Data Transmission and Acquisition in NEMO

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Abstract

A comprehensive system for data transmission and acquisition has been developed for an "à la NEMO" underwater neutrino telescope based on Čerenkov light detection using photomultipliers (PMTs) as sensors. Signals generated by each sensor are triggered, sampled and tagged by an electronics board, called Front End Module (FEM). Data streams from up to 8 FEMs located on one tower floor are collected by a concentration board called Floor Control Module (FCM) and sent to a twin FCM board — located at the onshore station and plugged into an interface machine (FCM Interface, or FCMI) via a PCI bus — through a DWDM-compliant optical fiber and using a self-synchronous serial protocol. All sensor data reach the onshore lab through FCMI where they are made available to subsequent elaboration processes, such as time-wise alignment and muon track event-triggering. To meet requirements of the latter, onshore data unpacking is carried out with respect to their topological origin. The system promised, and keeps on showing, very light charges on power consuption and infrastructure complexity, while having recently proved to behave at high performance levels in its optical part.

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1. Introduction

Due to assembly and deployment needs, all of the existing underwater neutrino telescopes [1] [2] [3] are organized as arrays of vertical detection elements, referred to as *lines*, *strings* or *towers*. Each of the latter exhibits aggregates of sensors placed at different heights. Even though the developed information transmission system was designed to fit the particular NEMO design constraints, many of the considerations will often hold true for other VLVnTs as well. While scalability of the system make it immediately suitable for a NEMO-like KM3 experiment, main reference will be made in the following to the probe NEMO Phase-1 apparatus. Under a general "à la NEMO" perspective, sensors are grouped in *floors*. Floors are spaced 40 m apart along a *tower*, with an initial gap of 150 m between the sea ground and the first floor. The NEMO Phase-1 underwater tower will be endowed with 4 floors, thereby being about 300 m high. From a mechanical point of view, a floor is a bar of about 15 m long, hosting 2 so-called benthospheres at each of its ends (i.e. 4 benthospheres per floor). Each benthosphere contains the so-called Optical Module (OM), i.e. a Photomultiplier (PMT) and a digitizing readout electronic board (FEM).

Generally speaking, when such an underwater infrastructure is involved, information transmission tasks consist in setting up a link between the so-called off-shore instrumentation and the on-shore laboratory. This means: (a) Provide control links between the laboratory and all the parts of the apparatus that need and support control-like interac-

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tions; these links should be supposed bidirectional — in the simplest interpretation, commands leave from on-shore, and answers come back — and of reduced capacity. (b) Provide a link for sensor data to reach the laboratory without losses; channel(s) offering this service shall be considered unidirectional, but generally need a much higher capacity, or bandwidth. In the following, attention will focus on sensor data transmission, unless differently specified.

The complete transmission architecture may be obtained via a multiplexing operation over a single *subsystem*, which is what will be considered first. Three main logical communication links are concerned with data transport from OMs to onshore facilities. The first provides the connection between an OM and a unique, floor-based, concentration device called Floor Control Module (FCM); four of these links are to be included in a single subsystem when NEMO Phase-1 is considered. The second — and more critical — link connects the underwater FCM to a corresponding onshore unit, whose task is to unpack the data (i.e. to extract and logically separate information coming from each of the four OMs) and make them available on an accessible volatile memory, namely on some Front End Buffers (FEBs), each related to a single OM; although carried out locally, this latter operation will be accounted of as the third link of the chain.

After first shortly introducing OM data generation and collection in section 2, the rest of the data transmission chain will be detailed (sections 3 and 4), with particular emphases on related data loads. The way a single subsystem can be brought back to the global transmission network will be dealt with in section 5. Finally, some conclusions will be drawn about the infrastructural advantages provided by the system, and the performance levels of its optical section, as recently assessed by the Italian Ministry of Telecommunications.

2. Optical Module overview: data production and collection

For simplicity's sake, it may suffice to say that PMTs produce short pulses, when hit by photons. These signals are band-limited to less than 100 MHz, and sampled at a rate of 200 MHz using 8 bits per sample. Assuming that the main contribution comes from the so-called *single photo-electron* (SPE) signals, each pulse would be 10 Bytes long, on average; the trigger time instant and some communication overhead complete the data packet. Note that zero-skipping is performed, i.e. no sample is transmitted if no hitting photon is triggered. A Poisson-like behaviour with 50 kHz mean is considered reasonable for the pulse (or *event*) rate in the selected site (refer to [4] [5] [6] for details about sea campaigns and to [7] for theoretical calculations). This leads to a reasonable estimation for the mean information load of about 500 kBytes/s, or 4 Mbps. Signal conditioning, sampling and triggering, and data buffering, encapsulation and transmission are carried out by an electronic board called Front End Module (FEM), placed inside the OM; refer to [8] and [9] for further details.

As described in [10], each FEM is connected to its FCM via a serial channel, using a 19.44 MHz clock and a *8b/10b* protocol [11]. Effective channel capacity is then found to be 15.55 Mbps, i.e. 1.944 MBytes/s. This is about four times the mean information load, and enough for the channel saturation probability to be negligible. In conclusion, a maximum incoming load of about 8 MBytes/s must be accounted of, if 4 OMs are hosted in one floor. Actual electronics allow up to 8 boards per floor.

3. From floor to onshore: the long-haul link

Data coming from OMs hosted on the same floor are concentrated on the just cited *offshore* FCM board, and sent to a twin FCM board located *onshore* via a 100 km, fiber optics-based, link, without any need of active signal regeneration. The onshore FCM board is perfectly identical to the offshore one, while performing slightly different tasks. It is to be noted that using the same board at the two sides of the long-haul fiber optics link has permitted remarkable savings in R&D resources: task diversification between the two boards is achieved by only using different softwares.

Among the many possibilities for the transmission protocol, a telecommunication standard was chosen: the SONET/SDH protocol, where SONET stands for Synchronous Over NETwork and SDH stands for Synchronous Digital Hierarchy. This standard is thoroughly defined by ITU-T recommendations and represents the *de facto* protocol adopted by all modern telecommunication systems. Possible data rates for the latter are defined starting from 52 Mbps (STM-0) up to 10 Gbps (STM-64) and even higher. Beyond the physical layer, a protocol layer is defined as well: user data are merged with an overhead stream packet which manages, controls and implements the details of the communication over the selected link.

The adoption of such a standard allows compatibility with a huge set of instruments available in order to debug, test and certify the board versus jitter performance, data integrity and consistency, BER measurements and protocol compliance.

One specific transmission scheme, namely *STM-1*, was again selected among the many offered by SDH format; this provides a total raw data rate of 155.52 Mbps. The basic aggregate data unit is called *frame* and lasts 125 μs; therefore changing data rate means modifying the number of transmitted bytes per frame: the STM-1 frame consists of 2430 bytes. Actually the useful data available to the user, called *payload*, consists of 2340 bytes per frame, which yields 18.72 MB/s, or about 150 Mbps. This capacity allows the static allocation of up two 8 logical channels (each holding a maximum of about 2 MBytes/s, as already stated), one for each FEM board. This means no need for any statistical multiplexing managing unit, and still enough space for integrating information flows coming from control devices such as environmental sensors, calibration boards, hydrophones.

4. Onshore data unpacking

The onshore FCM board is plugged into a PC-compatible machine (FCM Interface, or FCMI), and is accessible from it via a 32-bit, 33 MHz PCI bus [12].

From the OM data point of view, the PCI bus is used to extract data packets from the board, and write them onto some Front End Buffers (FEBs from now on), where they can be accessed from forthcoming processes. These can be time-wise alignment, direct muon track event-triggering, or just data displacement into a new concentrating machine. To make accessibility more direct, each FEB corresponds uniquely and statically to an underwater FEM, and must contain readable, self-explaining data packets.

The adopted PCI standard offers a clock period of $(33\ \mathrm{MHz})^{-1}$ for each 32 bit word transfer, yielding a *nominal* capacity of 132 MBytes/s. Actual capacity may be much smaller than this, depending upon many different factors: all must be taken into a careful account for best bus usage. Measured transfer rate for onshore FCM on the bus could be made as big as about $50 \div 60$ MBytes/s. This already implies taking advantage of the so-called *Bus-Master Direct Memory Access (DMA) mode*, that allows data to flow directly from the PCI bus to the RAM, without main processor intervention. Considering also the latencies due to data elaboration and packet formatting inside the FCM onshore and prior to transfer through the bus, the following considerations can be drawn for actual NEMO Phase-1 configuration: (1) the time required to deconcetrate the data, format the packets to fill the FEBs, and correctly address them, is perfectly consistent with the 2 MBytes/s upper bound allowed for each OM; (2) up to 4 onshore FCMs could be allowed on the same PCI bus — i.e. on the same FCMI — each having ideally its portion of bus bandwidth assigned statically (once again: no active queueing needed) at the price of pushing bus occupation next to saturation; (3) more likely, only one FCM per bus should be preferred, still leaving available a large portion of bus capacity in case of need for local or remote data displacement.

5. The complete optical network

Now that the single transmission subsystem has been outlined, a brief overview is needed of how channel multiplexing is carried out. Basically, all the logical channels that connect the two FCMs together — each based on the STM-1 protocol, as seen in section 3 — must be shipped on the same optical medium. This step is carried out by using standard DWDM techniques. DWDM stands for *Dense Wavelength Division Multiplexing*, i.e. a particular kind of frequency division multiplexing in the optical frequency domain. In the adopted scheme, carrier frequencies fall in the range between 192.1 THz and 196.1 THz with 100 GHz spacing. Each DWDM channel — or carrier — hosts a STM-1 FCM-to-FCM link. A completely passive optical network has been conceived and built to host this telecommunication architecture. The key points have been (1) to guarantee the needed power budget at the receiver, after the insertion of all the passive optical mux/demux devices, and (2) to provide the network with some kind of redundancy on the transmission media, against potential damages to the most critical and exposed branches.

6. System performance and assessment

The described configuration of the optical network, developed and previously tested by Tel.Con. S.R.L. for I.N.F.N., was assessed by the italian reference laboratory for information and communication technologies (Istituto Superiore per la Comunicazione e le Tecnologie dell'Informazione, or I.S.C.T.I.), at the Italian Ministry of Telecommunications during July 2005. A tower with 16 floor was set up in terms of fiber optics components (i.e. transceivers, fibers, *add* and *drop* modules, mux and demux units) together with its onshore counterpart. A real fiber was used to mimic the long haul underwater link, by using a multi-looped existing optical telecommunication backbone connecting Rome and Pomezia, a small town nearby, to reach an actual total length of more than 100 km. Additionally, an optical adjustable attenuator was inserted serially after the fiber link. Various tests were carried out in normal operating conditions. Among them, a set of BER measurements were made, for different additional attenuation levels. It was found that, considering the two furthest network entries (i.e. the uppermost floor and its onshore counterpart), an additional attenuation level of more than 24 dB still guarantees an "a posteriori" bit error probability less or equal to 10^{-9}.

7. Conclusions

A complete communication system has been developed to guarantee correct and lossless data acquisition for a NEMO-like underwater neutrino telescope. It has been shown that it is commensurate and specifically fit to the needs of the apparatus. It will soon be used in NEMO-Phase 1, but it is easily scalable for a km^3-sized infrastructure based on the same tower-oriented philosophy. Data transmission from underwater tower floors to onshore unpacking stages is carried out using a totally passive DWDM-compliant fiber optics network. This offers many advantages, thanks to the fact that no active node is needed offshore: this greatly simpifies underwater power distribution management, allows using fewer components, and thereby permits to enhance system reliability. Moreover, as a standard, features like durability, robustness, wide support and ease of integration with third parties components can be taken for granted. Similar considerations hold for the STM-1 protocol, used for data transmission over each of the DWDM channels. Additionally it is self-synchronous: clock is extracted from data stream, and no separated clock-shipping medium is needed.

References

[1] Amanda website.
URL `http://amanda.uci.edu/`

[2] Antares website.
URL `http://antares.in2p3.fr/`

[3] Nestor website.
URL `http://www.nestor.org.gr/`

[4] A. Capone, T. Digaetano, A. Grimaldi, R. Habel, D. L. Presti, E. Migneco, R. Masullo, F. Moro, M. Petruccetti, C. Petta, P. Piattelli, N. Randazzo, G. Riccobene, E. Salusti, P. Sapienza, M. Sedita, L. Trasatti, L. Ursella, Measurements of light transmission in deep sea with the AC9 trasmissometer, NIM A (487) (2002) 423–434.

[5] F. Ameli, M. Bonori, C. Coluzza, R. Masullo, M. Petruccetti, F. Massa, L. Pappalardo, A single photon detector for the measurement of optical activity in the deep sea, Review of Scientific Instruments 73 (12) (2002) 4164–4168, online Publication DOI: 10.1063/1.1515359.

[6] F. Ameli, M. Bonori, F. Massa, Measurement of optical background in the site for the NEMO KM^3 undersea neutrino telescope., The European Physical Journal C 25 (1) (2002) 67–75, online publication: 26 July 2002. DOI 10.1007/s10052-002-1015-x.

[7] F. Massa, Optical radiation background from ^{40}k decays in undersea neutrino telescopes, Eur. Phys. J. C 22 (4) (2002) 749–756.

[8] F. Ameli, M. Bonori, C. A. Nicolau, A 200 MHz FPGA-based PMT acquisition electronics for NEMO experiment, in: E. de Wolf (Ed.), Proceedings of the 1st VLVνT Workshop, Amsterdam (Netherlands), NIKHEF, Amsterdam, 2004, pp. 205–208.

[9] F. Ameli, C. A. Nicolau, A 200 MHz FPGA-based PMT acquisition electronics for NEMO experiment, in: Nuclear Instruments and Methods - Proceedings of the 2nd VLVνT Workshop, Catania (Italy), 2005.

[10] F. Ameli, The NEMO floor control module, in: Proceedings of the 14th IEEE-NPSS Real Time Conference, 2005.

[11] A. X. Widmer, P. A. Franaszek, A DC-balanced, partitioned-block, 8b/10b transmission code, IBM Journal of Research and Development 27 (5).

[12] PCI Special Interest Group, PCI Local Bus Spec. Revision 2.3 (March 2003).
URL `http://www.pcisig.com/`