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Evolution of the IceCube data acquisition system for IceCube-Gen2

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ABSTRACT: IceCube-Gen2 is a future large-scale extension to the IceCube Neutrino Observatory, a cubic-kilometer-scale neutrino detector at the geographic South Pole. The IceCube data acquisition system architecture, while running stably with over 99% uptime, will be re-optimized for IceCube-Gen2 to solve design challenges with power consumption, communications bandwidth, and cable specifications. In particular, we describe how distribution of the photomultiplier tube signal digitization and pre-trigger storage can reduce power and bandwidth requirements. Additional changes to IceCube's custom communications protocol can also relax crosstalk requirements on the copper cabling. We report on the status of these optimizations in the prototype Gen2 digital optical module design for the upcoming IceCube Upgrade.

Keywords: Data acquisition concepts; Neutrino detectors

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 $^{^1\}mbox{Full}$ author list and acknowledgments are available at icecube.wisc.edu.

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1 Introduction

The IceCube Neutrino Observatory, a cubic-kilometer-scale neutrino detector built into the ice sheet at the South Pole, uses an array of digital optical modules (DOMs) to detect the Cherenkov light from charged secondary particles produced in neutrino interactions [1]. A future large-scale extension, IceCube-Gen2, includes ~10,000 new optical modules with greater photocathode area instrumenting 8 km³, deployed as 120 additional strings (cables) of 80 DOMs each [2, 3].

Building an optical array 8× the volume of IceCube presents several scaling challenges if one simply extends the copper cabling to distances of up to 6 km. Not only would resistive losses and signal attenuation become problematic, but also the required power consumption would exceed the maximum power delivery of individual cables and, in aggregate, the generating capacity of the South Pole power station. Communications bandwidth also becomes an issue since the module dark noise will increase with the larger photocathode area. Finally, the cable cost and manufacturability become difficult due to tight specifications on the electrical crosstalk. Here we present solutions to these scaling challenges for IceCube-Gen2 by changing the cabling and data acquisition (DAQ) architecture and designing new electronics for the Gen2 DOM.

2 FieldHub

The primary copper cabling scaling issue can be solved by moving the custom electronics that communicate with the DOMs from the counting house (the IceCube Laboratory, or ICL) into the field. A "FieldHub" at the top of each Gen2 string contains the custom electronics that provide communications and timing to the optical modules. The downhole cable remains conceptually the same, as a collection of low-crosstalk "quads" (two twisted pairs) with multiple DOMs connected to each wire pair. The surface cable between the FieldHub and the ICL, however, is replaced with optical fiber and thicker-gauge copper power cable, where the fiber provides gigabit Ethernet and "White Rabbit" precision timing [4] to the FieldHubs, and the power cable can be run at higher voltage (400–600 VDC) to lower resistive losses. The metal FieldHub enclosure is insulated to

withstand the outside temperature range of -80° C to -15° C and elevated on poles to avoid being buried in the snow. The FieldHub architecture has been successfully demonstrated in a prototype cosmic ray detector station operating with the IceCube array since 2019 [5].

3 Gen2 DOM and Waveform Microbase

The power consumption of IceCube-Gen2 will be dominated by the optical array and thus the individual power consumption of each of the ~10,000 DOMs. By optimizing and distributing the digitization and processing of each of the photomultiplier (PMT) signals in the multi-PMT Gen2 DOMs [6], the overall power can be reduced significantly while still adding features to increase the DOM's dynamic range and time resolution. A model of the Gen2 DOM is shown in figure 1.

Compared to the multi-PMT mDOM for the IceCube Upgrade [7], the Gen2 DOM design:

- uses eighteen 4" PMTs instead of twenty-four 3" PMTs, providing the same photocathode area while reducing processing power;
- distributes the PMT signal digitization and processing to each PMT base (see below);
- reduces the digitization rate from 120 Msps to 60 Msps, possible since the photon arrival times are more spread out due to the larger string spacing;

Gen2 DOM Design vs. Upgrade mDOM

• 16–18x 4-in. PMTs vs. 24 3-in. PMTs

The primary custom electronies in this design is the • PMT signal capture and processing is ~70% of DOM power consumption Waveform Microbase (wuBase), which incorporates the PMTethight violitzagiongetricontaine and pethe signal digitization and processing onto each PMT base (figure 2a). The choices of TADIC, FPGA dirends microcontroller (MCU) are optimized for low power consumption, currently 140 mW PMT. Multaple waveform buffers are used in the FPGA in order to reduce deadtime. Figure 2b shows the data flow from the description of the desc $\,\cdot\,\,$ more important in Gen2 with higher energy events base is connected with a serial UART to a central MCU responsible item assembly of data packets to the surface. Clock signals are also distributed to each base so that the individual base timestamps can be synchronized or translated to a single DOM time domain, which in turn is translated to UTC in the FieldHubs using the reciprocal pulsing method (RAPCal) described in ref. [1].

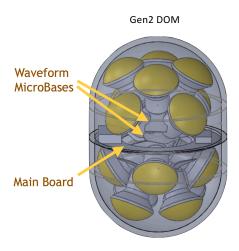
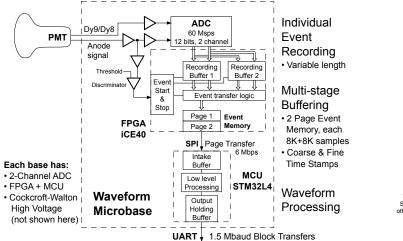


Figure 1. Preliminary model of the IceCube-Gen2 DOM.

The low power usage of the wuBase compared to using a monolithic, high-speed multi-channel ADC and a large central FPGA enables a reduction in DOM power consumption. We are targeting a total power consumption of 4W/DOM, compared to ≈ 10 W for the Upgrade mDOM. This solves issues with power distribution down the cable, where resistive losses at the bottom of the string can limit the number of DOMs per wire pair. This DOM power target results in a total Gen2 power budget of 85–100 kW, which is reasonable given near-term capacity limits on the South Pole Station power generation.



Additional PMTs Multiplexer UART Single-PMT Data Blocks 1.5 Mbaud 0.1 ~ 1 sec Time Span Main MCU Flash Memory STM32H7 1MB internal RAM Communication Module Requests / Commands 1 Mbps Coarse Trigger Data Requested Full-Hit Data Main Cable

PMT /

(a) Waveform MicroBase block diagram.

(b) Data flow from each PMT base to the main cable.

Figure 2. Data flow in the Gen2 DOM from each PMT to the main cable. Left: the Waveform Microbase on each PMT digitizes the signal high- and low-gain channels and records the leading edge time with a TDC. Right: data from each base are collected by a central microcontroller (MCU) and buffered in flash memory while coarse timestamps are sent to the surface DAQ. When an array-level trigger is formed, full waveform information is read out from the hit buffers.

4 DAQ architecture

In the IceCube DAQ system, each PMT photon detection or "hit" is registered by the DOMs, and an array- or subarray-level trigger is used to select collections of hits likely to be from particle interactions instead of background hits. When a trigger is formed, hits from all DOMs are bundled into an event that is passed to the higher-level processing and filtering system for directional and energy reconstruction. In the current DAQ and for the IceCube Upgrade, all DOM hits are sent to computers in the ICL where they are buffered on disk for up to two weeks. This long buffer (the "hitspool") allows readout of all raw detector data in case of an astrophysical event that might have resulted in sub-threshold neutrinos, triggered by an external gravitational wave or supernova alert.

Sending all DOM hits to the ICL, however, utilizes a significant portion of the communications bandwidth for background hit readout. In order to mitigate this in IceCube-Gen2, we are implementing a new architecture where the hitspool is moved to flash storage on the DOM itself. Coarse (sub-microsecond) timestamps of multi-PE hits are sent to the ICL for triggering, and then event readouts collect the hit data when needed for each trigger in order to build the events. This greatly decreases the bandwidth usage from ≈ 400 kbps/DOM in the IceCube Upgrade to ≈ 10 kbps/DOM for Gen2. This in turn allows us to attach more DOMs per wire pair, simplifying the downhole cable design. An additional optimization we are exploring is unfolding the PMT waveforms into (charge, time) pulse series on the DOMs [8], a processing step that serves both as a highly effective form of data compression and is also required by most of our reconstruction algorithms.

Finally, we consider the electrical requirements on the communications cable. Currently we require very stringent crosstalk suppression [1], primarily due to the fact that the RAPCal time

calibration procedure is inherently analog and measures delays with signal zero-crossings; any crosstalk can distort the waveform and result in significant time errors. If the current crosstalk specifications cannot be met for Gen2, this can be mitigated at the DAQ level simply by scheduling RAPCal pulses when neighboring wire pairs are quiet.

5 Summary and outlook

We have presented solutions to several of the scaling problems presented by the IceCube-Gen2 optical array. In particular, changes to the cabling and DAQ architecture solve issues with copper cable length and bandwidth, and a new electronics design for the Gen2 DOM increases efficiency and lowers power consumption. The cabling and FieldHub architecture is already in use at the South Pole in a prototype cosmic ray station; we continue to optimize the design of the FieldHub enclosure, facilitating the regular raising of the FieldHub to prevent it from being buried in the snow over decades of operation. Additionally, several prototypes for the Gen2 DOM will be deployed in the upcoming IceCube Upgrade, allowing validation of the design.

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