Synchronization of the 14 kTon NO$\nu$A neutrino detector with the Fermilab NuMI beam

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Abstract. The NO$\nu$A experiment is a neutrino oscillation experiment designed to measure parameters related to the neutrino mixing matrix, mass hierarchy and CP violation. The experiment measures neutrino and anti-neutrino interactions from the NuMI beam line at Fermilab in a Near Detector and a Far Detector located 810 kilometers away. Making these measurements requires precise synchronization of 344,064 channels in the Far Detector to an absolute wall time with a channel to channel variation of less then 10 ns. The experiment must correlate the presence of the relatively narrow neutrino beam in the detector with data readout. This paper will discuss the performance of the NO$\nu$A timing system during the first few months of operation at the Far Detector.

1. Introduction

The NO$\nu$A experiment is a currently active long-baseline neutrino oscillation experiment using the recently upgraded NuMI beam at Fermilab to measure $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \bar{\nu}_\mu$ oscillations[1]. A 300 ton Near Detector is under construction at Fermilab where the NuMI neutrino beam is produced, and a 1 kiloton Far Detector is located 810 kilometers away in Ash River, MN to observe the oscillated beam. The first kiloton of the Far Detector was installed in September of 2012 with an expected completion date in spring of 2014. The detector is instrumented as construction proceeds, with 2 kilotons taking data at the time of writing and over 8 kilotons outfitted with the timing system. The Near Detector will become operational in the spring of 2014. The NuMI beamline completed upgrades and began operation in September 2013. Before the Near Detector turns on the Near Detector On the Surface (NDOS) prototype at Fermilab is being used to time in the neutrino beam spills with detector readout. The detectors are functionally identical, highly active tracking calorimeters consisting of planes of extruded plastic cells filled with liquid scintillator. The detectors are low-Z and finely grained to be able to observe the characteristic shower of an electron in a $\nu_e$ charged current interaction and separate it from the $\pi^0$ background in neutral current events.

The NO$\nu$A experiment requires precise knowledge of the arrival of the 10 $\mu$s long NuMI beam spills in the detectors. The number and frequency of these spills varies depending on accelerator operations so they cannot be predicted in advance. The experiment solves this by globally synchronizing the detectors to an absolute time and continuously reading out data to a buffer farm. A pure software trigger is used to read out the desired spill windows after event...
triggers have been sent from Fermilab to the detector. The NOνA Timing System has been developed to use commercial GPS receivers and custom electronics to synchronize the readout of 344,064 channels in the Far Detector and 20,192 channels in the Near Detector to an absolute wall time and correlate with the arrival of beam spills[2]. This paper will discuss the system design, performance during current operations of the Far Detector, timing in the neutrino beam at NDOS and plans for a calibration system to monitor long term stability of the clocks among detector sites.

2. NOνA timing system design
The NOνA detector consists of planes of extruded plastic cells, alternating between horizontal and vertical orientations to provide 3D tracking. Each cell has a wavelength shifting fiber attached to a pixel on an avalanche photodiode detector (APD) to collect light from the liquid scintillator. A 32 pixel APD is mated to a front-end board(FEB) and 64 FEBs(2048 cells) feed in a data concentrator module(DCM) which group the data into time ordered packets to be sent to a buffer farm for further processing. The Far Detector readout is composed of 168 DCMs, split evenly between detector views, each representing a distinct readout region.

The NOνA timing system uses a hierarchical tree design to transmit commands and clock signals to each readout region in order to globally synchronize 344,064 readout channels in the far detector. This layout is shown schematically in Fig. 1. The detector operates two independent timing chains, although a DCM can only listen to one at a time. At the top of each chain is a master timing distribution unit (MTDU) which is connected to an external GPS antenna as described in section 3. The MTDU can take in external signals either from the accelerator or a reference pulser and time stamp signals to be used both as a system diagnostic and to trigger detector readout.

Figure 1: Schematic of the NOνA distributive timing system deployed at the Far Detector.

The MTDU is connected by a single optical fiber to the first slave timing distribution unit (STDU) in the chain. Fourteen STDUs are daisy chained together, one per kiloton of detector, with copper connections providing 4 LVDS lines, master clock, command, SYNC and SYNC return. Each STDU supports two branches of six DCMs, one for the horizontal planes and one for vertical. The DCM branch is terminated with a loopback connector so delay calibration can be performed. Each DCM fans out to 64 FEBs with copper links carrying master clock, command and SYNC lines. The SYNC return is replaced with a high speed data line to transmit hit information from the cells, meaning the delay cannot be individually calibrated and the length of all FEB cables must be uniform.
3. GPS source and master clock
The MTDU at the top of each timing chain is connected to a high precision Conner-Winfield FTS-125-C00 GPS receiver to derive the master clock. This commercial receiver locks on 3 to 12 satellites to provide a stable 10 MHz GPS disciplined oscillator and a 1 Hz reference pulse aligned with the GPS 1 second boundaries. In addition the unit provides a standard National Marine Electronics Association (NMEA) data stream for diagnostic information and error monitoring. The health of the satellite lock is tracked, as shown in figure 2. The master timing unit has an ARM microprocessor and Altera FPGA to interface with the receiver.

Figure 2: Tracking the number of GPS satellites used in a receiver lock at the far detector in Ash River, MN.

To establish a universal time along every step of the timing system, each TDU, DCM and FEB has a time stamp register driven by a 64 MHz clock that is derived in a phase lock loop from the 10 MHz oscillator. On each successive clock cycle the timing registers are incremented. The “NOνA Epoch” is defined as the number of 64 MHz clock ticks beginning at 00:00:00 January 1, 2010 GMT. The time stamp is encoded in a 56 bit register with the lower 32 bits containing the full 64MHz resolution of the last 67.1 seconds, and the upper 24 bits providing lower precision, for a validity of 35.7 years. The 56 bit base time stamp can be extended to support readout frequencies of 128 MHz up to 1.024 GHz through the use of an additional high word byte which serves as a base frequency tag indicator for the rest of the time stamp. During operations the readout systems use only the value in the time stamp counter to assign a time to the data packets. The system is never required to start or stop readout gates, which allows for periodic synchronization of the entire detector to keep all components within one clock cycle. If the satellite lock is lost, the 10 MHz oscillator remains stable to 2 ppb per day.

4. Detector synchronization and delay calibration
To precisely synchronize the time stamp counters to the NOνA time, the timing signal propagation delays between each component of the system must be calibrated. The delay calibration is initiated by setting the “learn enable” bit in the control register of the MTDU. This initiates the delay calibration in each STDU and DCM. The delay offset value, which is arbitrary but must be larger than the maximum travel time from the MTDU to the farthest element in the system, is loaded into each unit. Upon receipt of the next SYNC signal sent from the MTDU, every element of the chain clears its time register and initiates a counter. The counter is stopped when the unit receives a return SYNC from the loopback. Each STDU then loads one half of the time-of-flight (TOF) value into its delay register. Each slave keeps an independent counter for the delay value down each DCM branch. The delay offset value is added to the delay calculated for the slave backbone and then one half the TOF for the DCM branch is subtracted
to compute the value loaded into the STDU delay register for each DCM branch. The MTDU loads its delay value, which is the total delay down the STU backbone plus the delay offset value into the “early SYNC” register. This is the time prior to a GPS 1 second boundary that a sync procedure needs to begin to ensure all units see the same time. This delay calibration can be performed periodically to monitor stability and seasonal temperature variations. Figures 3 and 4 illustrate the stability of the calibration within one 128 MHz clock tick. The higher precision counter is used so the delay is known more precisely then the digitization clock sampling rate used on the FEB at the Far Detector (16 MHz) or Near Detector (64 MHz).

Figure 3: Delay measured from a DCM to the end of the timing branch. DCMs 1-6 are in a branch on top of the detector with 6 being closest to the STDU backbone. DCMs 7-12 are located in a branch on the side, with 7 being closest to the backbone. Statistics are for one timing chain and are summed over the first 8 kilotons of detector instrumented.

Figure 4: Delay calibrated from a timing unit to the end of the backbone. The MTDU is located off of the detector hall and has a longer delay. Each STDU is uniformly spaced 12 clock ticks apart. One timing chain is pictured, delay values are identical for the second chain.

The timing system uses the scheme “At the tone the time will be...” to synchronize the detector. When a SYNC is requested the master timing unit looks at the current time and determines how close it is to the next 1 second GPS boundary. It then uses the delay loaded in the “early SYNC” register to calculate the next 1 second boundary sufficiently far in the future to complete transmission of the sync to all regions of the detector. This new NOνA time is sent out and pre-loaded in to the registers of each system component. The SYNC pulse is sent prior to the upcoming 1 second boundary calculated so the pulse reaches all elements before the designated time. When a sync is received by an electronics component (TDU, DCM, FEB) it is placed in a delay loop buffered with the calibrated value. With proper calibration the entire detector will exit the buffer loop and begin counting from the new NOνA time simultaneously. After the SYNC is complete the time stamp register in each device runs free, driven by the 10 MHz reference clock.

5. Decoding and transmitting accelerator events
At Fermilab the master timing units are connected to inputs from the accelerator controls network to decode and time stamp signals. These signals provide the neutrino beam spill event times in addition to reference pulses for diagnostics. The MTDU deterministically decodes and time stamps these signals in the NOνA time with the full 64 MHz resolution. This is necessary to
accurately identify the 10 $\mu$s NuMI neutrino beam spills to a higher precision than the ACNET system used to log data from the accelerator system.

The TDU takes inputs from both the Fermilab beam-synchronous (BSYNC) clock, as well as the Tevatron Clock (TCLK)[3]. The Altera FPGA on the TDU decodes the events and filters out selected signals to a buffer that can be accessed from the ARM microprocessor or an attached PowerPC single-board computer. Figure 5 illustrates the model used to transmit spills to the detector. A spill server application runs on the PowerPC on the TDU, accesses the event queue, and publishes spills over XML/RPC to the cluster at Fermilab. On the cluster a spill repeater application broadcasts messages over the internet to the Far Detector cluster and also to spill receivers on the Fermilab cluster. The far detector cluster has a second repeater application that broadcasts to receivers. A spill receiver communicates with the global trigger application when a run is in progress to trigger a readout of data from the buffer farm. Both the near and far detectors continuously write data to the buffer farm, where data is held for 20 seconds allowing time for spill messages to be received and converted to triggers. The backbone of spill server and spill repeater remains up at all times broadcasting to up to 10 receivers simultaneously, allowing for multiple runs to be taken simultaneously.

Figure 5: Schematic of the spill server system designed to relay accelerator event time stamps from the MTDUs at Fermilab to applications running on the Near and Far detectors triggering data readout.

To test the production system spill server applications were run on two independent TDUs located in the MINOS surface building at Fermilab. The time stamp of the very stable 1 Hz signal coming from the TCLK (event type $8F$) was compared between units to an agreement of $\pm$ 1 clock tick. This signal is also used to monitor the long term stability of the NO$\nu$A clock, shown in figure 6.

The NuMI neutrino beam at Fermilab began operations after a series of upgrades in September of 2013. The number and spacing of NuMI spills (event $74$ on the BSYNC clock) within one Super Cycle of the accelerator varies and depends on the experiments running. This is why NuMI spill times cannot be predicted and must be time stamped by the TDU. The $00$ accelerator event on the TCLK designates the start of a Super Cycle and is decoded by the MTDU as a diagnostic tool in understanding the spill patterns. Figure 7 measures the propagation time from a $74$ event time stamped at Fermilab to reception at a spill receiver at the Far Detector. In tests with up to 5 receivers running on both the Near and Far Detectors all spills were received within 10 seconds, well inside the storage time of the data buffer. Spill messages are broadcast asynchronously to each destination. Multiple attempts are made to send each message to minimize the chance of network traffic causing a spill to be dropped. In tests...
Figure 6: a) The 1 Hz $8F tclk$ signal was time stamped by two independent spill servers running in the MINOS surface building, producing triggers within 1 64 MHz clock tick of each other. b) The difference between the time stamp of a $8F$ event on the TDU and the closest 1 second boundary in the NOνA time epoch. This offset is stable within 10 clock ticks and provides a measure of the propagation delay from the $8F$ source to the TDU and a check that the TDU is not drifting. The $8F$ event has a low priority on the accelerator and can be artificially delayed, causing the outliers in the plot.

spills were lost at a rate of less than 0.01% at the Near Detector and 0.2% at the Far Detector.

Figure 7: a) The average time between NuMI $74$ events within one Super Cycle. The spacing of spills varies depending on which experiments are running. b) The time between the time stamp of a NuMI trigger at Fermilab and its reception at the far detector. Three spill receivers running simultaneously received messages within 10 seconds, well within the buffer storage time of 20 seconds. During operations 99% of spills have been received on the first transmission attempt within 2 seconds. The bump starting at 3 seconds is messages that had to be resent.

While the Far Detector construction is being completed and the beam power is ramping up statistics are too low to see the 10 $\mu$s excess of neutrino events over the cosmic background in data at the Far Detector. The NDOS prototype located at Fermilab where statistics are higher was used to time in the beam. The detector reads out a 500 $\mu$s data window when a trigger
was received indicating the start of a beam extraction. In data taken from September 12 - 27, 2013 the sharp peak of events seen in figure 8 is due to the neutrino interactions on top of the constant cosmic background. Selection cuts based on track angle, fiducial containment and activity were used to reduce cosmic background. The GPS coordinates of both detectors have been accurately measured so the NuMI spill window can be projected to the far detector, the global trigger application adds this calculated value to the time stamp of trigger events to produce the predicted readout window for the Far Detector.

Figure 8: Selection of events in the NDOS detector at Fermilab passing containment, activity and beam angle cuts. The data is read out in 500 $\mu s$ windows. The excess of events in the 217 $\mu s$ to 227.8 $\mu s$ window is due to neutrino events over the cosmic background.

6. Plans for calibration system

To ensure that both near and far detectors are seeing the same NO$\nu$A time, a calibration system is in development to monitor the GPS clocks. This system will consist of a Trimble Thunderbolt E GPS disciplined clock connected to an independent external GPS antenna. The stable 1PPS output from this clock will be fanned out to MTDU’s. The MTDU will time stamp these reference pulses and the tagged times will be compared to the known times. This calibration module can be transported between detector sites to monitor systematic offsets in the timing system. The calibration unit will also be capable of supplying a trigger pulse to an FEB which will serve as a check that the delays have been properly calibrated in the timing system and that the electronics is time stamping hits with the correct time.

7. Conclusions

The NO$\nu$A timing system at the Far Detector is through the commissioning stages and is in stable operation for the duration of the experiment. The ability to calibrate and synchronize this large detector that will contain over 344,000 readout channels to an absolute wall time with a variation of less then 10 ns has been shown. With the upgraded NuMI beam back in operation the system is accurately time stamping accelerator signals and has found the narrow 10 $\mu s$ neutrino peak in the prototype detector at Fermilab. The system is in place to transmit spills to the far detector and trigger readout at the expected arrival of beam spills. The system has succeeded in delivering triggers within the time data is stored in the buffer and spills are lost less than 0.2% of the time. A long term monitoring system is in development to monitor systematic offsets between the timing systems at each detector location.

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