The evolution of the KM3NeT Data Acquisition System for Phase-2 of the experiment

Francesco Benfenati Gualandi[1,3,*] on behalf of the KM3NeT Collaboration.

[1]Istituto Nazionale di Fisica Nucleare - Sezione di Bologna, Viale Berti Pichat 6/2, 40127, Italy
[2]Università di Bologna, Dipartimento di Fisica e Astronomia, Viale Berti Pichat 6/2, 40127, Italy

Abstract. The KM3NeT experiment is composed of two underwater large-scale neutrino telescopes currently under construction and located in the Mediterranean Sea, namely ARCA and ORCA, mostly designed for studying cosmic neutrinos and neutrino properties respectively. The two KM3NeT detectors share a common modular Data Acquisition System, which is designed to be scalable with the size of the detectors. The KM3NeT/ARCA detector design has changed from a previous network architecture, based on a customized version of the White Rabbit time synchronization protocol, to the current network, which follows a standard White Rabbit use case. This solution allows us to expand the telescope to the foreseen cubic kilometer volume. In this presentation the evolution of the Data Acquisition System according to the new architecture is presented.

1 Introduction

The KM3NeT Collaboration is building and operating two underwater neutrino telescopes in the Mediterranean Sea: KM3NeT/ARCA and KM3NeT/ORCA. The KM3NeT/ARCA detector aims at performing astrophysical studies with cosmic neutrinos from the TeV to PeV energy scale, while KM3NeT/ORCA is optimized for the detection of atmospheric neutrinos at GeV energy scale for oscillation studies. Despite the different physics goals, the two detectors share the same detection principle: the neutrinos direction and energies are reconstructed from the photon hit produced by the Cherenkov effect in water along the passage of the charged leptons produced in the neutrino interaction with the medium. The photon hits are recorded by photomultiplier tubes, encased in pressure-resistant spherical optical modules (DOMs) distributed along floating strings, the Detection Units (DUs). The detectors are described in Sect.,2. The KM3NeT Data Acquisition System (DAQ), described in Sect. 3, is responsible for controlling the detector optical modules, collecting and storing the acquired data by the PMTs. To achieve an angular resolution for reconstructed neutrino tracks smaller than 1°, DOMs must be synchronized with nanosecond precision [1] and their position known with O(10) cm accuracy [3]. The former is obtained by means of the CERN White Rabbit (WR) time synchronization protocol [2] implemented with WR switches onshore and with a dedicated WR core on the FPGA operating in the electronic boards of the optical modules offshore. The positioning of the modules is determined through an acoustic positioning system [3] composed of acoustic emitters, located in the subsea network, and receivers, located on

---

[*] e-mail: benfenat@bo.infn.it

DOMs and on the DU anchoring frames. The acoustic signals are triangulated to reconstruct the module positions. A first bunch of 30 DUs (Phase-1) of the KM3NeT/ARCA telescope, whose deployment concluded in October 2024, and the KM3NeT/ORCA DUs deployed so far were built according to an asymmetrical network topology, referred to as the "Broadcast" scenario. Its design implies the use of a customized WR protocol: details are given in Sect. 4. Starting from October 2024, the design of the seafloor network of KM3NeT/ARCA has changed, adopting the "Standard White Rabbit" approach (Phase-2) for three additional newly deployed DUs. Thanks to the introduction of additional WR switches offshore, the time synchronization of the optical modules can exploit the standard WR protocol. This scenario is illustrated in Sect. 5. The two parts of the KM3NeT/ARCA detector (Broadcast and Standard White Rabbit) will contribute together to the data taking, as explained in Sect. 6.

2 The KM3NeT detectors

The KM3NeT detectors [4] consist of large volume three-dimensional arrays of spherical Digital Optical Modules [5] hosting 31 3-inch PMTs and are placed at the Mediterranean seabed at a depth of ~3500 m (ARCA) and of ~2450 m (ORCA). DOMs are vertically aligned on strings named Detection Units, each hosting 18 DOMs. At present, KM3NeT/ARCA and KM3NeT/ORCA have 33 DUs and 24 DUs respectively; at completion, they will have 230 DUs and 115 DUs. Each DOM also hosts a piezoelectric sensor to record the acoustic waves of the positioning system emitters. The readout electronic board of the DOMs is the Central Logic Board (CLB) [6]. The CLB is responsible for the data acquisition from the PMTs, the piezoelectric sensors, the other ancillary monitoring sensors that are integrated on the board, and for the data transfer via optical fibers to the shore stations where the processing occurs. The anchor frame of the DU hosts a Base Module: a pressure resistant container which include the electronics for powering the DU, a dedicated CLB for readout of the powering boards parameters, and, in the Standard White Rabbit scenario, two WR switches.

3 The Data Acquisition System

The communication between the shore stations and the detector CLBs occurs through a Ethernet network on optical fibers, exploited also by the WR protocol to distribute time from the GPS in the shore stations to the CLBs with sub-nanosecond precision. According to a triggerless readout design, no trigger is implemented on the CLB and all data acquired by the PMTs and by the acoustic sensors is delivered to the shore stations. The average data throughput from a DU is $\sim$ 250Mb/s. Only a small percent fraction of this traffic is due to packets from DOM monitoring sensors, CLB replies to control commands and WR packets.

Once in the shore station, optical and acoustic data streams are routed through a standard switch fabric to the *Trigger and Data Acquisition System*: this is a framework composed of consecutive processing stages, implemented with C++ software applications, running on dedicated servers. The first step of data processing is a queueing stage where a modular number of programs (called optical and acoustic *DataQueues*) takes care of collecting and assembling in common time frames the optical and acoustic data packets from the CLBs and sending the resulting packets to the second stage, i.e. the filtering. Here, a modular number of processes (called optical and acoustic *DataFilters*) apply the trigger algorithms, implemented in the KM3NeT Jpp [7] framework, to data. Eventually, filtered data are routed to a process which writes them to ROOT [8] files and store them on a local server. Copies of the ROOT files are also saved on remote storages: CNAF-INFN, in Italy, and CC-Lyon, in France. The orchestration of the routing of the packets from the different stages of data processing, as well as of the configuration and data taking of the DOMs, is done by the Control Unit [9], a collection of software processes and a web-server-based interface, through which users can start and stop data acquisition sessions, segmented into runs, with the desired DOMs, trigger and data acquisition settings. The Control Unit is also responsible for collecting and logging data from DOMs ancillary instruments to the experiment central database. The Control Unit and the Triggering and Data Acquisition System processes are deployed on the available computing resources in an automatized framework based on Ansible [10]. The modular design of the DAQ system allows it to scale up as more DUs are deployed and the data throughput increases by simply increasing the number of switches and installing additional copies of Triggering and Data Acquisition system processes on new computing resources.

4 The *Broadcast* scenario

The *Broadcast* architecture involves the optical [11] and networking systems of the first group of 30 DUs of KM3NeT/ARCA and the DUs of KM3NeT/ORCA. In this architecture, the layout of the connections between the shore stations and the CLBs is asymmetrical: timing and control commands from the shore stations are broadcasted to all CLBs through a single optical channel, whereas each CLB exploits an uplink channel to send data packets and command replies to standard frontend switches onshore. The CLBs of DOMs do not reply with any WR packets. In order to prevent the occurrence of uncontrolled packets loops in the switching fabric, the standard switches used to interface the Trigger and Data Acquisition processes with the WR and the frontend switch fabrics are configured as to make use of Software Defined Networking rules [12] which are created to explicitly map any possible network flow in the devices, routing the packets only to the due ports. Due to its intrinsic design, the Broadcast architecture is incompatible with the standard WR protocol. A customized version of the protocol has been put in place to synchronize the CLBs of the DOMs, by modifying the firmware of the WR switches in the shore stations and the WR core of the CLBs inside DOMs. On the contrary, the CLBs in the Base Modules exploit the standard WR protocol. The time front of CLBs inside DOMs is shifted of the master-to-slave delay with respect to the shore station. The PMT hit times are later corrected, at trigger level, by applying a calibration procedure.

5 The *Standard White Rabbit* scenario

Due to the limitation on the available number of fibers inside the deployed submarine electro-optical cables which connect the shore stations with the offshore infrastructure, the *Broadcast* scenario is not scalable to the configuration of the KM3NeT/ARCA detector at completion, limiting it to the first group of DUs. For the remaining DUs, a different optical network has been adopted. In this scenario, referred to as the the *Standard White Rabbit* architecture, the Base Module has been redesigned in order to include two WR switches made of standard switching core boards and custom backplanes with a form factor adapted in order to fit inside the module. These two WR switches, called *Wet* are synchronized through bidirectional link fibers by other WR switches onshore, called *Dry*, and in turn synchronize (and redirect the data) through bidirectional fibers the CLBs of the DU, which thus exploit the standard master-slave relation of the WR protocol. Thus, only two fibers (the Wet switches uplinks towards the Dry switches) are required in the submarine cables to synchronize and deliver data from each DU to the shore station. Usually, each Wet switch synchronizes 9 DOMs, but the number of available ports on the Wet switches is such that 12 CLBs of the DU are connected to both switches, implementing redundant links that can be activated in case of failure of the primary link. An interlink between the two switches allows also to synchronize one switch with the other, and to redirect its data to shore, in case of failure of the uplink towards shore. The 1 Gbps bandwith of the Wet WR switch uplink is four times larger than the average (~ 250Mbps) throughput from the entire DU. Onshore, a fabric of WR switches synchronizes the Dry switches starting from a GPS clock. Data from the Dry switches is aggregated on standard switches.

6 Full KM3NeT/ARCA detector operation

The KM3NeT/ARCA detector must operate and acquire data at the same time with DUs of both the Broadcast and Standard White Rabbit architectures and process it as a single detector. To do so, some DataQueues are dedicated to process the data packets from the Broadcast DUs, others process data packets from the Standard White Rabbit DUs. All DataQueues then send the assembled packets to the DataFilters which apply the trigger algorithms to data from the full detector. An additional standard switch, named *STRIDAS*, is used in the shore station to aggregate and route the raw traffic from/to the Broadcast DUs, the Standard White Rabbit DUs and the Control Unit, as well as the filtered traffic between the DataQueues, the DataFilters and the writing process. Due to the different implementation of the Broadcast and Standard White Rabbit networks, the respective data flows are kept separated through the use of different VLANs on the *STRIDAS* switch and the separation by IP addresses of the CLBs of the two sectors. The Control Unit, which must communicate with both sectors, is connected via two IP-different interfaces to the *STRIDAS* switch. Since October 2024, the three deployed DUs in the Standard White Rabbit architecture are taking data independently from the other 30 DUs of the Broadcast sector; from the beginning of 2025, when the commissioning phase of the Standard White Rabbit architecture will be completed, this merged DAQ system is going to be effective.

References

[1] R. Coniglione *et al.* [KM3NeT], *KM3NeT Time Calibration*, *PoS ICRC2019, **868** (2021).* https://doi.org/10.22323/1.358.0868

[2] White-Rabbit website: http://white-rabbit.web.cern.ch/

[3] S. Viola *et al.* [KM3NeT], *KM3NeT acoustic positioning and detection system*, *EPJ Web Conf., **216** 02006 (2019).* https://doi.org/10.1051/epjconf/201921602006

[4] S. Adrian-Martinez *et al.* [KM3NeT], *Letter of intent for KM3NeT 2.0*, *J. Phys. G **43**, 084001 (2016).* https://doi:10.1088/0954-3899/43/8/084001

[5] S. Aiello *et al.* [KM3NeT], *The KM3NeT multi-PMT optical module*, *JINST **17**, no.07, P07038 (2022).* https://doi.org/10.1088/1748-0221/17/07/P07038

[6] S. Aiello *et al.* [KM3NeT], *KM3NeT front-end and readout electronics system: hardware, firmware and software*, *J. Astron. Telesc. Instrum. Syst., **4**, 046001 (2019).* https://doi.org/10.1117/1.JATIS.5.4.046001

[7] The JPP framework: https://sftp.km3net.de/documentation/Jpp/v17.2.0/

[8] The ROOT website: https://root.cern.ch/

[9] S. Aiello *et al.* [KM3NeT], *The Control Unit of the KM3NeT Data Acquisition System*, *Comput. Phys. Commun., **256** 107433 (2020).* https://doi.org/10.1016/j.cpc.2020.107433

[10] Ansible website: https://www.ansible.com/

[11] S. Aiello *et al.* [KM3NeT], *KM3NeT broadcast optical data transport system*, *JINST **18**, no.02, T02001 (2023).* https://doi.org/10.1088/1748-0221/18/02/T02001

[12] T. Chiarusi, E. Giorgio [KM3NeT], *The Software Defined Networking in KM3NeT*, *EPJ Web Conf., **207**, 06009 (2019).* https://doi.org/10.1051/epjconf/201920706009