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The new generation of the Data Acquisition System of KM3NeT

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PoS(ICRC2023)1220

The KM3NeT Collaboration is installing two neutrino telescopes at the bottom of the Mediterranean Sea, ARCA and ORCA. These detectors are built in the form of very large 3D arrays of photomultipliers (PMTs) detecting the Cherenkov light induced by relativist particles propagating in the sea water. The PMTs are installed inside pressure-resistant glass spheres, the Digital Optical Modules (DOMs), each containing 31 PMTs together with the electronics for data taking and communication. Eighteen DOMs and a base module are comprised in a detection unit (DU), a structure standing on the sea bottom with a height of almost 700 m for ARCA (200 m for ORCA). For optimal performance of the detectors, a good synchronization of all parts of the detectors is required. The data acquisition system of KM3NeT has been designed based on the White Rabbit (WR) protocol. In a first phase of construction of the detectors, this has been developed in a tailored design based on a "broadcast" approach: in such scheme, the communications from the shore station to the detectors is performed by distributing the same data stream to all underwater nodes, while in the opposite path each single DOM sends data to shore through its own communication channel. For the next phase of construction, a new system has been developed, based on the standard WR protocol. This approach has some significant advantages, in terms of maintainability and scalability of the system, which are obtained with a non-negligible cost, however, since it became necessary to design tailored WR components which would meet the KM3NeT requirements and to modify the full design of the apparatus consequently. In this paper we will present and compare these two DAQ system designs.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

1. Introduction

KM3NeT is the next-generation neutrino telescope project, being implemented in the Mediterranean Sea [1]. KM3NeT comprises ARCA (Astrophysics Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss), which are under construction at almost 3,500 m depth, 80 km offshore Capo Passero at the southern tip of Sicily (Italy), and at about 2,500 m depth, 40 km offshore Toulon (France), respectively. The two detectors share the same technology and neutrino detection principle. They are built as very large, 3D arrays of photosensors, called digital optical modules (DOMs) [2], capable to detect the Cherenkov light induced during their propagation in the sea water by relativistic particles emerging from neutrino interactions. The DOMs are made with pressure-resistant glass spheres, each housing a set of 31 photomultipliers (PMTs) of 3” photocathode diameter, the electronics for data taking and transmission, and calibration devices. The DOMs are arranged on detection units (DUs), which are anchored on the sea bottom and stand due to the buoyancy of the DOMs and a top buoy. Each DU comprises 18 DOMs connected through a backbone cable to a base module (BM), which is located on the DU anchor. The BM is connected to a submarine network of Junction Boxes (JBs) and cables, which is connected to the shore with a long-distance cable, the MEOC (Main Electro-Optical Cable). Due to the size of the detectors and the distance from shore, all data communications take place on an optical fibre system.

There are significant geometrical differences between ARCA and ORCA. ORCA has been optimized for studying neutrino oscillations and mass hierarchy with atmospheric neutrinos in the few-GeV energy region. In ORCA the DOMs are spaced by ~9 m, and the distance between the closest DUs is of ~20 m. ARCA, which aims at the search of high-energy neutrinos from astrophysical sources, is considerably larger, with a DOM spacing of 36 m and a distance between the closest DUs of about 90 m.

The challenges for implementation of the data acquisition system for such detectors are manifold. KM3NeT is based on the approach of sending all data to shore, with minimal filtering performed offshore. In this scenario, all signals detected by all PMTs above a set threshold (which can be controlled from shore and is typically set at the level corresponding to 0.3 of the average signal expected for a single photoelectron) are sent to a cluster of computers onshore where the data are filtered according to various filtering algorithms and dispatched for all usages (including an online alert distribution system, a prompt data analysis system for swift analyses to be done in response to alerts and to a data storage system for offline analysis). The DAQ system has therefore to ensure the necessary throughput to cope with the PMT signal rate. Due to the optical background, which is unavoidable in the sea water, due to the decays of ^{40}K and bioluminescence, each PMT has a signal rate of about 7 kHz, which can increase occasionally due to bioluminescence bursts. In the design of the DAQ system a target throughput corresponding to about twice the expected PMT signal rate has been conservatively assumed. The system has also to provide the necessary reliability for long-term operation (10 years minimum). Redundancy, when possible, is a plus. Finally, for optimal detector performance, a good synchronization and time calibration of the large number of PMTs included in the detectors, which are distributed in very large volumes and at a considerable distance from the control station, is required.

The DAQ system of KM3NT was designed taking into account all such requirements. In particular, in order to satisfy the requirement about synchronization, an approach based on the White Rabbit (WR) protocol [3] has been adopted. This was implemented in two different designs: a “broadcast” system, which has been used in the first phase of construction of ARCA and ORCA, and a WR-standard system, which will be used next. These two systems are illustrated in the next sections.

2. The "broadcast" system

In the "broadcast" system, used so far in the construction of ARCA and ORCA, the White Rabbit protocol is used in a non-standard way, since the same data stream is distributed from shore to all offshore nodes. The distribution of such "broadcast" channel requires therefore no Ethernet or WR switching and is implemented directly inside the optical system, whose architecture is shown in Figure 1. Long-distance data communications take place thanks to Small-Factor Pluggable (SFP) electro-optical transceivers; these have been used in two versions: either transmitting at a predefined wavelength or with a wavelength tunable by remote control. The purpose is to implement a DWDM (Dense Wavelength Division Multiplexing) approach in which the data streams from 72 DOMs (i.e., 4 DUs) are injected into a single fibre of the MEOC and demultiplexed onshore.

In such "broadcast" system, the BMs work as "slaves" of the WR "master" onshore, which is synchronized, through a "Grand master" switch to GPS; this allows to use the WR approach to dynamically reconstruct a time offset between the downstream and upstream clocks at the level of the BMs. The DOMs instead communicate with shore over a standard Ethernet protocol. The time offsets between the master clock onshore and the local clocks running in the different DOMs cannot be determined through WR. Consequently time calibration procedures, which include the usage of optical calibration sources as well as data analyses performed on coincident signals detected by the PMTs due to the optical background and particle events, have been developed.

The "broadcast" system was designed in order to rely as much as possible on solutions which could be more easily implemented, considering that a fully WR-compliant design would require a significant effort, as explained in the next section. This system has been proven to be fully functional. At the moment of writing this text, in total almost 40 DUs are in operation in ARCA and ORCA.

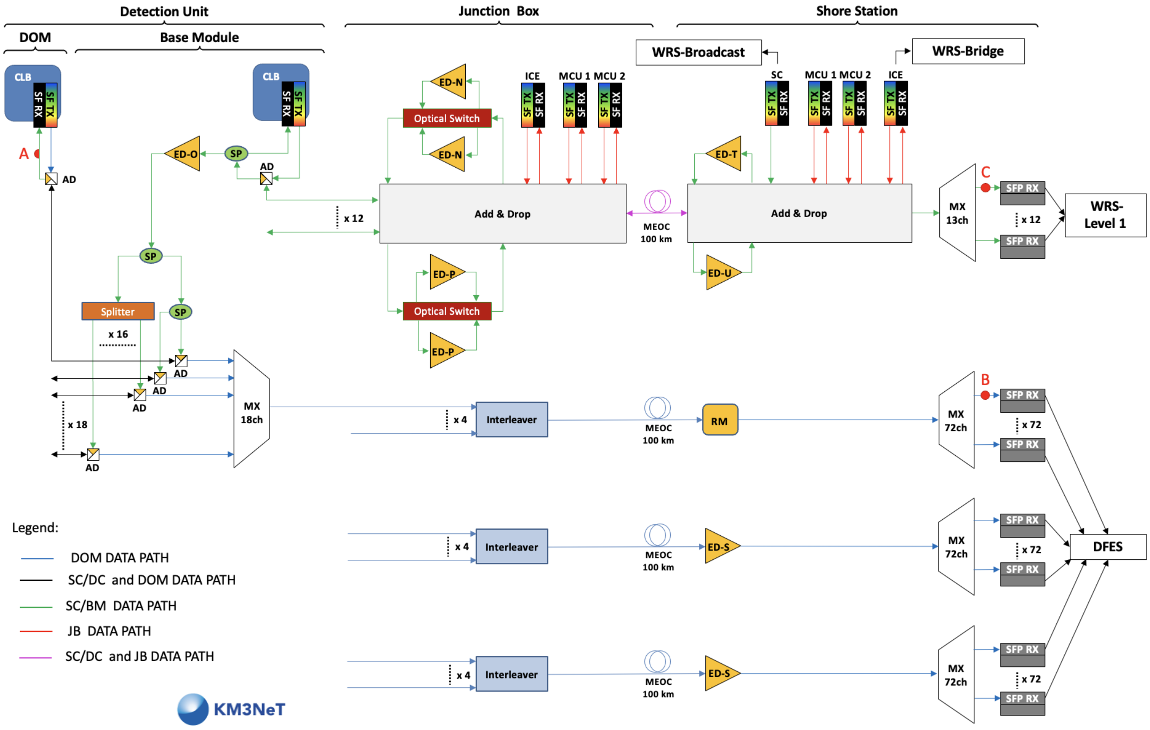

Figure 1: The optical network for the "broadcast" DAQ system of KM3NeT ARCA (the design for ORCA is similar, but not the same). The system requires the usage of Erbium-doped optical amplifiers (ED-x) both onshore and offshore. For additional details on this scheme see the text and [4].

1. The upgraded WR system

A non-standard WR system like the "broadcast" system illustrated above, leads to some disadvantages on the long term, in particular for maintaining the system compatible with the latest WR releases. This requires a continual effort from the Collaboration. Furthermore, the complexity of the network increases significantly with the size of the detector. Due to these reasons, a new implementation of the DAQ system has been designed, following a standard WR approach. It should be noted that, even if this development pays in terms of maintainability and scalability of the project, it comes with a significant cost, requiring several actions not only for redesign of the DAQ system itself but also in the following areas:

- Electronics: the necessary circuitry for implementing the WR system offshore had to be designed specifically, as none of the already available solutions could fit in the KM3NeT detectors.
- Power system: the new electronics requires increased power consumption, in particular inside the BM. The power system has therefore to be able to deliver such power with the required reliability.
- Optical system: this has been upgraded, starting with an adequate choice of the electro-optical transceivers to use inside the DOMs and BMs and redefining the optical network.
- Mechanics: the design of the DOMs and the BMs of the DUs had to be modified in order to accommodate the changes in the electronics and optical system. This was quite a demanding task in particular for the BM, due to the increased size of the instrumentation to be located inside it and the significant increase of power consumption.
- Calibration: the calibration procedures need to be updated in order to include the additional functionalities provided by the new DAQ system

The architecture of the new system is illustrated in Figure 2. The main feature of the new system is that the BM has been upgraded so as to provide a WR switching capability. This has been done by implementing tailored electronics boards equipped with the switches and the electro-optical transceivers for communication with the DOMs of the DU (for more details on such implementations and other recent upgrades of the electronics see [5]). Inside a BM there are two of such switches, each equipped with 18 ports. One of such ports is needed for the long-range communication with the shore station, another one is used for the control board inside the BM. A port on each switch is used for establishing a direct communication between the two switches, for redundancy. Therefore, a total of 12 ports, extra to the 18 needed for communication with the DOMs, remain available on the two switches. They are used for performing redundant (cold) communication channels with selected DOMs of the DUs.

The DOMs have been upgraded as follows: the central logic board has been modified in order to host the electro-optical transceiver for communication with the BM and the firmware which is run inside the DOM is a standard WR release.

The optical network in the submarine part as well as onshore has also been upgraded: each DU now communicates with shore with just two communications channels, and this allows a different DWDM scheme to be implemented, in which the communication channels for 7 DUs are multiplexed into a single optical fibre inside the submarine junction boxes. In this new system the circuitry of the shore station is fully WR-compatible.

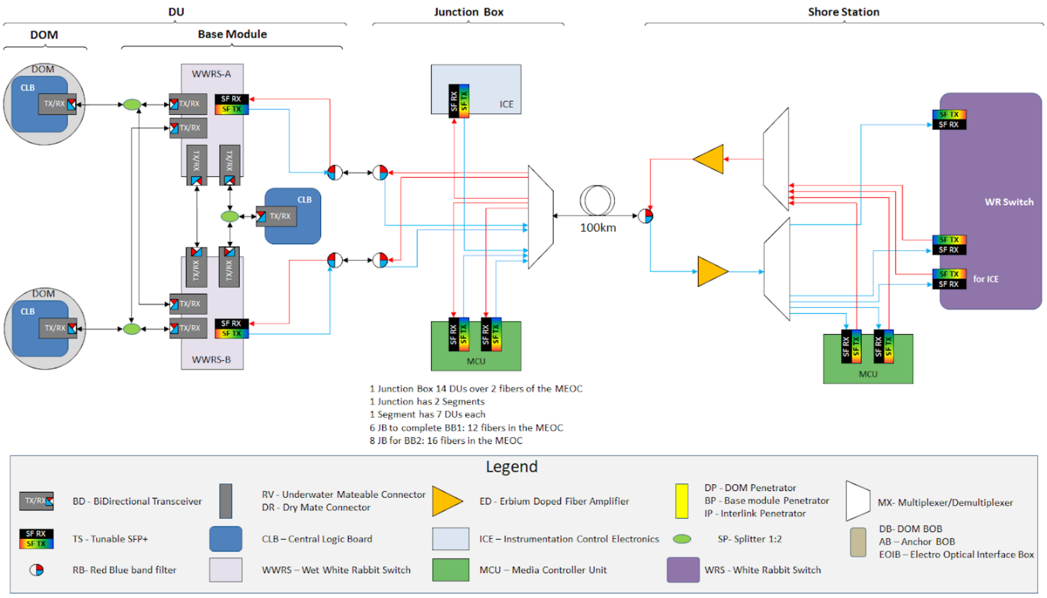

Figure 2: The architecture of the new DAQ system of KM3NeT ARCA (the design for ORCA is similar, but not the same). BB stands for Building Block, a set of 115 DUs (two BBs are foreseen in ARCA, one in ORCA).

2. Conclusions

The implementation of large, deep, submarine detectors, like ARCA and ORCA comprised in KM3NeT, requires highly reliable solutions. The DAQ system in particular has to satisfy demanding requirements as to data throughput and the need of synchronization at the level of the nanoseconds of detection elements distributed over very large volumes and at a very large distance from the control station. The KM3NeT Collaboration has implemented two layouts of the DAQ system, based on the White Rabbit protocol. The first sectors of ARCA and ORCA have been built with a DAQ system implementing a "broadcast" approach, i.e. a system in which the same data stream is distributed from onshore to all offshore nodes. A new system, implementing a standard WR network has been later implemented for the purposes of increased maintainability and scalability. Construction of new DUs equipped for such DAQ system and of the corresponding sector of the submarine network is starting.

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