Photonics-oriented data transmission network for the KM3NeT prototype detector

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Abstract

The design of the readout and data acquisition system of the future KM3NeT neutrino telescope employs 10Gbps photonic technologies for data transmission to shore. The photonic architecture can handle standard transmission protocols. The generic scheme is based on DWDM technology using lasers on shore and optical modulators in each of the 12,800 Digital Optical Modules arranged on several hundred vertical detection units anchored to the seabed. Each 0module will house 31 photomultipliers together with auxiliary instrumentation and readout electronics. A 100 km electro-optical fibre cable will connect the optical modules to the store. The readout system will guarantee an individual optical connection between each optical module and the shore. A small-scale prototype of a detection unit with four optical modules is in a realization phase and will allow for in-situ testing of the data transmission network. We will present results of laboratory tests of the photonics-oriented transmission layer of the network that have been realized for the prototype detection unit.

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1. Introduction

The KM3NeT neutrino telescope will instrument a volume of several cubic kilometers of seawater to detect Cherenkov light from traversing neutrino-induced muons [1], [2]. Suspended by 320 vertical structures - detection units - 12,800 Digital Optical Modules (DOMs) with 31 photomultipliers each will be distributed over the volume of the detector [3]. A vertical electro-optical cable will carry 11 optical fibres to connect 20 of the 40 optical modules in a detection unit to an Optical Fan-Out Module (OFM) located at half the unit's height [4]. The optical fibres are configured in a star topology transmitting a single wavelength out of a 20-wavelength comb to each DOM. Separation of the individual wavelengths is achieved using an Arrayed Wave Guide (AWG) de-multiplexer that is housed in the OFM container. A single fibre, carrying a comb of 20 wavelengths runs from the OFM to the connector at the anchor of the detection unit. From there, a horizontal cable on the seabed connects each detection unit to a secondary junction box. In this, a single fibre carries simultaneously all data from the junction box to 20 DOMs and vice versa. Thus each DOM is assigned with its unique wavelength. The network connection to and from shore is distributed over a primary junction box and several secondary junction boxes. The architecture of the photonics oriented transmission layer of the network inherently provides the facility to measure the signal propagation time over the network during operation. As a tool to evaluate the physical implementation of the KM3NeT network design, the SPARK II test bench facility has been designed and built. It has been used to determine the parameters for the network for a prototype detection unit to be deployed in 2012.

2. The KM3NeT network architecture

In Figure 1, the schematic layout of the SPARKII optical test bench is shown. It reflects the architecture of the KM3NeT network [5] which is based on the concept of "wave length seeding". In this concept, a single optical fibre in the main cable from shore (up to 100km away) will carry a wavelength comb of 80 channels from the shore station to the seabed. There, optical amplifiers increase the optical power of all channels. After amplification, the channels are distributed via the combs over the various branches of the seafloor network. Apart from optical fibres, the network will contain passive and active components like Erbium Doped Fibre Amplifiers (EDFAs), optical power splitters, DWDMs (Dense Wavelength Division Multiplexers) and connectors. A full wavelength comb is distributed over 80 DOMs, residing in two detection units. Data from the 80 DOMs are multiplexed by DWDM technology and sent via a circulator and over a dedicated fibre to the corresponding DWDM in the shore station, thus

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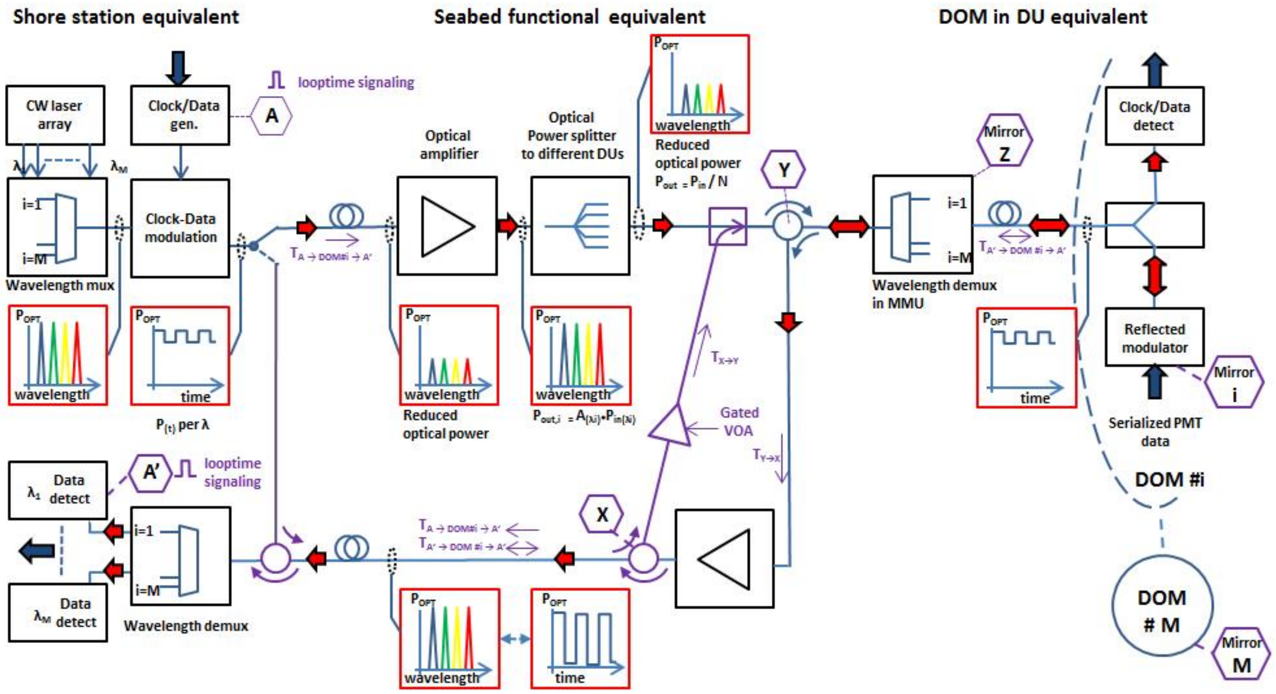

Figure 1: Schematic layout of the SPARK II test bench.

establishing point to point connection with each DOM in the detector.

2.1. Measurement of the Signal Propagation Time

In the passive optical network (PON) designed for KM3NeT, the optical signal propagates from the shore station to each individual DOM with a fixed time delay and without time jitter. Differences in time delays between the DOMs and the on-shore detector are compensated for by using a complementary hardware circuitry in the network architecture (Fig. 1). By "pinging" each DOM from shore using FPGAs with embedded software/firmware, the propagation delay to and from each DOM can be measured with a time resolution better than 1 ns, independent of the distances used in the PON span. As the propagation time from each DOM to the shore station is crucial, the timing measurement is done via a "folded path", starting with a timing pulse from the *receiver* in the shore station (point B in Fig. 2). This is opposite to the normal mode of operation, where clock-data pulses are sent from the transmitter in the shore station (point A in Fig. 2). In the timing mode, a VOA (Variable Optical Attenuator) is used as a "switch" to allow pulse propagation in reverse direction over the seafloor network. The propagation time from a specific DOM$_i$ is derived from

- $T_{X-Y} = T_{Y-X}$, the time between circulators X and Y. This value is tuned during construction;
- $T_{DOM_i - B} = \frac{(T_{B-DOM_i-B})}{2}$ in which T_{B-DOM_i-B} is the pulse echo time measured at B (the shore) via circulator X and Y and the AWG to DOM_i and back. During these timing measurement the gated Variable Optical Attenuator (VOA) is conducting.
- $T_{A-DOM_i} = T_{A-DOM_i-B} - T_{DOM_i-B}$, in which T_{A-DOM_i-B} is the measured clock/framing round trip of a pulse via the amplifiers, splitter, circulator Y, AWG to DOM_i and reflected via the AWG circulator Y, amplifier and circulator X back to shore.

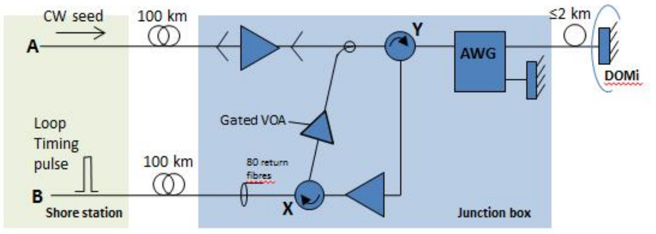

Figure 2: Timing circuit

The measured propagation times will include all parameters which will have an influence on the signal propagation time such as fibre length, fibre temperature, chromatic dispersion, non-linear refractive index effects etc.

2.2. Network optimization

In the KM3NeT network, 80 optical CW (continuous wave) channels or more will be transported over a single fibre in the cable to shore. The maximum optical power to be launched and propagating in an optical fibre is limited by various optical phenomena, resulting in transmission impairments. Linear effects are fibre attenuation, insertion losses of components and chromatic dispersion. Non-linear effects are self-phase and cross-phase modulation, four wave mixing and stimulated Raman and Brillouin scattering. Optical attenuation can be compensated for by proper optical amplification. The effect of chromatic dispersion can be reduced by the use of an appropriate optical fibre. The "wavelength chirp" of the CW laser can be eliminated using an external intensity modulator for encoding of data on the CW light emitted by the laser. This eliminates unwanted variations in the laser wavelength due to on-off switching of the laser. The non-linear effects can be reduced by e.g. the use of a Large Effective Area Fibre (LEAF), which will reduce the intensity (the optical power per unit of core area). Introduction of very small laser frequency deviations (up to e.g. 1GHz) can suppress the effects of Brillouin scattering.

3. SPARKII test bench

The SPARKII test bench has been designed and built to evaluate and optimize the physical implementation of the KM3NeT optical network architecture (Fig. 1). It consists of equivalent units to mimic a shore station, the seabed infrastructure and several DOMs. The modularity allows for relatively easy adaptation to optical components, which are often specified for use in a specific multi-wavelength architecture. Moreover, the requirements and operational settings for major components like e.g. optical amplifiers can only be specified once all parameters such as the geometry of the seabed cable network and the length of the main cable to shore have been fixed. In the on-shore unit, 8 optical ITU-channels are employed at a wavelength spacing of 0.8 nm (100 GHz). The (test) control data are generated in the on-shore unit by the Clock/Data generator and sent to an electro-optic modulator that encodes the data to all wavelengths simultaneously. After passing the downstream fibre link which connects to the seafloor network unit of the test bench, and de-multiplexing of the wavelength comb, each of the data-encoded wavelengths is fed to a PIN/R-EAM (Detector/ Reflective Electro Absorption Modulator) combination in each DOM. An important parameter in the coding of data is the extinction ratio, ϵ_r, being defined as $P_{\max}/P_{\min}$, with $P_{\max}$ being the maximum optical power and $P_{\min}$ the minimum optical power. The extinction ratio indicates the change in optical power per data bit, being superimposed on the laser signal. The extinction ratio is reduced to a minimum value being large enough for reliable detection of clock/data by the PIN diode receiver in each DOM. Here, an optical power splitter taps a fraction (e.g. 20 %) of its input signal to the PIN detector. The remnant power of the input signal is sent to the R-EAM. The tap ratio must be chosen accurately because of the relatively small optical signal margins involved. The benefit of this approach is that each DOM is connected via a single fibre, carrying a single wavelength for up-and downstream communication. Data generated by the electronics in the DOM is modulated by the R-EAM and reflected to the shore station, using a maximized extinction rate in order to override the low modulation-index input signal and to relax the margins for optical data transmission to the shore station.

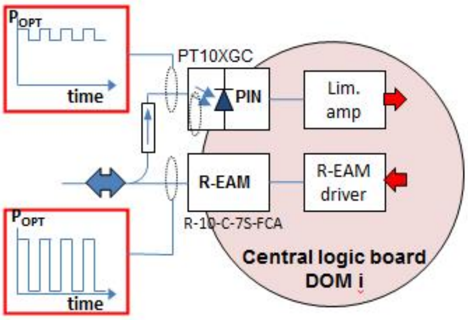

Figure 3: Optical input/output port in the DOM

3.1. *Test results*

With the SPARK II, Bit Error Rate (BER) tests were performed using a Pseudo Random Binary Sequence (PRBS). Gigabit Ethernet (GbE) was applied for data transport and for the signal propagation time measurements over the network. Reliable detection of the low-extinction ratio encoded clock/data communication is largely determined by the PIN/R-EAM/splitter combination residing in the DOM (Fig. 3). The Continuous Wave (CW) laser light with superposed low extinction-modulated data arriving at the optical port of the DOM must have enough optical power for the PIN/TIA (detector and limiting amplifier) combination to produce reliable data with an acceptable BER figure as input to the central logic board. During extensive experiments with the SPARK II test bench, an optical splitter with a tap ratio of 30% of optical power to the PIN was selected, feeding the ≈ 70% remnant optical power to the R-EAM. Experiments indicated an optimum power level of -7 dBm at the input of the Oclaro PT10XGC PIN/TIA. This level is composed of the continuous wave level with superimposed low-ϵ_r modulated data. For transmission to shore, the reflected and by the R-EAM modulated signal of -10 dBm with an extinction ratio of $\epsilon_r = 7$ fits in the return path of the network. The signal amplification is adapted to data transport over the maximum specified length for the MEOC of 100 km.

4. Conclusion

The SPARK II test bench serves as an efficient test platform for further optimization of the photonic network architecture of KM3NeT. To achieve this, many additional test experiments are foreseen. One of the major issues is the optimization of the optical power required at the

PIN/TIA combination in an OM, since this power level determines to a large extent the requirements for optical amplification throughout the network. Also the reduction of optical losses in the R-EAM contributes to the overall optical efficiency of the network. In that respect, the current test bench configuration (using up to 8 wavelengths) serves as a decisive guide for the realization of the a prototype model of the detection unit of KM3NeT. This prototype detection unit will contain four DOMs. It is planned to be deployed in 2012 at a distance of 100 km off the coast, to investigate the deployment characteristics of the design of the detection unit, the DOM readout electronics and the performance of the photonic network.

5. Acknowledgment

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