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Analysis of a DWDM transmission system for multichannel long haul link

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ABSTRACT: Dense wavelength division multiplexing (DWDM) is an optical technology that allows transmitting across a fiber many wavelengths, which can be added and dropped by means of passive optical components. The performance of a complex DWDM network data transmission system that will find an application in the NEMO underwater neutrino telescope. The tests cover the qualification of a complete multipoint DWDM network consisting of transponders, fibers, passive optical filters, and an optical amplifier. The behavior of the network is evaluated in the final arrangement by means of bit error ratio (BER) and optical signal-to-noise ratio measurements at 800 Mb/s rate. In order to test the network, a board, developed for the NEMO experiment, has been used. A custom DWDM module, capable of data rates up to 1.4 Gb/s and specifically designed for real-time data acquisition systems, can be hosted by the board. A dedicated application runs on the board programmable logic controlling the module, monitoring the transceiver's functionalities and running the BER test.

KEYWORDS—Data acquisition (DAQ), dense wavelength division multiplexing (DWDM), real-time systems

I. INTRODUCTION

The performance of a dense wavelength division multiplexing (DWDM) optical network. The DWDM technique multiplexes up to 132 wavelengths, or *colors*, over a single mono modal fiber allowing the coexistence of many logical channels over the same physical medium; the DWDM frequency grid at 100-GHz channel spacing is defined by the ITU-T G.694.1, which fixes the reference frequency at 193.1 THz. Different colors, i.e., communication links, can be added (multiplexed) and dropped (demultiplexed) from the fiber by means of passive optical components. The passive *mux/demux* process, compared to active sectioning of data, guarantees independence from specific protocols and data rates allowing all the allocated channels to have the same latency. These features have great impact on the reliability and the simplicity of the network; moreover, it is possible to exploit the huge fiber bandwidth transmitting at the same time many high-speed streams.This technology cheaply solves the problem of increasing communication channels without deploying new cables or when the number of fibers in the cable is limited; this solution makes it very attractive not only for telecommunication products, but also for the design of real-time data acquisition systems when the required bandwidth is on the order of many gigabits per second. Since the introduction on the market of small form factor optical transceivers, which are also interoperable between different manufacturers, the DWDM technique is receiving great attention: The last generation of DWDM lasers exhibits lower power consumption than previous devices, can be easily interfaced with most of the high-speed electrical transceivers available, reaches data rates up to 2.7 Gb/s, and, not least, is not extremely expensive anymore. To test the behavior of the optical network, we used a board designed for the NEMO experiment that hosts a DWDM link for data transmission, as explained in Section 2; such a link was designed as a pluggable module to permit its reuse in other projects. In Section 3, the experimental test-bench setup to assess the performance of the network is described. In Section 4, the results of this characterization will be shown, and, finally, the conclusions are drawn in Section 5.

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II. FLOOR CONTROL MODULE BOARD

The principal indicator applied to measure the performance of the DWDM network, whose layout is being explained in Section 3, is the bit error ratio (BER), i.e., the ratio between the number of wrong bits received to the total number of transmitted bits. To transmit and receive bits over the optical channels under test and calculate the BER, the board developed for the NEMO experiment, the so-called Floor Control Module (FCM),has been used. The FCM hosts a plug-in module which is based on a transceiver chip-set and a DWDM laser. Fig. 1 shows the FCM board hosting the DWDM link board.

Fig. 1. Picture of the FCM board with the DWDM link plugged-in. The link interface and the test-bench controls are implemented by a software program running on an embedded microcontroller synthesized in the programmable logic.

In order to make the design of the DWDM e/o transceiver independent from a specific optical component, the optical layer complies with the DWDM Small Form Pluggable (SFP) Multi Source Agreement (MSA). This standard specifies the transceiver's package outlines, pin function definitions, and optical and electrical interfaces and characteristics. The module form factor is much smaller than previous MSA versions permitting the mating with a 20-pin connector soldered on the printed circuit board. This connector is designed so that the device is *hot-swappable*, allowing an easy replacement in case of fault or if a different wavelength is required.The transceiver has multirate capability starting from 622.08 Mb/s up to 2.7 Gb/s, has a maximum output power of 4 dBm, and a typical reach of 100 km; the input dynamic range at full data rate comprises between 9 and 28 dBm. The clock recovered by the receiver is phase-locked to the transmitter clock, with data rates that range from 400 Mb/s to 1.4 Gb/s. The user bus consists of a 16-bit data word plus some control signals. The G-Link protocol adds four control flags, called the *C-Field*, which add many features: dc-balance control through word inversion; possibility of sending *control*, *data*, or *idle* words; insertion of the *Conditional-Invert Master Transition* (CIMT) in each transmitted word; error checking. For a detailed description of the complete set of features. The total amount of data transmitted is 20-bit multiplied by the clock frequency of the parallel bus, which ranges from 20 to 70 MHz. During all the tests, we fixed this frequency at 40 MHz, which yields 800 Mb/s of total bit rate, as it is in the NEMO experiment. The receiver in turn extracts the 800-MHz serial clock from the bit stream with a Clock and Data Recovery (CDR) module, which divides the line clock down to 40 MHz and filters it with a phase locked loop (PLL), providing both the parallel word data and the control flags extracted from the C-field.

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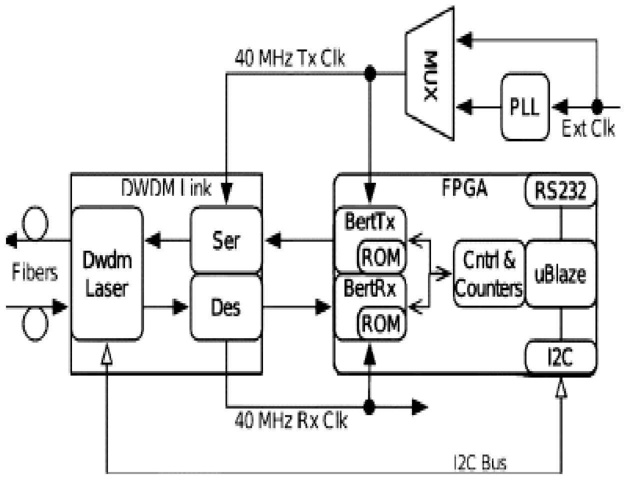

Fig. 2. Diagram of the FCM blocks, including the DWDM link and the FPGA functionalities.

Fig. 2 shows the block diagram of the DWDM link module and of the functions implemented inside the field programmable gate array (FPGA). In this test, the 40-MHz parallel clock is obtained by multiplying a local 4-MHz clock with an on-board PLL.

The FPGA implements a full-duplex bit error ratio tester (BERT) consisting of a transmitter and a receiver section. After an initial delay that allows the receiver to start up, the *BertTx* module starts sending to the serializer parallel 16-bit words, which are read from a read-only memory (ROM) made up with FPGA's internal RAM. The ROM is preloaded with random words to minimize systematic errors in bit recovery. As soon as the transmission starts, the BERT receiver module starts receiving data and control flags decoded by the deserializer and compares the received words to the same content of the ROM used by the transmitter. After the receiving process is started by reception of the first valid word, then it is not stopped anymore assuming that for each clock transition a word has been transmitted and must be received even in case of protocol errors. This procedure prevents from loosing the lock between BERT transmitter and receiver. An error counter is assigned to each bit of the 20-bit line pattern and is incremented in case of mismatch. A Xilinx MicroBlaze embedded processor has been instantiated in the FPGA to manage the test-bench. The processor initializes the laser and the transmission with the correct startup sequence, monitors transceiver functionalities, starts the BERT transmitter and receiver modules, reads back the results from the BERT receiver, resets the bit error counters, and shows errors number after a predefined time interval. Interaction with the user is accomplished through an asynchronous serial port, which sends the system status and accepts commands from a terminal running on a host machine.

III. DWDM LINK TEST BENCH

In this section, the test bench for evaluating the performance of the optical network is described. The proposed setup closely reflects the network layout used in the NEMO experiment, as explained in detail in .For the sake of simplicity, the test bench network has less nodes than those needed in the NEMO architecture, but this choice does not affect performance as soon as adjacent channels move away from the one under test.

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Fig. 3. Pictorial view of the experimental setup used to test the performance of the DWDM network

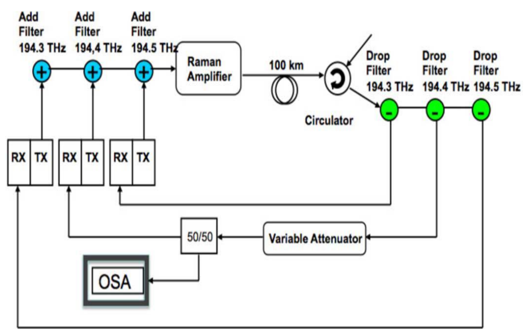

Fig. 4. Block diagram of the test-bench.

The bitstream generated by the first FCM is transmitted through fiber. The DWD Maggregate of three adjacent channels is realized feeding the output of three FCM transceivers into the optical network by a chain of three Add filters. At the fiber trunk output, the aggregate is de multiplexed by a chain of three Drop filters. The central channel is passed through Agilent 8164B Light wave Measurement System, which acts as programmable optical attenuator, before it is fed into the receiver.The attenuation can be set very precisely, and the output power is measured by the instrument itself. The attenuator has been set to give a fixed output power during the measurement time window in order to avoid the instability of the power level fed into the FCM transceiver. The instrument can be tuned at the wavelength of the DWDM transmitter under test. The optical path is split at the attenuator output with a 50/50 ratio in order to measure it with the OSA, the EXFO FTB-5240. Data stream is sent and received from the same FCM, which extracts clock and data from the bitstream. The received data is used by the BERT receiver module inside the FPGA to measure the BER. Both the operations of the FCM board and the measurements results are supervised by a host PC that communicates with the embedded processor through the RS232 connection. The optical power at the variable attenuator output has been regulated, and once the receiver loses the link [asserting the *Loss Of Signal* (LOS) flag], the BER has been measured, increasing the optical power level fed to the receiver input.

IV. TEST RESULTS

The measurements described in this section aim at evaluating how the BER increases when the optical signal is attenuated, worsening the signal-to-noise ratio (SNR). The minimum optical power allowed at the receiver section of the 194.4-THz transceiver is 37.2 dBm. Below this value,the receiver loses the link and asserts the LOS flag. To regain the lock, the optical power must be greater than 34.5 dBm.This behavior implies an hysteresis mechanism implemented by the e/o transceiver. The output power of the laser has been measured by the Agilent 8164B and is 1.05 dBm, i.e., about 1.3 mW. Hence, the total link budget is about 38.2 dB, largely exceeding what is stated in the laser data sheet.

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The reason for this behavior is that the link budget is measured at the highest rate, i.e., 2.7 Gb/s; roughly, when the rate is doubled, the budget decreases of 3 dB, hence transmitting at 800 Mb/s will yield 6 dB.

A. DWDM Optical Spectrum

Spectral measurements have been taken during the BER analysis at 194.4 THz. The calculation of the optical signal-to-noise ratio (OSNR) for the DWDM channel has been done measuring the Drop filter in-band power and the noise floor. The measured noise floor is 74.93 dBm. The spectrum of the 3 DWDM channels at the circulator output is shown in Fig. 5. The power levels shown present an offset of about 10 dBm less than the power.

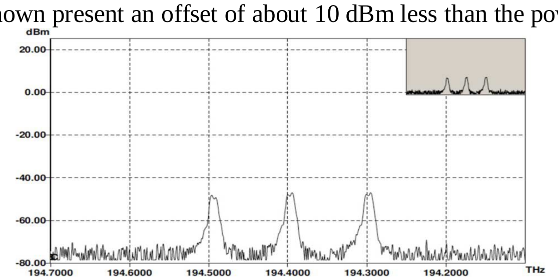

Fig. 5. Three-channels WDM spectrum with 100-GHz spacing.

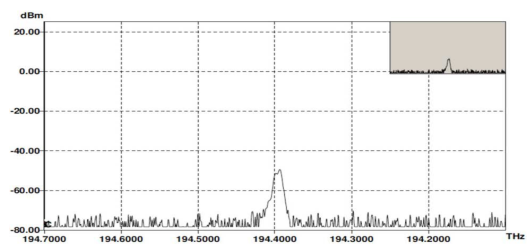

Fig. 6. WDM spectrum after Drop filtering.

This difference is most probably due to a defect of the input connector of the OSA that could not be fixed during the measurements. The spectrum shows no trace of nonlinear interactions between the three channels. This is mainly due to the low output power level at the transmitter and the wide frequency span between channels compared to their modulation bandwidth. The spectrum of the 194.4-THz channel at the receiver input is shown in Fig. 6. The spectrum shows the very good behaviour of the Drop filter, which acts almost as a perfect passband filter.

B. BER Versus Optical Power at the Receiver

As stated in Section 2, the main parameter used to evaluate the performance of the data transmission system is the BER. Along with the BER, the confidence level must also be indicated in order to assess up to which degree the result can considered

significant. For the calculation of the confidence level, we will use the following classical formula, which is based on the binomial distribution of errors .

$$CL=1-\sum_{K=0}^{N}(n!/k!(n-k)!)ph^{k}(1-ph)^{n-k}$$

where is the hypothetical value of BER, is the total number of bits transmitted during the measurement window, and is the total number of bit errors. Applying formula on the measured data sets, the confidence level results to be more than 90%.

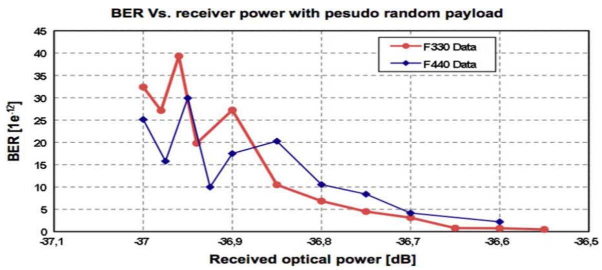

Fig. 7. Measured BER as a function of optical power at the receiver at two different DWDM wavelengths.

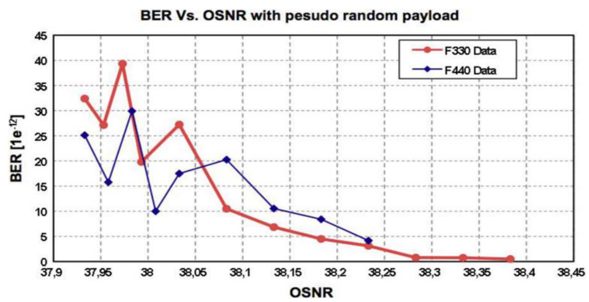

Fig. 8. Measured BER as a function of optical SNR at two different DWDM wavelengths.

Fig. 7 shows the BER measured as a function of the received optical power using the pseudorandom payload. The BER remains below 10 for a received power level higher than 36.6 dBm for both frequencies. When the optical power approaches the LOS state, the BER reaches for F440 transceiver and for F330. The errors were equally distributed between the 20 bits of the CIMT pattern. Fig. 8 shows the measured BER as a function of the measured OSNR, for the same data set of Fig. 7. An instability in the BER curves is observed for both transceivers as the power level approaches the LOS state; this behavior could be due to an instability of the output power of the Raman pumps affecting the overall amplifier gain. These values have been measured more than once to show that they are not due to measurement errors, even though this can be considered just a qualitative statement without a deep statistical analysis. The performance gets worse with respect to the system without amplification, and this is reasonable because of the higher noise level introduced by the Raman amplifier into the receiver bandwidth. The negligible effect of the interfering signals was expected. The 100-GHz spacing between adjacent wavelengths and the small modulated bandwidth make the channels completely independent from each other as shown in Figs. 5 and 6.

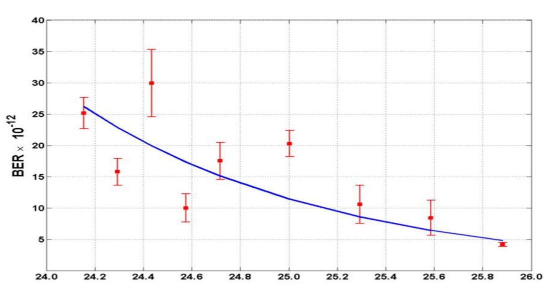

Fig. 9. Comparison between calculated BER and measured BER as a function of optical SNR (linear) for F440 transceiver.

In order to quantify the noise contribution due to the Raman amplifier, the OSNR measurements should take into account the in-band noise level. The add/drop filters in the network suppress the noise between optical channels. The OSA offers two methods to estimate the level of the noise present at the channel wavelength the linear interpolation and the in-band methods. The former uses interpolation of the noise level measured on both sides of the

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signal peak to estimate the noise. The latter uses a series of scans having different polarization states to estimate the noise level at the wavelength of the channel; during the series of scans, the fiber is coiled twice to for a 3.5-cm-wide loop that is rotated about 30 for each scan. Using the linear interpolation method, the noise level is underestimated, resulting in a misinterpretation of the OSNR values. In-band method offers a better noise level estimate. The measured in-band noise level for the F440 transceiver is 48.38 dB, thus leading to a mean OSNR of 11.50 dB; the measurement is done by the OSA over a 12.5-GHz band around the channel frequency. In order to calculate the BER from the measured OSNR, we have the following empirical approximation of the classical formula found in literature [8].

BER=(1÷2).e^0.98.OSNR

For a BER 1.10^12 of , an OSNR of 14.39 dB is required at the input of the ideal receiver. For a real receiver, a correction factor should be introduced to take into account the ratio between the 3-dB bandwidth of the optical filter at the receiver input and the bit rate of the signal. We consider a 12.5-GHz optical bandwidth and 0.8-GHz modulated bandwidth for the NRZ pseudorandom signal; the calculated correction factor is

P=(Bopt ÷r) ≈15.62

The OSNR penalty due to the nonideal receiver is 2.45 dB, and the resulting corrected OSNR is 13.95 dB. Introducing the OSNR corrected values, the BER values are calculated using the simplified formula. Fig. 9 shows the calculated and the measured BER, with statistical error bars, as a function of the measured OSNR including the penalty induced by the non ideal transceiver F440. For error bars calculation, a binomial error distribution has been assumed. The calculated BER remains below 2.10^-11 for a received OSNR higher than 13.88 dB. F330 transceiver shows a behaviour analogous to F440.

V. CONCLUSION

In this paper, we evaluated the performance of a DWDM optical network measuring the BER and the OSNR in the final network configuration with three DWDM channels on the same medium. The measured BER is in the worst case for values of optical power at the receiver close to the LOS state. As a consequence of the introduction of the Raman amplifier, the OSNR does not drop as the signals travel along the optical path as it would have in a system where a discrete amplifier is placed at the receiver input. Moreover the introduction of optical filters increases the system performance due to the reduced amount of optical noise fed to the receiver. The results show a high optical power budget around 38 dBm. This optical power budget allows to operate the DWDM network with a system margin up to 8 dB. The OSNR measured with the linear interpolation method by the OSA is an overestimated value. The in-band noise measurement method should be introduced for a correct OSNR measurement, and corrections should be done to account for the non ideal behavior of the receiver. The next steps will be the BER measure for more wavelengths and the addition of the counter propagating wavelengths on the same optical network. The oscillating trend of BER points close to the LOS state should also be confirmed, enriching the data set. The behavior of the system for higher data rates must be also evaluated to verify the receiver input range at full speed.

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