NuMI beam spills occur once every 2 seconds with a spill length of 10 μs. As a result, the amount of data that is recorded for the core neutrino oscillations measurements represents only one part in 200,000 of the actual data that is read out and buffered by the NOνA DAQ system. This sample, while containing all the information required for performing the core oscillation measurements, is so small that it can not be used for performing many types of detector calibration and can not be used for performing physics searches outside of the beam-related physics topics.

1.1.1. Motivation for a Data-Driven Trigger (DDT) The rare event topologies that detector alignment, calibration and systematic studies all require are not possible to obtain using the standard minimum bias data stream. Instead, the data samples must be enhanced through the selection of specific event topologies that are tailored to the task. This type of selection can only be accomplished by looking at the raw hit data to identify events, causing a "data driven" trigger decision, resulting in the saving of a time window of interest.

A data-driven triggering system compliments and extends the core neutrino oscillation measurements by improving calibration and allowing access to non-accelerator physics. In particular it can be used to search for and identify:

Horizontal muons Calibration and alignment of detector cells require multi-GeV muons that traverse the detector in a narrow angular range corresponding to the detector's z-axis (not the common angle for cosmic rays).

Neutrino interactions Detecting the interaction of neutrinos within the detector volume allows for both an independent verification of the detector/beam timing and allows for observing sources of high-energy neutrinos with non-accelerator origins.

Exotic phenomena The NOνA detector is well suited to detecting certain classes of exotic particles including the signatures of slow-moving high-mass relic magnetic monopoles. The 100% live-time of the NOνA detector makes searches for these types of phenomena extremely competitive with previous searches from the MACRO collaboration[2].

Supernovae Neutrinos A neutrino burst emitted by a type-II core-collapse supernova within 15 kpc of Earth will result in a significant low-energy signal in the NOνA detector. The time and energy distributions of this signal can increase our understanding of the stellar dynamics of supernova.

The NOνA DDT system design is uniquely different from traditional Level-3 software triggering systems, in that it must operate on a deadtime-less data stream that has had no preselection applied to it. The nature of NOνA as a surface detector prevents the use of a Level-0 or Level-1 style hardware triggering systems due to the large amount of activity that is always present across the detector. As a result, the DDT system sees, in real-time, the full, unfiltered data volume that is acquired by the front-end electronics. The DDT system must be capable of performing reconstruction on a "stream" of detector data that is not partitioned into well-defined windows or "events" in the way that must traditional Level-3 systems operate.

The NOνA DAQ and data-driven triggering design goes beyond many traditional activity-based trigger system to meet these requirements. The NOνA buffering system allows for extremely long latencies between when the data is initially collected and when a decision on the data must be issued. The DDT exploits this feature. The triggering system operates directly on the raw data while it is being held in the online buffers. It uses a robust, high-speed analysis framework that can perform near-real-time reconstruction of the event data and also handle, at run time, optimizations related to reconstruction paths followed for each trigger decision issued from the multi-layer decision trees configured within the DAQ.

This design permits NOνA to improve the collection of data, matching both their calibration and core physics goals, while simultaneously opening additional non-accelerator based physics.

2. NOνA-artdaq – a Platform For the NOνA Data Driven Triggering

The Data-Driven Trigger (DDT) must be integrated into the existing DAQ systems. It will consume a large fraction of the extra computing cycles available on the buffer node farm and must not interfere with the standard data collection modes required by the experiment. The NOνA-DDT is implemented using a subset of the **artdaq** toolkit [3]. The **artdaq** project at Fermilab is under active development and has been established as a generic toolkit for the construction of robust event building, filtering, and analysis programs; it is to be included as part of an integrated data acquisition system. The **artdaq** toolkit allows for sharing of DAQ software infrastructure between experiments, and supports the use of commodity computers and hardware accelerators (GPUs) as close to the data source as possible.

To facilitate integration of online and offline event-processing code, **artdaq** makes use of the **art** [4, 5, 6] event-processing framework, which is used as the offline framework by NOνA and other Fermilab experiments. Thus, code to be run in online triggers can be developed, verified, and profiled for performance in the offline environment. An **art** filter module available in the offline code can be used, without change, within NOνA-DDT. The advantages of shared algorithms include transparent simulation of triggers, accurate measurement of efficiencies, and reuse of offline reconstruction and analysis modules. This commonality aids in testing and validation of algorithms, along with permitting comparisons of multiple algorithm implementations in the offline environment.

These features make **artdaq** a natural environment for implementing the NOνA-DDT. NOνA-**artdaq** has been attached to the existing event builders and reads from their shared memory. To improve system robustness, the processing of trigger decisions in NOνA-**artdaq** is separate from the primary data path. If the DDT processes fall behind or die, the consequence for the main global trigger is minimized. In this case the overall decision only depends on the beam spill timing.

2.1. The NOνA DAQ Readout

The NOνA event builder is a major part of the DAQ system. One side of the builder consists of Data Concentrator Modules (DCMs). A DCM is designed to integrate a continuous data stream from 64 front-end boards into partially time-sorted data blocks. The 64 boards constitute 2048 detector cells or one geographic quadrant of the detector. The DCM contains a large FPGA and a single-board computer to aggregate 5 ms data slices. DCM embedded processors run Linux and have been demonstrated to read data out of the near detector at a rate of 24 MB/s.

The data from DCMs are sent to a farm of buffer nodes. Every 5 ms the data stream from all DCMs are transmitted to one of the buffer nodes, giving a complete 5 ms time window of the detector readout. The destination buffer node is chosen in a round-robin pattern throughout the entire cluster. With a nominal farm of 200 buffer nodes for the far detector, it takes about one second to return to the first node. Each buffer node is designed to hold many 5 ms slices, allowing for an overall trigger decision latency of at least least 20 seconds. At the projected data rates, we can buffer up to 69 minutes of raw, minimum bias readout system-wide.

2.1.1. DAQ Topology The NOνA DAQ system provides continuous readout of over 368,000 detector channels, utilizing a hierarchical readout structure that aggregates time windows into larger and larger segments until an event is formed. Data moves from Front-End digitizer Boards (FEBs), to DCMs, to Event Building and Buffering nodes, and finally into a data logging station.

The flow of data out of the Buffer Nodes is controlled by a Global Trigger. The Global Trigger issues extraction directives describing time periods (or windows) of interest, causing Buffer Nodes to move data segments to storage. The windows can represent beam spills, calibration triggers, or DDT periods of interest. The Buffer Nodes are a farm of high performance commodity computers. Each node has a minimum of 16 cores and 32 GB of memory. This permits them to run both the Event Builder and then a fully multi-threaded Data-Driven Triggering process. These nodes also provide sufficient interim storage for triggering based on full, continuous, zero-bias data readout.

2.2. DAQ Event Building and DDT Buffering

The NOνA-DDT system has two distinct buffer pools: the circular data buffer in the Global Trigger Pool (see figure 1) and the DDT event pool. The 5 ms data slices residing in the 200 Buffer Nodes is copied to a small shared memory circular event queue. This queue is the source of data for the DDT system. Trigger Processors pull the 5 ms data slices from the event queue for analysis. The accept decisions they generate are sent to the Global Trigger Processor, where the logic and authority reside to command the Buffer Nodes to store data. The Global Trigger Processor also receives trigger information packets sent from Fermilab, (the packets have an average one-way flight time of 11 ms). The Global Trigger Processor causes any 50 us data slice in the Data Buffers to either be logged, or expired and discarded.

Because the DAQ system performs a 200-to-1 synchronized burst transmission from the DCMs to Event Builder Buffer Nodes, a large amount of network buffering is required to handle the rate. This buffering has been tuned by adjusting the size of data packets to match a single complete time window, reducing the number of transmission and queue-entry overheads. The

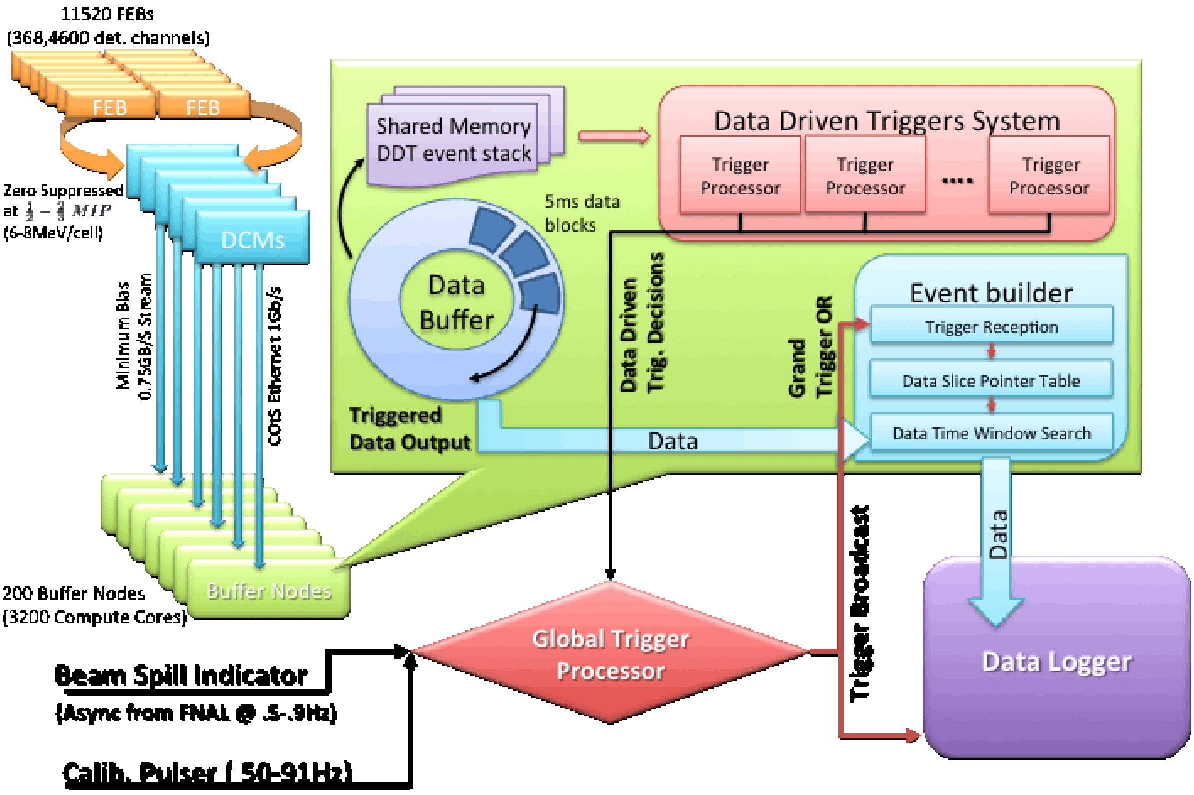

Figure 1: DAQ topology—An overview of the DDT design.

receive window on the buffer nodes has also been tuned to exploit the buffering capability of the Cisco 4948 high-speed switched fabric between the DCMs and the Buffer Nodes as shown in figure 2.

The system can retain time slices written to the Global Trigger pool (the circular data buffer in figure 1) for twenty seconds. The Global Trigger must extract event data within this buffering period or it is lost. The DDT shared memory interface is designed and optimized to be used in a one-writer-many-readers setting. The shared memory DDT circular queue has N fixed size segments used by the writer to reduce collisions with reader processes. The writing process uses guard indicators before and after the event data, allowing reader processes to detect if read data segments have been over-written during read-out. Note that the asynchronous aspect of the system means that even if the DDT were to fall behind, the main data buffering would not block. The key zero-bias beam-spill triggering decisions degrade very gradually under load; logging of events based on that key trigger and on other individual triggers can still proceed.

3. Performance of the NOνA-artdaq DDT

The NOνA-DDT prototype system is a customized application utilizing parts of the **artdaq** framework. The system uses the event input and filtering components of **artdaq** to provide a real-world proof-of-concept application that meets the NOνA trigger requirements.

3.1. Real-time Event Filtering

The NOνA-DDT prototype system takes the already-built 5 ms-wide raw data windows from shared memory and injects them into the **art** framework. The **art** framework is used to run several different software modules: an unpacker that translates the raw data format to one

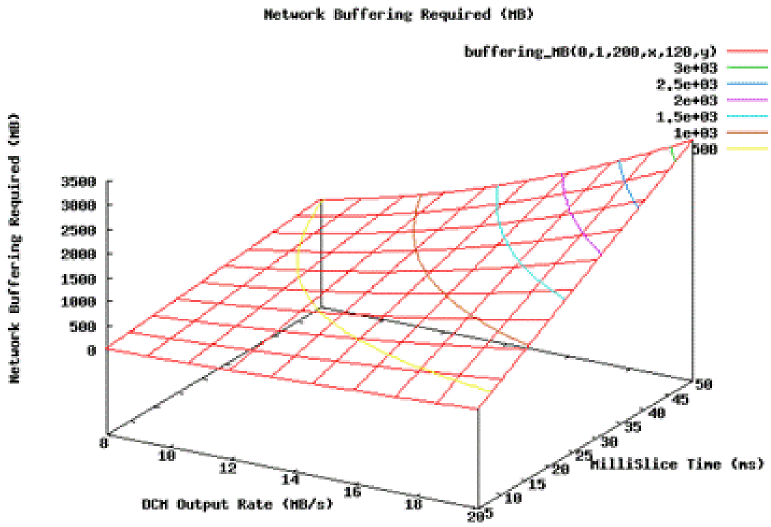

Figure 2: Network (switch) buffering optimization as a function of far detector average DCM rates and acquisition window time.

suitable for use in physics algorithms, a filter module that uses the Hough transform algorithm to identify "interesting" events[7] (those which contain tracks identfied by the Hough algorithm), and a module which broadcasts decision messages to the NOνA Global Trigger System. A schematic diagram of the software is shown in figure 3. Because the **art** framework is also used in the NOνA offline setting, these modules can be developed, tested, and tuned in the offline environment before being deployed online.

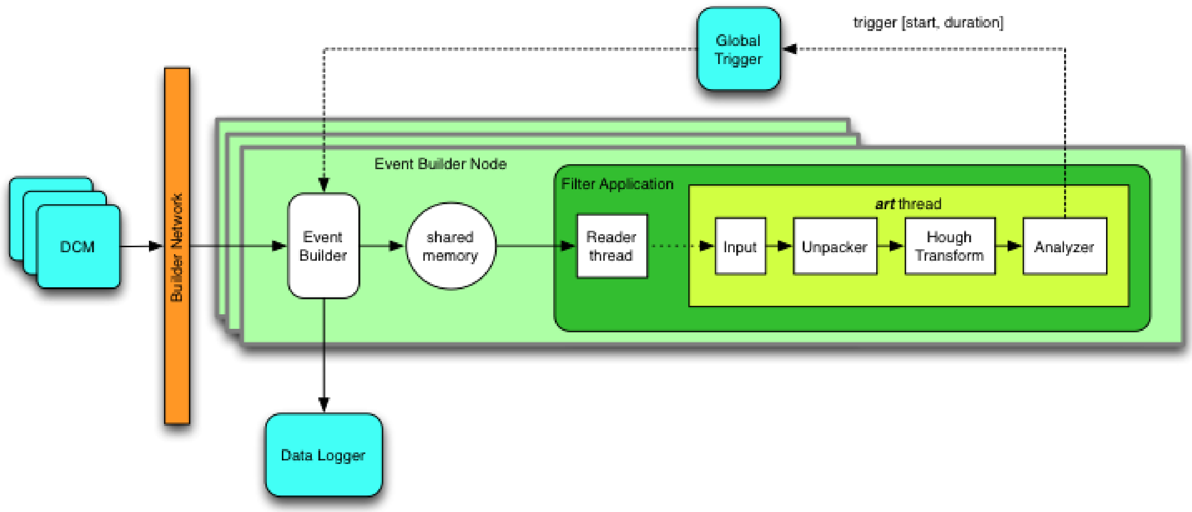

Figure 3: The NOνA Data Driven Trigger (NOνA-DDT) prototype system

The algorithm used by the NOνA-DDT filter module partitions the hits into separate XZ and YZ views, and for each calculates the Hough pararameters for each pair of detector hits, identifying the resulting peaks in Hough parameter space as track candidates. This algorithm is of particular interest because of its ability to identify candidate slow-particle tracks in the far detector, one possible signature of exotic particles, *e.g.*, magnetic monopole candidates with $\beta > 10^{-5}$. The Hough transform methodology can be expanded into more than two dimensions, combining the XZ and YZ detector views into a single 3D track, or possibly incorporating timing and pulse height information, allowing discrimination of tracks from differenty types of particles. This, or course, would increase the computational burden.

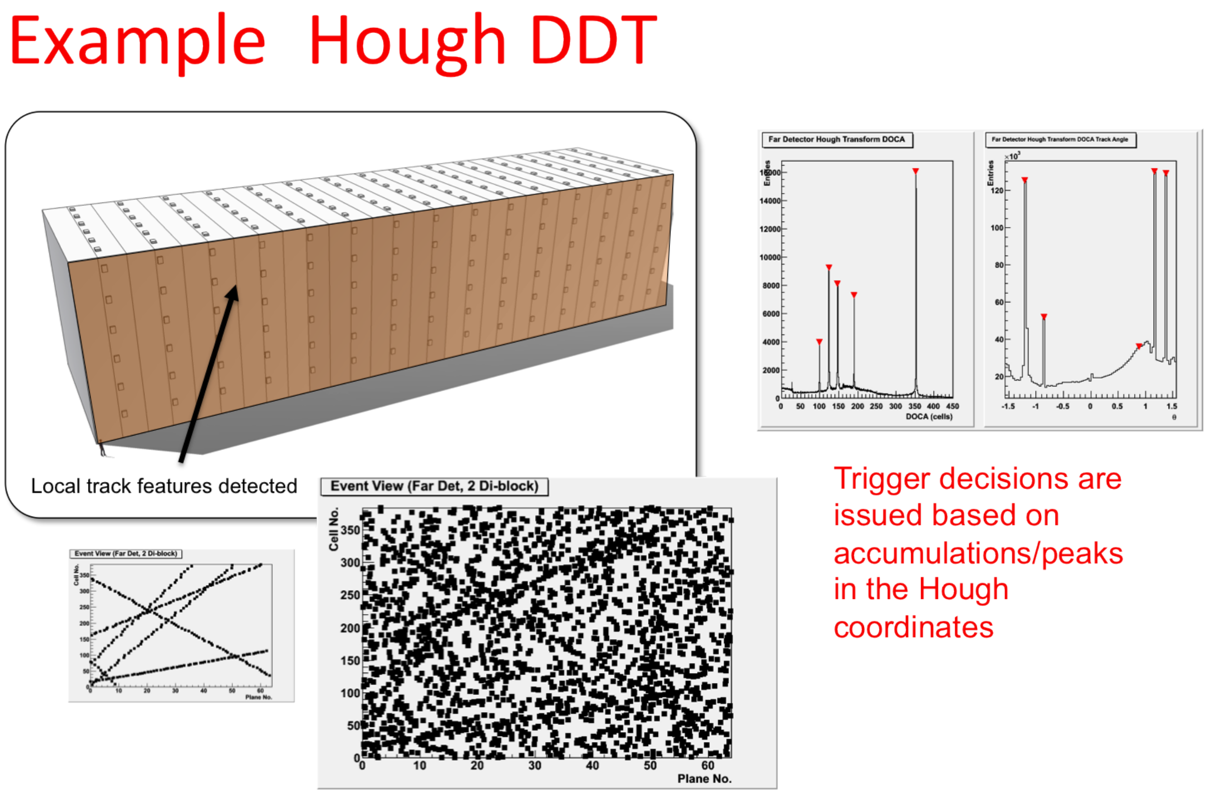

Figure 4: A Data Driven Trigger based on a 2D Hough transform.

3.2. Performance Measurements on the Prototype System

The implemented algorithm, without parallelization, was run on a single core of a Buffer Node within the near detector compute cluster using a zero suppression threshold matching that of the far detector data stream rate. Total readout of each 5 ms slice of data (500 times the beam spill window) was processed as a single block. The near detector compute cluster is identical in architecture to the far detector cluster, allowing us to measure the time performance of the prototype algorithm on data read from the detector rather than simulated events. The target performance goal for this proof-of-concept algorithm was an average rate of 60 ms per trigger decision. The average observed decision time, based on a sample of 1539 events, was 98±14 ms. The distribution of processing times is shown in figure 5. Since the Buffer Node computers each contain 16 cores, and since the Hough algorithm is amenable to parallelization, this initial test shows that the system, after data partitioning, parallelization and algorithm optimizations, will be able to meet the NOνA trigger requirements.

A common concern when embedding time-critical calculations in an organizing framework is the overhead incurred due to that framework. Using the same event sample, we measured this overhead for the **artdaq** framework. We defined the "overhead" as the time required by all

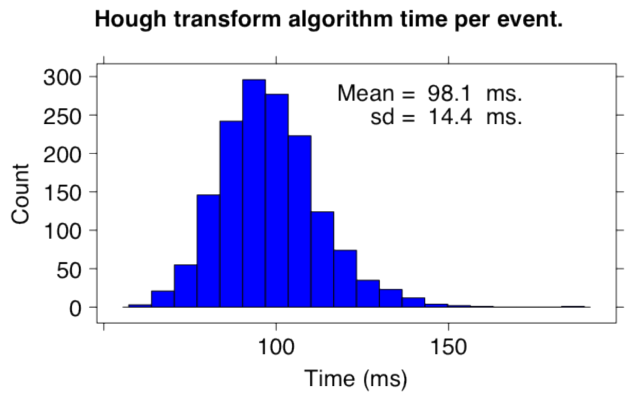

Figure 5: Hough transform execution time for 5 ms time windows of NOνA near detector readout. No parallelization was applied to the algorithm.

framework code, as well as the time taken to unpack the raw data and to form the objects used as input to the filter module. The distribution of the overhead fraction for each event is shown in figure 6. The mean value of the distribution is 2.5%.

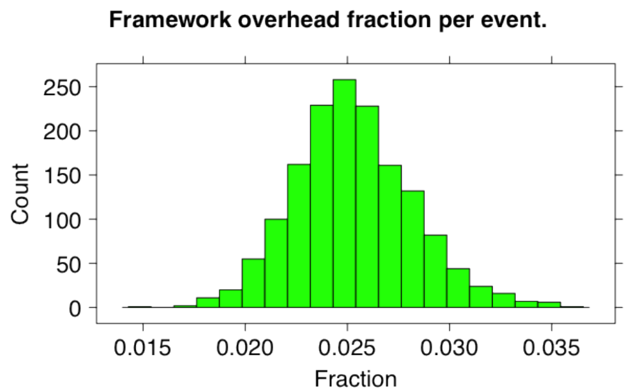

Figure 6: The **artdaq** framework overhead for processing of 5 ms time windows of NOνA near detector readout.

4. Summary

We have built the foundation for a unique, free-running DAQ event building and filtering system, suitable for the purposes of NOνA and other Intensity Frontier or medium-scale experiments. With **artdaq** as a foundation, we have build a prototype system which can solve the problem of beam-spill time correlation and synchronization. The NOνA-DDT has been shown to reliably perform continuous processing of event data. Tests using actual data from the near detector clearly indicate that the NOνA-DDT architecture can handle their triggering and event analysis needs. Further work needs to be done to exploit the available parallelism of the system. We have just begun to explore the full power and opportunities that open up when Data Driven Triggering can be done using a well-structured framework, permitting use of all the experiment's offline components.

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