Photonic readout of optical modules in neutrino telescopes

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Abstract: The readout of optical modules for deep-sea kilometer sized neutrino telescopes is challenging for many reasons. Power consumption of the electronics placed at the bottom of the sea must be low. The shipping of the data to shore requires a transport over distances up to possibly 100 km. We present a novel readout system - developed in the framework of the KM3NeT design study - where the data from the optical sensors are rapidly transformed into optical signals, using reflective optical modulators. The system uses point-to-point transfer of data over a DWDM fiber optic network. Laser light sent from shore is reflected and modulated by the data signals at the optical module. In accordance with ITU recommendations bitrates of 10 Gb/s, over a 100 km distance are foreseen.

Introduction

At present a design of a neutrino telescope is being contemplated in Europe, which is to be deployed at the bottom of the Mediterranean Sea. This telescope is to have a size of at least one cubic kilometer. Being placed at the bottom of the sea the detector modules must be able to resist pressures of more than 300 bars and the harsh corrosive action of the seawater. Glass spheres are the containers of choice as they are transparent, pressure resistant and insensitive to corrosion. They do however have one major flaw in that the glass is a very poor heat conductor and so whatever is placed inside the spheres must consume little energy. In the pilot projects that have been built in the past years readout electronics have been placed in separate pressure vessels mostly made of titanium. When scaling the present projects up to the size of a cubic kilometer one faces several challenges. Overall power consumption must be reduced, as the transport of many hundreds of kilowatts to the bottom of the sea is both very costly and impractical. The design of the optical module must be simple in order to make the production of several thousands of these modules in as short a time as possible. There is a premium on reliability as repair of such underwater apparatus is highly impractical. The functionality of the module can also not be compromised. Most importantly the accuracy of the timing obtained from each of these modules must be maintained to a level better than a nanosecond. The way to both reduce power consumption and increase reliability of the underwater modules is to reduce the number of their active components. If this reduction is sufficient it opens up the possibility of discarding the separate electronics container and placing all electronics in the glass spheres.

Boundary conditions

At Nikhef we have been investigating the use of many small photomultipliers inside a glass sphere as the basic detection unit for a large under water neutrino telescope. This design is described in a separate contribution to this conference. In this design we have dispensed with the separate electronics module and have concentrated all electronic and photonic circuitry inside a single glass sphere which also houses a very large area of photocathode. In this design, the reduction of the total power consumption inside the sphere becomes a major issue. Measurements and calculations have shown that if one wants to keep the temperature inside the sphere below 30°C the total power consumption must be kept below 7W. As the high voltage supplies for the photomultipliers already take 3 to 4 W, only 3 W remains for the readout electronics. To do this we have concentrated the readout primarily in photonic circuitry which has intrinsic properties of ultra-high bandwidth and low power consumption.

We are thus faced with producing a readout system for about 40 photomultipliers with very low power consumption, while retaining a timing accuracy of a nanosecond. Pulse height information must also be retained.

Conventionally the method of store-and-forward has been used. This method requires an accurate clock in order to timestamp each photomultiplier signal, a pulse height digitization, a large memory to store the time-stamped amplitude data and a processor to communicate the data to shore using a network protocol such as TCP/IP all installed underwater. The data must be transferred over up to 100 km to shore. So a fiber optic network is used which requires a communications laser underwater. This amount of electronic apparatus is excluded if one is to reduce the power consumption to the required level.

Recent developments in fiber technology make it possible to contemplate a different setup where the time stamping is no longer performed under water and the amplitude information is encoded differently.

Implementation

The readout system is a fiber optic network making use of dense wavelength division multiplexing (DWDM) [1]. A schematic diagram of the system is shown in figure 1. The communications laser, which is placed on shore, is of the continuous wave multi-wavelength type [2]. These lasers are capable of producing 50 to 100 discrete wavelengths. The laser light is sent via an optical circulator and through dispersion compensation down the optic fiber [3,4,5] of 100 km length to the detector units on the seabed. In the present thinking a detector unit is a vertical line of approximately 500 m length along which 20 to 25 optical modules are suspended. This line is held vertical by a buoy. At the foot of this line the laser light is sent through a DWDM bidirectional multiplexer [1] and split into the separate wavelengths that continue via separate fibers up the line each to a separate optical module. Here the light is reflected and modulated by the signals coming from the photo-multiplier tubes in real time in a reflective electro-absorption modulator.

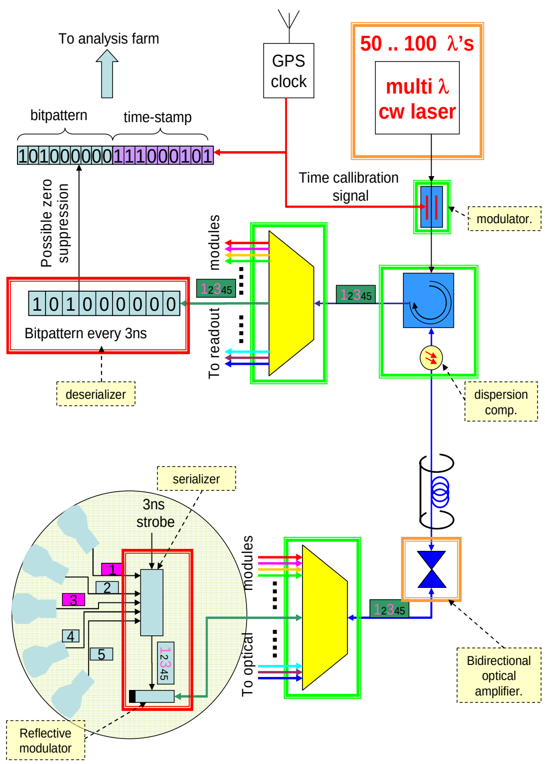

Figure 1: Schematic diagram of the readout system. Items in green box are off the shelf items, in orange box have working demonstrators and those in red have working demonstrators that require some modification for this project.

The modulated light then proceeds back down the fiber to the multiplexer where it is combined with the other wavelengths that have followed similar paths to the other optical modules on the line. These travel the 100 km back to shore where they enter the circulator and are sent towards a second DWDM demultiplexer. Maintaining the optical power budget may require optical amplification through the use of Erbium doped fiber amplifiers. On shore demultiplexing allows a single transparent connection between the optical module and the shore.

This optical channel also identifies the optical module uniquely. It should however be noted that the electro-absorption modulators are wavelength independent over the broad wavelength span centered at 1550 nm used for the optical channels and so are universal for all optical modules. All components of this system are either readily available off-the-shelf or are available as full demonstrator modules in the telecommunications market. As the telecommunications market is now aiming at providing fiber connections to the home for program on demand viewing, the development of optical components for 10 Gb/s communication over up to 100 kilometer has taken off rapidly.

Custom needs

The most important information to be transferred is the arrival time of photons at the optical modules. This time should have an RMS accuracy of 1ns. This requirement is to ensure optimal accuracy of the directional reconstruction of the neutrinos detected in the telescope. In order to suppress background from other sources than a passing muon from a neutrino interaction it is important to know how many neighboring photomultipliers are hit in each optical module.

The signal from each photomultiplier is translated into a time-over-threshold signal, with the threshold set at approximately 0.3 photoelectron equivalent. The typical length of the time-over-threshold signal for a single photon signal is 15 ns. The signals from each of the phototubes are then sampled every 3ns. This gives the required RMS resolution of 1ns. The samples are translated into a serial bit stream. The output bit rate is 10-20 Gb/s. This depends somewhat on the most suitable (return or non-return to zero) modulation used. Together with identifying bits and the stuffing bits required by the receiver amplifiers this allows 20 to 40 photomultipliers to make use of the same optical connection. Serializing circuits running at 10 Gb/s are becoming commonplace and those for 20 Gb/s are starting to become available. The output of the serializing circuit is fed to the reflective optical modulator which is again available for speeds of 10 Gb/s. Here there are even prototype modules available reaching 40 Gb/s in laboratory conditions [6].

This method of encoding complies with the timing requirement and encodes the number of photomultipliers hit in the transmitted bit pattern. More information on the pulse height can be obtained from the length of the time-over-threshold signal. This gives a typical logarithmic dependence on the pulse height.

It should be noted that the system could easily be modified to send any encoded information such as pulse-code-modulated waveforms to shore.

Calibration

The system has essentially been set up as a point to point communication from the shore to each optical module in the detector. This point to point connection runs via a single fiber with a reflection taking place at the optical module. This allows a signal to be sent from shore and the time of arrival back on shore to be registered. As the path length for the signal to propagate to the optical module is identical to the length of the return path, the recorded time difference can be used to determine the propagation delay from the optical module to shore.

On shore encoding

The onshore electronics has to merely decode the arriving bit pattern and to add a time stamp. As the propagation delay is known the actual time at the optical module can be recorded. This also means that the clocks used for the sampling underwater do not need to be synchronized. Each arriving bit pattern receives its own time. The system is effectively dead-timeless as it is a pure sampling system.

Conclusions

Advances in photonics in the telecommunication industry have allowed the design of a readout system for a large volume neutrino telescope which effectively transfers all readout electronics to shore. Taking advantage of the increases in bitrates in present *photonic* telecommunication technology it is possible to remove almost all electronics from the underwater modules and consequently enhance the reliability of the system. The power consumption of the underwater electronics is such that it can be placed together with the photomultipliers inside glass spheres. The system is dead-timeless. The necessary timing calibration is naturally incorporated due to bidirectional design. A full demonstrator system is being produced.

References

[1] ITU recommendation G694.1: Spectral grids for WDM applications: DWDM frequency grid. http://www.itu.int/ITUT/publications/recs.html

[2]For instance: Multi-Channel Laser Array (MCLA), Peleton Photonic systems http://www.peleton.com/Site2007/Products/Index.html

[3]For instance: Corning SMF-28 Optical fiber http://www.corning.com/opticalfiber

[4] ITU recommendation G650: Definitions and test methods for relevant parameters of single mode fibers. http://www.itu.int/ITUT/publications/recs.html

[5] ITU recommendation G655: Characteristics of non-zero dispersion shifted single mode optical fiber and cable. http://www.itu.int/ITUT/publications/recs.html

[6] For instance: C.I.P. 40G-SR-EAM-1550: a 1550nm Short Reach modulator and 10G-LR-EAM-1550: a 1550nm Long Reach modulator http://www.ciphotonics.com/cip_electroabsorption.htm