Low-latency NuMI Trigger for the CHIPS-5 Neutrino Detector

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Abstract

The CHIPS R&D project aims to develop affordable water Cherenkov detectors for large-scale underwater installations. In 2019, a 5 kt prototype detector CHIPS-5 was deployed in northern Minnesota to study neutrinos generated by the nearby NuMI beam. This contribution presents a dedicated low-latency time distribution system for CHIPS-5 that delivers timing signals from the Fermilab accelerator to the detector with sub-nanosecond precision. Exploiting existing NOvA infrastructure, the time distribution system achieves this only with open-source software and conventional network elements. In a time-of-flight study, the presented system has reliably offered a time budget of 610 ± 330 ms for on-site triggering. This permits advanced analysis in real-time as well as a novel hardware-assisted active triggering mode, which reduces DAQ computing load and network bandwidth outside triggered time windows.

Keywords: Water Cherenkov detectors, Time synchronization, Software engineering

1. Introduction

The goal of the CHIPS R&D project is to develop affordable water Cherenkov detectors that are suitable for large-scale distributed deployments. In spite of their reduced cost per unit volume, CHIPS detectors aim to produce results of quality comparable with that of other current water Cherenkov experiments. This is achieved mainly by employing the following techniques:

1. Exploiting structural support and natural overburden of underwater deployments.
2. Utilising off-the-shelf components and readily available materials.
3. Designing modular parts that can be rapidly scaled and easily serviced.

1.1. CHIPS-5 Detector

The CHIPS-5 detector is the latest-generation CHIPS prototype that was deployed in 2019 in the north of Minnesota, USA. Using a 12 m tall cylindrical volume of 12.5 m radius (illustrated in Figure 1), the detector provides 1924 m² available surface area, offering the first practical insights into construction, deployment and operation of CHIPS devices at such scale. The site in northern Minnesota lies 7 mrad off the axis of the NuMI neutrino beam, a well-understood source of muon neutrinos that originates at Fermilab near Chicago, Illinois.

1.2. NuMI Beam Spill Cycle

The NuMI beam produces neutrinos in periodic spills. In order for these spills to be correctly scheduled, the Fermilab accelerator employs precise timing systems to track operation of its principal components: (1) the beam-synchronous clock system (BSYNC), and (2) the Tevatron Clock (TCLK) [2]. Under normal conditions, these systems emit characteristic hardware signals that describe various events of interest in the accelerator duty cycle. The triggering system presented here relies on a low-latency relay mechanism that communicates some of these signals to the detector site, where they are consumed by CHIPS data acquisition (DAQ) systems.
Available accelerator signals that are relevant to the NuMI beam are shown in Figure 2. Out of these, in order to be considered viable for triggering, a time signal must satisfy several requirements. Firstly, the time elapsed between the signal and the accelerator neutrino spill must have minimal jitter. Secondly, the signal must be reliably emitted for all spills. And finally, the signal must be available with a sufficient time in advance. With these requirements, two possibilities remain: (1) the TCLK signal $A5$, which marks the reset of the accelerator prior to the start of a new spill cycle, and (2) the BSYNC signal MIB$74$, which is emitted when neutrinos exit the accelerator complex.

2. Implementation

The triggering system is implemented as three subsystems, each dedicated to a specific task. First, the precisely measured accelerator signals are shared with the NOvA experiment. Second, a specific subset of signals is selected and delivered from the accelerator site to the detector site with low latency. Lastly, these delivered signals are consumed on-site by CHIPS DAQ systems, specifically the DAQonite data taking program.

2.1. NOvA Time Distribution Units

To access Fermilab accelerator signals, CHIPS-5 relies on existing facilities used by the NOvA experiment. In particular, its proprietary Time Distribution System (TDS) [4]. CHIPS utilised a prototype TDS unit which will be referred to here as the CHIPS TDU, although it should be stressed that the hardware was provided by the NOvA experiment. The TDS timestamps the accelerator signals with high-precision UTC provided by a commercial GPS satellite receiver. This information is transmitted through a hierarchy of Timing Distribution Units (TDUs, shown in Figure 3) that permit system-wide synchronization to within 7.8 ns across all elements.

Internally, NOvA TDUs contain a PowerPC 8347 computer providing a Linux platform. Usually, this computer hosts NOvA software that is responsible for consumption of the received timing signals. All timestamps handled at that point are compliant with the NOvA time specification that measures time elapsed as UTC ticks from the “NOvA Epoch” defined as 00:00:00 January 1, 2010 GMT.

The source of information for the CHIPS-5 TDS is a prototype NOvA TDU, which was procured and installed at Fermilab in the autumn of 2019. To serve as an adapter between NOvA and CHIPS
timing systems, a dedicated program was developed to replace standard NOvA software in the TDU. Among other tasks, this program is responsible for decoding consumed timing signals, converting timestamps from NOvA to UTC specification and forwarding data to the CHiPs-5 detector site through a low-latency communication channel.

2.2. Signal Delivery Chain

The signal delivery chain must overcome vast physical distance between sites as well as a variety of security measures while maintaining relatively short delivery times. For this purpose, a relay computer was installed at Fermilab to facilitate an elaborate tunnelling scheme (illustrated in Figure 4). From the CHiPs-5 detector site, a reverse SSH tunnel was initiated to the relay that permits the DAQonite program to expose a server interface. By a similar mechanism, an identical interface was proxied from the relay to the TDU, completing the delivery chain. Under normal operation, when a timing signal is consumed by the TDU, the information travels through the relay to the DAQonite server backend with standard latency within 10 ms.

For the purposes of monitoring, the relay computer software was further upgraded. In particular, the relay program was generalized to multiplex transmitted signals to an arbitrary number of destinations. In addition to the CHiPs-5 site, a virtual destination was added that points to a monitoring backend, which is capable of tracking signal frequencies. If signals of interest fail to be observed on a pre-programmed schedule, the backend generates warnings that alert detector operators. Furthermore, the relay was programmed with an automatic fault recovery failsafe that addresses a known issue of occasional spurious TDU reboots, which reset the TDU into an inoperable state. When such conditions are detected, the relay automatically reconfigures the TDU and boots the proprietary CHiPs software.

2.3. On-site Triggering

Once received by the DAQonite program, timing signals serve a variety of purposes in CHiPs DAQ. First, along with other information retrieved from the Fermilab accelerator complex, all signals are logged in the on-site storage facility, which supplies information to DAQ monitoring displays (shown in Figure 5) and offline analysis jobs. Next, if a data run is ongoing, timing signals can be used for passive triggering, where data are taken continuously but later rejected by the DAQ software. Last, if the detector hardware supports the latest generation of CHiPs plane optical modules (POMs), received signals may also be utilised for active triggering, where thanks to hardware-assisted scheduling data are only taken inside triggered time windows, removing the need for later software rejection and reducing network bandwidth considerably. Depending on the desired type of an ongoing data run, both passive and active triggering modes support in-phase and out-of-phase operation, effectively determining whether data are recorded during time periods of NuMI beam activity, or their complement respectively.

Passive triggering is realised by a continuous period of data acquisition combined with software rejection of undesirable PMT hits downstream in DAQonite. Conveniently, software components that facilitate passive triggering are also responsible for time window scheduling. For that reason, no additional implementation was required to implement per-timestamp data rejection.

In contrast to passive triggering mode, active triggering does not require continuous data taking, implying considerable reductions to DAQ load. Instead it relies on hardware support of detector POMs. During active triggering runs, detector remains in idle state by default, ready to start data acquisition at short notice. When a timing signal is received, a corresponding time window is calculated and programmed in its POMs. Since their PMTs are already precisely synchronised with UTC for the purposes of data timestamping, POMs can then control their own data acquisition and only measure hits inside of the programmed time window. For that reason, no out-of-window hits are
transmitted to, and processed by DAQonite, reducing upstream network bandwidth as well as computing load.

3. Benchmark Results

The CHiPs TDS was successfully implemented and its software packages were deployed to the Fermilab and CHiPs-5 detector sites. To thoroughly test the new system, real timing signals were observed and recorded in runs, each spanning a period of several days during the NuMI beam operation in late 2019. Throughout the monitored period, the system demonstrated resilience to random as well as deliberately introduced failures, and the capability to automatically recover into the nominal state once all faults were corrected.

The relative accuracy of delivered timestamps was evaluated by analyzing frequencies of various periodic timing signals and comparing them with the known durations in the Fermilab accelerator duty cycle. Among the examined signals, one that is of particular interest is the $74$ signal, which can be expected to show a consistent period of 1.333 s. Aggregating roughly 128,000 signals observed over a 3 day run (shown in Figure 6), the period was experimentally determined to be $1.333 \pm 317.7 \mu s$.

While this agreement provides independent verification of the system, the $74$ signal appears unsuitable for use in triggering due to occasional discrete variations in its period. Following further examination, it was determined that the $A5$ signal would be used instead.

In order to assess trigger signal viability, the amount of time from its emission to the subsequent arrival of neutrinos at the CHiPs-5 detector must be considered. This period represents the total time budget, during which the signal must be delivered between sites in order to remain viable for triggering. The budget is constituted by two components: (1) the time from the signal emission to the neutrino spill at the accelerator site $t_{A5\rightarrow\text{spill}}$, and (2) the neutrino time of flight $t_{\text{travel}}$ that is given

$$t_{\text{total}} = t_{A5\rightarrow\text{spill}} + t_{\text{travel}}$$

Even though the observed period is known to vary in discrete increments depending on the active Fermilab accelerator cycle, the given period can be expected to be dominant.
Time between $A5$ and $74$ [s]

$$t_{\text{budget}} = t_{A5 \rightarrow \text{spill}} + t_{\text{travel}}$$

$$= t_{A5 \rightarrow 74} - \sigma_{A5 \rightarrow 74} + t_{\text{travel}}$$

$$\approx 1.437 s - 3.48 \mu s + 2.5 \text{ ms} = 1.4395 \text{ s}$$

After subtraction of the signal delivery time due to network latency, the remaining budget for scheduling time windows at the CHiPs detector site based on this calculation is plotted in Figure 8.

According to the analysis, out of roughly 160,000 observed signals, approximately 3.69% had negative time budget, meaning that in such cases signals were delivered to the detector only after it had already encountered NuMI neutrinos. The remaining 96.3% of the accelerator signals preceded their corresponding neutrino spills, opening the possibility for scheduling time windows ahead of the incoming spills. At this point, it should of course be noted that this fraction does not include the latency of the final DAQ implementation.

Figure 6: Time between subsequent emissions of the $74$ signal aggregated in a histogram over the period of roughly 52 hours of NuMI beam operation.

Figure 8: Histogram of the budget remaining to schedule time window in CHiPs DAQ. Negative values are not viable since neutrinos beat the signal to the detector.

by $d/c$, where $d = 707$ km is the baseline length and $c$ is the speed of light. Since the $74$ signal marks the moment of the accelerator neutrino spill, the duration between two subsequent signals $t_{A5 \rightarrow 74}$ known from the accelerator duty cycle can be used to calculate $t_{A5 \rightarrow \text{spill}}$ in theory.

Alternatively, the same duration can also be measured experimentally (as shown in Figure 7) with the added benefit of considering the jitter $\sigma_{A5 \rightarrow 74}$ in the calculation. In such case, the estimate is conservatively given by $t_{A5 \rightarrow 74} = t_{A5 \rightarrow \text{spill}} - \sigma_{A5 \rightarrow 74}$. Combining all the listed components, the time budget evaluates as

$$t_{\text{budget}} = t_{A5 \rightarrow \text{spill}} + t_{\text{travel}}$$

$$= t_{A5 \rightarrow 74} - \sigma_{A5 \rightarrow 74} + t_{\text{travel}}$$

$$\approx 1.437 s - 3.48 \mu s + 2.5 \text{ ms} = 1.4395 \text{ s}$$

Figure 7: Time between subsequent emissions of the $A5$ and $74$ signals aggregated in a histogram over the period of roughly 52 hours of NuMI beam operation.
4. Conclusion

A new triggering system was developed that allows delivery of nanosecond-precise hardware signals from the Fermilab accelerator site to the CHIPS-5 detector 707 km away. Aside from existing NOvA infrastructure, the presented system relies only on open-source software and conventional networking infrastructure to provide a resilient low-latency trigger.

In a benchmark test, the system delivered over 96% of trigger signals ahead of their corresponding neutrino spills. This permits the use of a novel hardware-assisted active triggering mode, which reduces network bandwidth and DAQ computing load outside of triggered time windows.

Acknowledgements

This work was supported by Fermilab; the Leverhulme Trust Research Project Grant; U.S. Department of Energy; and the European Research Council funding for the CHROMIUM project. Fermilab is operated by Fermi Research Alliance, LLC, under Contract No. DE-AC02-07CH11359 with the U.S. DOE.

References


