Design of a Robust Fiber Optic Communications System for Future IceCube Detectors

MICHIGAN STATE UNIVERSITY

R. Halliday*, T. DeYoung, C. Ng, D. Grant, B. Ferguson, D. Shooltz for the IceCube Collaboration

ICECUBE UPGRADE

1. Background:

IceCube is a gigaton-scale neutrino detector located at the geographic South Pole:

- Instrumented by >5000 Digital Optical Modules (DOMs) w/ 10” PMTs
- Records the Cherenkov light from interactions with high energy neutrinos.
- IceCube Upgrade will deploy in 2022/23 austral season [1] including future prototype/test devices for IceCube-Gen2.
- Looking forward: possible future IceCube-Gen2 detector instrumenting 8 km^3 for high-energy astrophysics [2]

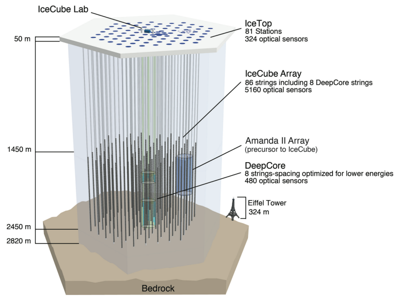

Figure 1: IceCube and sub arrays with Eiffel Tower for scale. Each vertical main cable connects 60 DOMs, and there are 86 cables (or “strings”) total.

Communications and timing in IceCube and beyond:

- IceCube DOMs communicate signals over long-run copper cables using custom communications protocol where two DOMs share a wire pair. Time tagging uses call and response scheme requiring low noise, driving stringent cross-talk suppression requirement for cables. This system achieves bandwidth capacity of 720 kbps per wire pair, timing accuracy of 1.2 ns [3].
- IceCube Upgrade deploys multi-PMT DOMs, raising the requirements on bandwidth capacity per wire pair, while in IceCube-Gen2, the larger detector will need longer runs (up to 6km).

->Moving to a larger detector (see fig. 4), IceCube’s communications protocol will be strained to meet requirements, while at the same time becoming prohibitively expensive. Going forward, we explore a hybrid fiber + copper system to mitigate these challenges.

AMANDA Fibers:

Optical fibers were used in the AMANDA experiment for signal collection in the ‘99/00 season. ~95% of fiber connections survived freeze-in. Since then, armored fiber technologies have advanced significantly.

2. Requirements:

Reflecting on the bandwidth capacity needs for IceCube-Gen2 and fiber experience from AMANDA, we set forth the following requirements:

- >1.5 Mbps bandwidth capacity per wire pair,
- <1.2 ns timing accuracy,
- Survives 10 kpsi pressure testing (standard IceCube deployment req.),
- Full system operation under ≥ 5% fiber breakage,
- More robust fiber and penetrator combination than used in AMANDA, and
- Cost and deployment complexity must be comparable or less than that of copper cables.

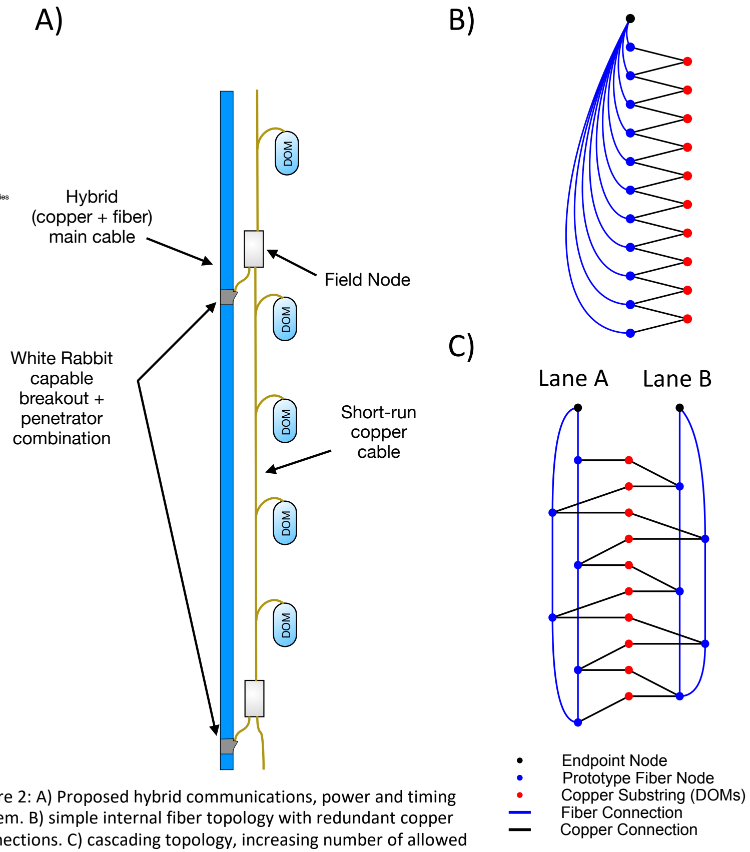

Figure 2: A) Proposed hybrid communications, power and timing system. B) simple internal fiber topology with redundant copper connections. C) cascading topology, increasing number of allowed fiber breaks before performance loss from one to three

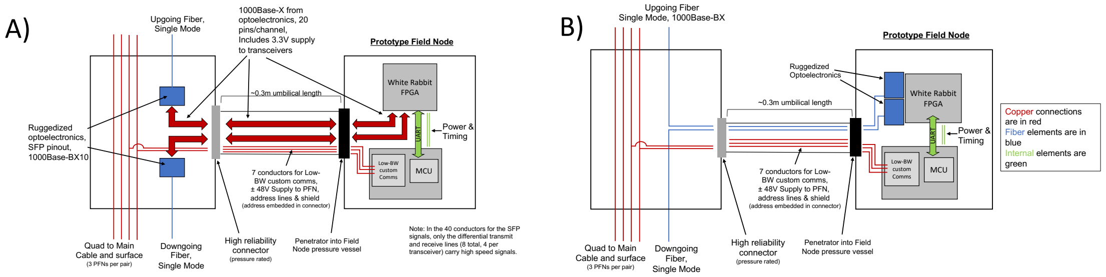

Figure 3: Block diagrams for FTS, A) High Speed Copper (HSC) design, using optoelectronic conversion in a pressure-vessel/breakout to bring White Rabbit signals in through a copper penetrator. B) Hybrid Fiber Penetrator (HFP) design, which brings fibers all the way to the Prototype Field Node. Both designs omit short-run copper connections for the prototype, which will be added for the full deployment.

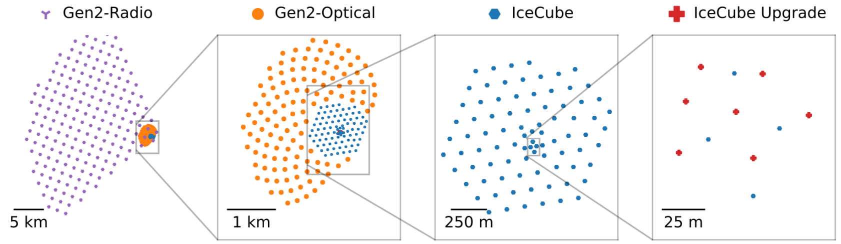

Figure 4: Maps showing the footprint of IceCube, the IceCube Upgrade and the components of IceCube-Gen2

3. IceCube-Gen2 Fiber Option:

Hybrid fiber/copper communications system (figure 2A) containing three novel assemblies: 1) Fiber Main Cable, 2) the Field Node and 3) the penetrator. The proposed fiber main cable goes 1.5-2.7km down hole, connecting the 1200m with 11 Field Nodes placed every 120m along the line. Field Nodes act as power, data and timing distribution hubs with eight sensors redundantly connected to both vertically adjacent Field Nodes via short run copper cables.

Timing/Data: IEEE1588-2019 High Precision "White Rabbit." gives ~100 ps timing and gigabit fiber Ethernet [4].

Redundancy: Internal fiber topology creates two looped fiber lanes, regenerating signals at each Field Node. Shown in fig. 2C, this retains full functionality up to a breakage of 23% of its fibers (in contrast with fig. 2B at 7%).

Short run copper connection: based on CHIPS and microDAQ systems, delivers PPS, 10 MHz, data and power [5,6].

Pathfinder System: IceCube Upgrade will deploy a pathfinder system dubbed the Fiber Test System (FTS). It will consist of six Prototype Field Nodes, attached to a Fiber Test Cable through one of the two proposed penetrator choices (HSC or HFP, see fig. 3). FTS will test the three novel assemblies (main cable, Field Node, and penetrator).

4. Conclusions:

Towards the design of a robust fiber optic communications system:

- We have compiled a selection of requirements and considerations based on the IceCube Upgrade, IceCube-Gen2 and experience from AMANDA
- Optoelectronic conversion in the breakout and/or ruggedized components satisfy concerns about fiber exposure and integrity under pressure
- Application of the White Rabbit PTP Protocol exceeds the timing and data throughput requirements
- By appropriately arranging fibers within the main cable, we gain a large redundancy improvement
- We will deploy the Fiber Test System in the IceCube Upgrade, giving us critical validation data for IceCube-Gen2

References:

[1] **IceCube** Collaboration, A. Ishihara *PoS* **ICRC2019** (2021) 1031

[2] **IceCube-Gen2** Collaboration *Journal of Physics G: Nuclear and Particle Physics* **48** no. 6, (Apr, 2021) 060501

[3] **IceCube** Collaboration *Journal of Instrumentation* **12** no. 03, (Mar, 2017) P03012–P03012

[4] J. Serrano *et al.*, “The white rabbit project,” in *Proc. 2nd Int. Beam Instrumentation Conf. (IBIC’13)*, pp. 936–942. JACoW Publishing

[5] D. Van Eijk, “Electronics and DAQ for the CHIPS Experiment,” in *Prospects in Neutrino Physics*. 5, 2018. arXiv:1805.12206 [physics.ins-det]

[6] T. Huber, J. Kelley, S. Kunwar, and D. Tosi *PoS* **ICRC2017** (2017) 401.

NSF

*Corresponding Author: Robert Halliday, rhalliday@icecube.wisc.edu