

Non Coherent Experimental In-Band OSNR Monitoring using Cost-Effective DSP Technique Insensitive to Polarization Effects

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Abstract— We develop and demonstrate an experimental cost-effective solution for non-coherent single polarization channel in-band OSNR estimation, using a digital signal processing (DSP) technique, insensitive to effects of different states of polarization. It was verified that previous reported methods when applied in a real optical network scenario (without polarization control), provides an OSNR error estimation above 8 dB when different states of polarization are considered. We analyzed, modeled and implemented this influence through numerical simulations and applied to the experimental device, resulting in a successfully OSNR estimation from 5.5 to 17 dB (range of 11.5 dB) with error below 2 dB for OOK modulated channels

Index Terms—DSP, Monitoring, OSNR, Photodetection, Polarization.

I. Introduction

Nowadays, considering the fast growing demand for optical communications, the DWDM optical networks must be improved in both ways, quantitatively through development of transmitters with higher data rates, and qualitatively adopting smart network concept to estimate the end-to-end link performance and/or quality of transmission (QoT) [1]. The use of optical channels monitors in the optical layer at strategic points of the networks allows us to forecast the network health through estimation of QoT. One very important parameter used to evaluate the link quality is the optical signal to noise ratio (OSNR), which quantifies the level of noise in the optical signal. This measure is often used since its value is directly related with the link Bit Error Rate (BER), which is the foremost QoT related link parameter.

In the past point-to-point DWDM networks, the OSNR in an optical channel was estimated using an

optical spectrum analyzer (OSA), which acquires the DWDM spectrum and by a linear interpolation method to measure the OSNR, assuming that the out-of-band noise is the same that the in-band noise. However, with the incoming of new generation dynamic DWDM optical networks, through the use of reconfigurable optical add-drop multiplexers (ROADM), the number of channels in an optical link turns a random variable. In addition, many channels pass through different number of links, and some signals accumulate more noise than other, then the conventional interpolation method to measure the OSNR fail because each channel will have different transmission history, passing through different filters and amplifiers, losing the reference noise level.

To overcome the loss of precision in the conventional method of linear interpolation, it was proposed several methods to estimate the in-band noise level, like the polarization nulling technique [2], interferometric technique [3], the method based on EDFA operation [4], noise beat method [5]. However, these techniques are very costly and/or sensible to dispersive effects such as polarization mode dispersion (PMD), with low accuracy [9].

Then, the use of DSP technique to estimate the in-band OSNR is a very promising method due its simplicity and precision. The method developed by [6], is based on polarization diversity technique with digital signal processing, where the influence of PMD in the estimation can be neglected, maintaining a low error in the estimation and allowing an easy and cheap hardware implementation. Despite the advantages, this method has some limitations when applied to real optical networks scenarios to estimate channel OSNR. At first the thermal noise limitations were considered in [7], which the effect was modeled, included and validated in a simulation environment. Furthermore, in an experimental network scenario other impairments need to be considered, such as the signal noise beating under the influence of effects of different states of polarization.

In this work was developed an experimental in-band OSNR estimation device through DSP for single polarization signals, and was proposed a new mathematical model to avoid estimation errors due the influence of random states of polarization. The new proposed model reduce the OSNR estimation error from 8 dB to 2 dB considering OSNR range from 5.5 to 17 dB.

The rest of this paper is organized as follows. Section II presents details about the original mathematical model and its problems, and proposes a new mathematical model to solve these problems. Section III presents the developed OSNR monitor experimental device, embedded the original and the new mathematical model to validate the performance enhancement. Section IV presents the simulation and experimental results. Finally, we give our conclusions in section V.

II. OSNR Monitoring Through Polarization Diversification Method

The OSNR monitor setup through digital signal processing and using the polarization diversity method was proposed by [6], and the setup is based on a singular analysis of the orthogonal polarization components present in the input signal. Using a polarization scrambler (PS) followed by a

polarization beam splitter (PBS), the polarization of signal is divided into two orthogonal components at the monitor module, these two components are converted from the optical domain to electrical domain by the photodetectors, and, then, digital signal processing techniques are applied to estimate the OSNR of the optical channel. The fig.1 shows a schematic of the proposed setup for this method.

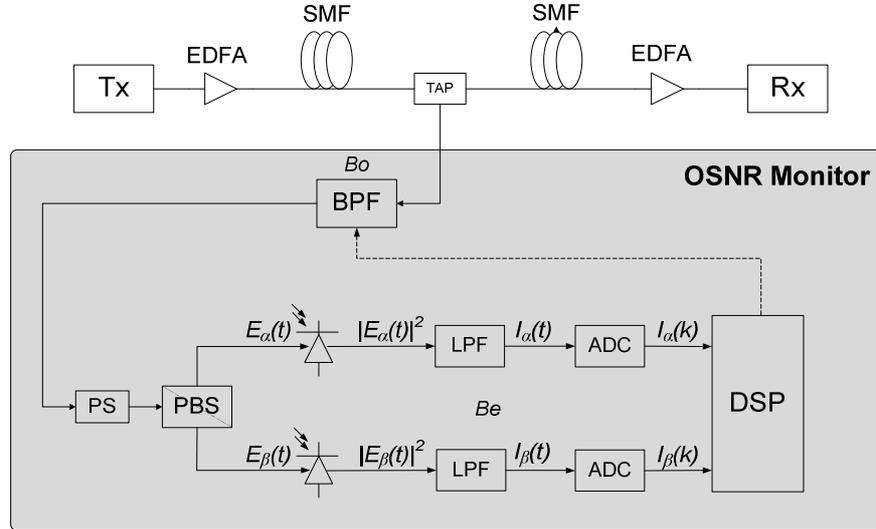


Fig.1 – OSNR monitor schematic diagram.

When the optical signal arrives at the OSNR monitor, an optical band pass filter with a bandwidth B_o selects the channel to be analyzed, then a PBS splits its polarization components into the orthogonal axes α and β . After the conversion to electrical domain, the signal is filtered by an electric low pass filter with bandwidth B_e and an impulse response $h_e(t)$, providing the currents $I_\alpha(t)$ and $I_\beta(t)$ that will be sampled by a analog-to-digital converter and then sent to the DSP. Keeping in mind the described setup, to estimate the OSNR the fiber nonlinearity and the multi-channel effect will not be considered, which implies in no consideration of the second e third order dispersion coefficients.

The currents $I_\alpha(t)$ and $I_\beta(t)$ can be express by the equations 1 and 2 [6], in which are considered the ASE noise and the thermal noise.

$$I_\alpha(t) = |E_\alpha(t)|^2 = \left(E_{\alpha,s}(t) + E_{\alpha,s+ase}(t) + |n_\alpha(t)|^2 + n_{t1}(t) \right) \otimes h_e(t) \tag{1}$$

$$I_\beta(t) = |E_\beta(t)|^2 = \left(E_{\beta,s}(t) + E_{\beta,s+ase}(t) + |n_\beta(t)|^2 + n_{t2}(t) \right) \otimes h_e(t) \tag{2}$$

Where, $E_{\alpha,s}(t)$ and $E_{\beta,s}(t)$ are the signal components in each arm, $E_{\alpha,s+ase}(t)$ and $E_{\beta,s+ase}(t)$ are signal to noise beating components, $|n_\alpha(t)|^2$ and $|n_\beta(t)|^2$ are the noise beating and $n_{t1}(t)$ and $n_{t2}(t)$ are the thermal noise from photodetectors.

First mathematical model

Given the equations of the electric currents get from the photodetectors, the mathematical model

proposed by [6] to estimate the OSNR assumes that the thermal noise is like a white Gaussian noise. The same consideration can be made to the signal to noise beating in an ideal situation, that it has its behavior like a white noise too.

These adopted considerations simplify the mathematical model, but they only work when an ideal situation. Still to simplify the solution, the photodetectors will be considered similar, so the thermal noise and the signal to noise beating will be present in the same way for both axes in the OSNR monitor.

Among equations that define the showed model, equation 3 and 4 relate the signal and noise average electric currents from photodetectors in each arm of the PBS. These equations report the operating principle of the PBS, which distributes the ASE noise equally in the both arms of the PBS, since the ASE noise is fully depolarized. However, the signal power is distributed in a weighted form between the arms, and this weighing can be represented by the multiplicative factor r .

$$\langle I_{\alpha}(t) \rangle = rP_s + P_{ase}/2 \tag{3}$$

$$\langle I_{\beta}(t) \rangle = (1 - r)P_s + P_{ase}/2 \tag{4}$$

From the equations 3 and 4, equation 5 can be written.

$$\langle I_{\alpha}(t) \rangle + \langle I_{\beta}(t) \rangle = P_s + P_{ase} \tag{5}$$

To become the system possible to be solved, one more equation is needed. This equation was proposed by [6] and is represented by equation 6.

$$\langle [I_{\alpha}(t) - \gamma \cdot I_{\beta}(t)]^2 \rangle = \langle [(1 - \gamma) (P_{ase}/2)]^2 \rangle \tag{6}$$

Where, $\gamma = r/(1 - r)$

The system built through equation 5 and 6, together with the equation 3 and 4, allows the signal and noise power to be calculated, and, then, the OSNR value can be estimated by the equation 7.

$$OSNR (dB) = 10 \cdot \log_{10} \frac{P_s}{P_{ase}} \tag{7}$$

Beyond the advantage of easy implementation on hardware, using the adequate electrical filtering this technique can be considered insensible to polarization mode dispersion (PMD), as demonstrated in [6], but this method was not evaluated related to variation in the states of polarization of input signal.

Impairments influence in the OSNR estimation

The mathematical model described in the last section is valid to prove the concepts of the OSNR monitor, however, once an experimental setup is intended, these considerations made for an ideal model must be reviewed. In this way, should be considered the photodetector operation and its impairments. At the photodetector there are the shot noise, the thermal noise and the beating between signal to signal, noise to noise and signal to noise. Despite the shot noise presents in the photodetectors, there is not a problem, since only a small portion of the signal goes into the monitor,

due to the input power of the optical signal is low the shot noise can be negligible. Although, the thermal noise does not depend on the input power of the signal, it is as a function of a group of variables like the physical constants (Boltzmann constant), the temperature and the resistance of the receiver's circuit. Then, the considerations made to the shot noise can not be extended to the thermal noise.

Through the simulation environment OptiSystem® the setup shown by fig. 1 was made following the layout depicted in the fig. 2. In this figure a signal modulated at 40Gbps in a NRZ-OOK was made and to simulate the variation in the state of polarization it was put a polarization rotator, besides an attenuator with a model of an optical fiber. After that the signal was coupled to the ASE noise comes from an erbium-doped fiber amplifier, EDFA. Once the noise and the signals were together in the same fiber, this set goes to an optical band pass filter with a bandwidth of 50GHz, and, then, follows to a PBS and a set of photodetectors and the low pass band filter with a bandwidth of 150MHz. After that, the signal was sampled at 320Bbps and processed by the software Matlab®.

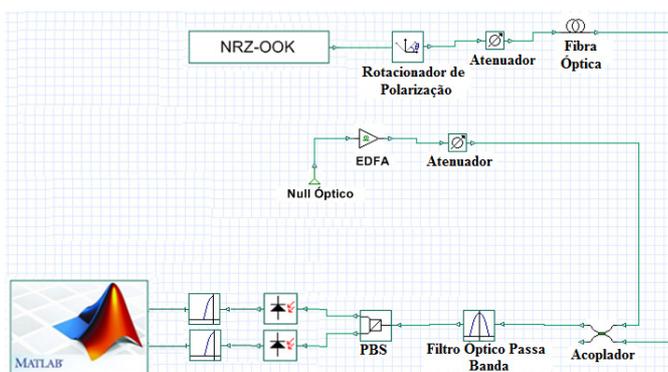


Fig. 2 – Simulation by OptiSystem® for the proposed OSNR monitor

From the simulation environment shown in fig. 2, considering only the effects related to thermal noise in the model proposed by [6], it is possible to achieve the results described in [7], in which when evaluated under the influence of the variation in the state of polarization of the input signal gives a quality of estimation shown in fig. 3.

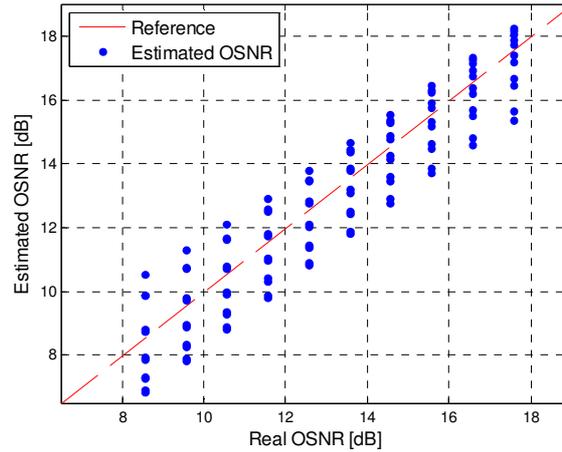


Fig.3 - OSNR estimation for different conditions of the polarization variation; Pin: -9.8dBm.

In fig.3 is possible to see the behavior of the OSNR estimation as function of variation in the state of polarization of the input signal. For each value of OSNR the estimate method was applied and the difference between this estimation value and its respective OSNR reference indicates the influence of the state of polarization. Through the analysis of fig. 3 it is possible to conclude that considering this method to estimate OSNR by polarization diversity with digital signal processing, its performance is dependent on the state of polarization of input signal. Therefore, it is still necessary to improve the estimation model to take out this dependence, allowing the method to have the necessary robustness to ensure the OSNR estimation in a real network scenario.

Simulation Analysis and proposed new mathematical model

Keeping in mind the mathematical model proposed by [6], the signal from each arm of the PBS passes through photodetectors and originates an average current as described by the equations 3 and 4, which are related to the orthogonal polarization components of the input signal. The sum of the output powers present in the two arms must represent the total power of the system, and this value should remain constant for all polarizations states of the input signal, as shown in equation 5.

To verify this, the proposed setup was implemented in a simulation environment thought the software Optisystem®. In this way, a signal modulated at 10Gbps in a NRZ-OOK modulation format was generated for this simulation, and it was coupled with ASE noise to generate a resultant signal with about 10dB of OSNR. This last signal goes to the PBS, which splits the signal in two orthogonal polarization components, and these two components are then converted to the electric domain by a group of photodetectors. The behavior of total power was obtained when the effects of the shot noise, thermal noise and signal to noise beating were considered, and that is shown in fig. 4 as function of the factor r .

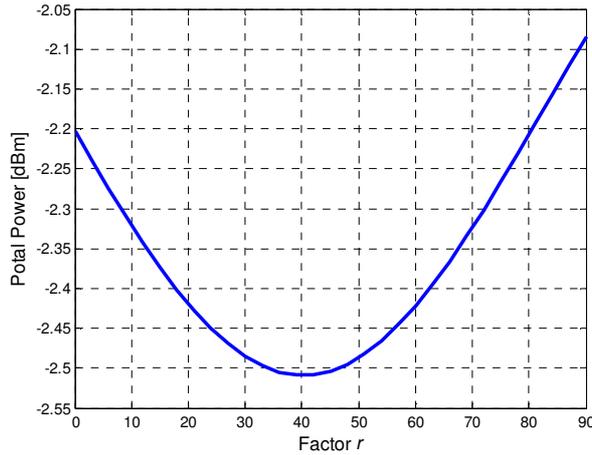


Fig.4 – Behavior of the total power in the electric domain in function of the polarization change.

As can be seen in fig.4, the system power does not remain constant with the variation in the state of polarization of the input signal. To explain this behavior the mathematical model made to characterize the system need to be revised to include other photodetector impairments, such as the signal to noise beating presents.

The stochastic behavior of the signal to noise beating allows represent it by its variance, described by the equation 8 [8], which is related to signal power.

$$\sigma_{s-ase}^2 = 4 \rho^2 P_{ase}(t) P_s(t) \tag{8}$$

How shown by the equation 8, this variance depends on the photodetector responsivity, ρ , the signal power, $P_s(t)$, and noise power, $P_{ase}(t)$.

When the photodetector effects are inserted in the analysis, the behavior of the power system in the electrical domain is different from the optical domain. How discussed, between photodetector effects the main are the thermal noise and the noise to signal beating. If we consider equals the photodetectors in both axis with orthogonal polarization components, the influence of the thermal noise can be approached in a simple way, with the same load resistance and transimpedance gain. Also, the signal to noise beating will influence in the power system behavior in the electrical domain, because with the variation of the state of polarization the signal ratio that goes to each PBS arms change, and, as presented in the equation 8, it will influence in the noise to beating variance.

In a real network scenario, once the variance is related to the signal energy and to the square of the signal mean, this mean is influenced in a non linear way with signal variance. In this way, if it is consider the effect of the noise to signal beating, the significant influence of its variance means another system different from the one described by the equation 5, because with the variation in the state of polarization, the linearity in the power ratio between PBS outputs does not exist in the electrical domain.

Consider the simulation as shown in the fig. 3, the system power does not remain constant with the change in the state of polarization of the input signal, as can be seen in fig.4, This result enhances the need of compensate the effects of the photodetector impairments, mainly the signal to noise beating, on the OSNR estimation. This can be done by characterization of the error estimation behavior as function of the state of polarization of the input signal. The use of this characterization only will be possible because for a range of OSNR and of input power the error behavior follows a pattern, which can be used to mitigate the effects of the variation of the state of polarization in the system. Applying this characterization, the signal state of polarization conditions analyzed in fig. 3 were evaluated and the results are described in fig. 5.

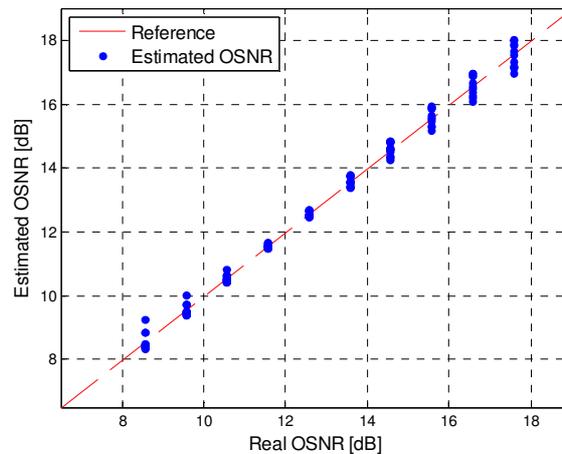


Fig.5 - OSNR estimation with the correction of the polarization effects; Pin: -9.8dBm.

III. Experimental Analysis

After applying the modification in the OSNR monitor mathematical model and verifying its validity in simulation environment, the next step is to build an experimental device to evaluate its performance. Fig. 6 illustrates the experimental OSNR monitor functional block diagram, and a device was built according to the schematic illustrated in fig. 1.

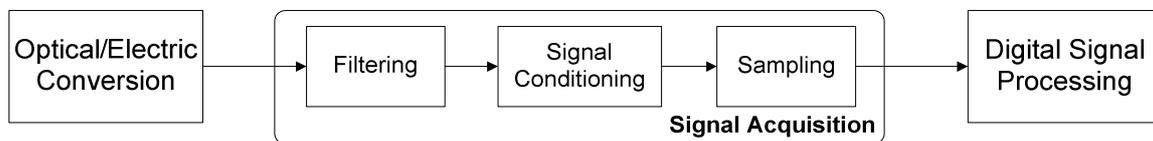


Fig.6 - Experimental setup block diagram.

Fig. 6 shows the electrical signal conditioning process executed after the optical to electrical domain conversion made by the photodetector, and in the end there is a DSP to estimate the OSNR.

The approach chosen to the experimental solution was to develop a PCB (*Printed Circuit Board*) to integrate the needed components to enable the OSNR estimation solution with DSP according to the

fig.1 schematic diagram. Fig.7 presents the OSNR monitor schematic diagram containing the optical and the electrical circuit.

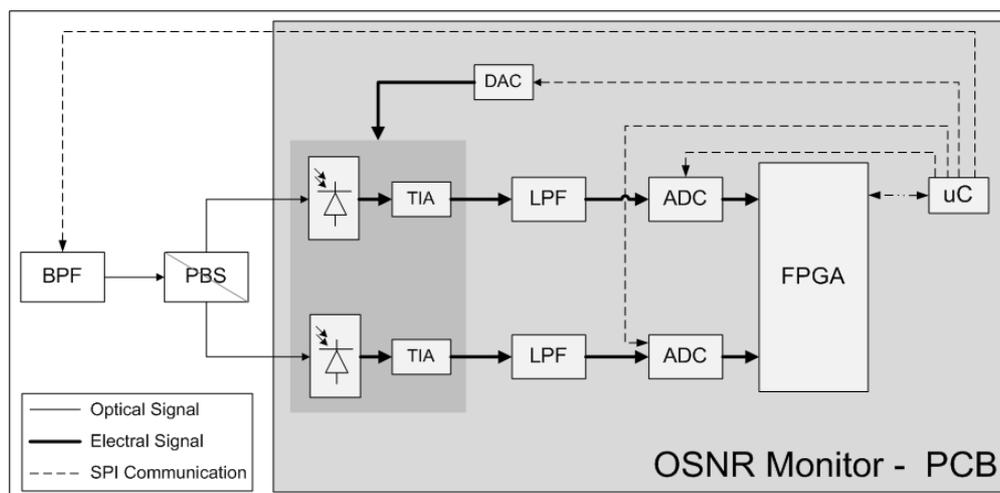


Fig.7 – OSNR monitor optical and electrical (PCB) schematic.

The description presented in fig. 7 follows the schematic depicted in the fig. 1, but, in the experimental environment, there are some additional components that must be used to do the signal conditioning, the digital signal processing, and the communication with all peripherals according to correctly control the OSNR monitor device, which is made through a serial peripheral interface (SPI).

Inside the OSNR monitor device, the optical channel to be monitored is selected through a tunable band pass filter (BPF) with 50 GHz of bandwidth, which could be tuned through SPI communication. After the BPF, the signal is splitted by a polarization beam splitter (PBS), and each PBS arm signal is converted from optical to the electrical domain by means of a photodetector. A digital to analog converter (DAC) will be necessary to dynamic adjust the transimpedance amplifier (TIA) gain, which depends on the input voltage level, while communication with the ADC must guarantee the full scale of the sampled signal, improving the quality of acquisition. Furthermore, there is a Field-Programmable Gate Array (FPGA) that supports the high transmission rates required by the solution. A microcontroller (uC) was used to read and to control the peripherals (BPF, DAC, ADC, FPGA), making the OSNR estimation. The FPGA was used to acquire each PBS arm signal digitalized by the ADC, and to make the pre-processing steps.

Following the electrical PCB schematic in fig. 7, fig. 8 illustrates the hardware (PCB) developed to estimate the optical signal to noise ratio (OSNR).

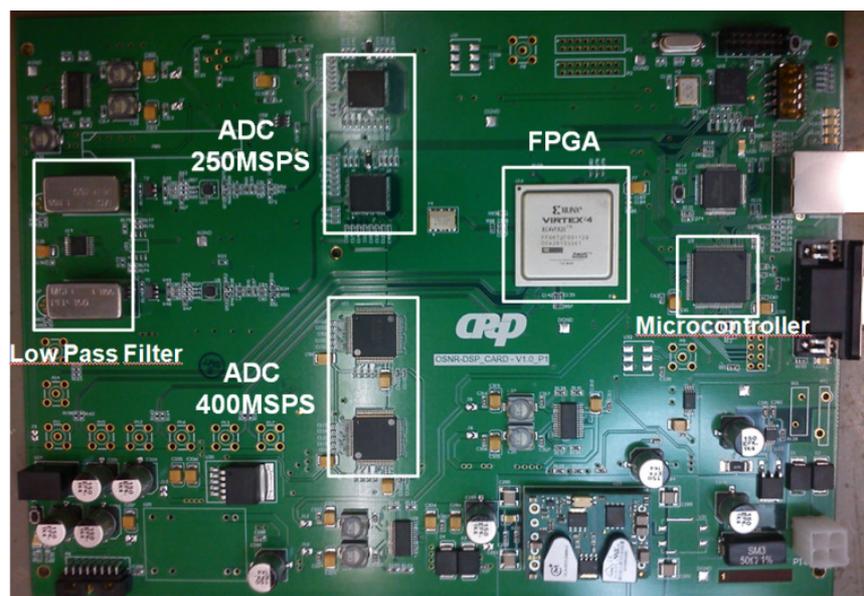


Fig.8 - PCB for OSNR estimation

In this PCB there are two kinds of ADC's, one with the sample rate of 250 MSPS and another with 400 MSPS. The design with two ADC's was intentionally made to study the influence of the sample rate in the quality of estimation, making the solution more robust for an experimental setup.

About the digital signal processing in the FPGA and microcontroller, the FPGA has two functions, first one is working as a dual port ram (DPRAM), receiving the signal in the ratio fixed by the ADC's and changing it to microcontroller. It is important for the solution because it makes the FPGA able to do its second function, which is to start the digital signal processing and to send only some parameters for the microcontroller, which will finish all digital processing. The solution was improved with this approach due to the frequency of operation of the FPGA to be faster than the microcontroller, so, beyond the digital processing to be shared between both components, the FPGA does what need to be fast and the microcontroller finishes the OSNR estimation.

Once defined the PCB used to measure the OSNR, it is important to calibrate this PCB, because there are some parameters in the electrical components do not modeled in the mathematical model used for the estimation. This calibration was made considering a known state of polarization, and following a configuration look-up table, which relates each estimated OSNR with the respective real OSNR. In this way, an state of polarization described by the ratio between output powers of PBS arms equals to 0.4 was chosen for the calibration and three different input powers were used to evaluate the system: -7.9dBm, -9.9dBm and -12.5dBm. Once made this calibration, it was added to the model and fig. 9 illustrates the influence of the state of polarization in the OSNR estimation using the experimental device, considering the input signal modulated at 10Gbps non returning to zero (NRZ) on-off keying (OOK).

From fig. 9 it is possible to see the same behavior has already seen in simulation, proving that the quality of OSNR estimation depends on the state of polarization of the input signal. For the calibration made in the experimental analysis, the state of polarization was chosen through a ratio between output powers of PBS arms equals to 0.4 due to minimum estimation error presents at PCB. In simulation it happens for an input polarization described by this ratio close to 0.5, where the power in each PBS arms are balanced, guaranteeing the same behavior in the photodetectors.

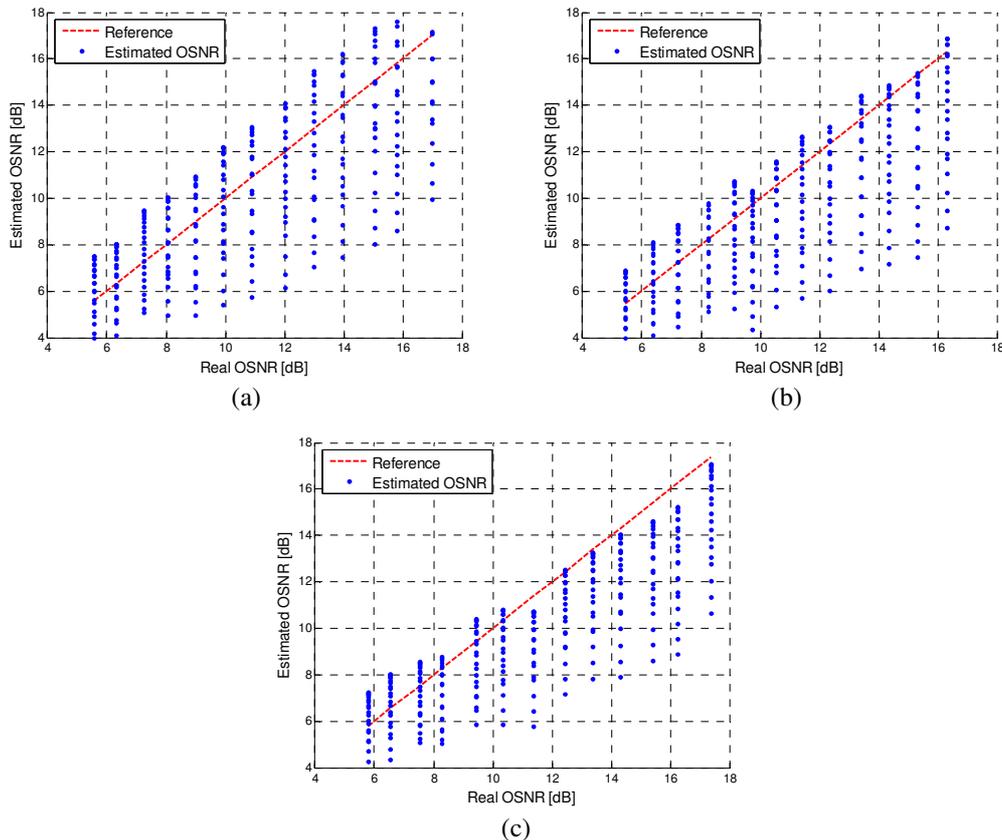


Fig.9 -OSNR estimation through the influence of the input polarization variation. Input Power of (a) - 7.9dBm; (b) - 9.9dBm; (c) - 12.5dBm.

As has already seen in simulation, fig. 4, the experimental analysis shows the influence of the state of polarization in the quality of OSNR estimation. Such results confirm the need to compensate the impairments present in the photodetector, mainly signal noise beating, to estimate the OSNR in a real network scenario. To solve this problem is proposed an error characterization like the one made in the simulation environment, in which a pattern was defined for this error and, then, it was compensated. However, when consider experimental analysis, only was able to find an error pattern for a limited range states of polarization. So, a polarization controller was inserted in the experimental setup to reduce the range of variation in the state of polarization, guaranteeing a compensation of the error pattern to increase the OSNR estimation. This polarization controller was put between the band pass filter and the PBS, and the microcontroller was used to define the way how that works through a PI controller. So, by the two terms control, proportional and integral term at PI controller, it is possible to

limit the polarization variation at the experimental device to about 2% of a reference point. The fig. 10 shows the experimental device with the polarization controller and fig. 11 presents the OSNR estimation for input powers of -7.9dBm, -9.9dBm and -12.5dBm, with the use of a polarization controller and applying the error characterization to define its pattern and ensure the quality of estimation.

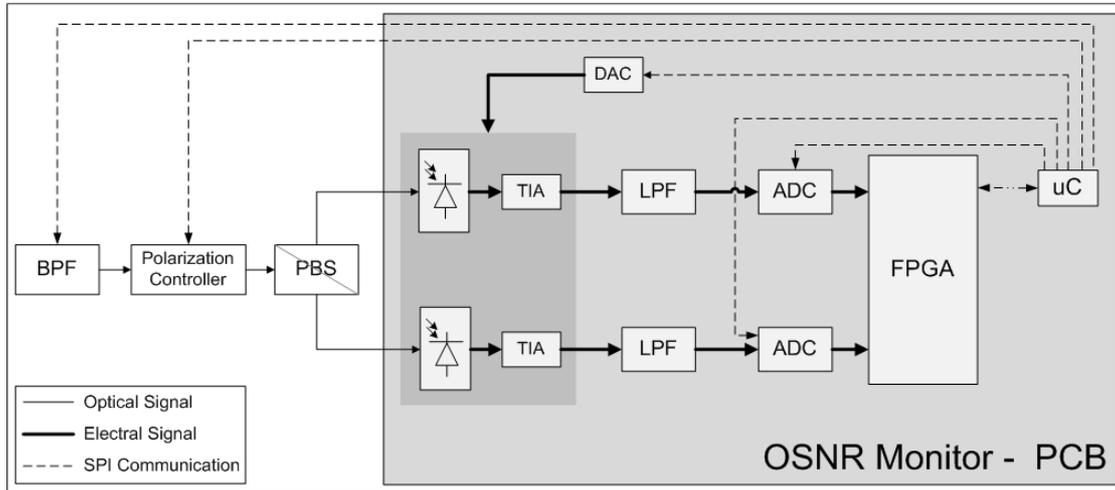


Fig.10 - PCB schematic with the polarization controller.

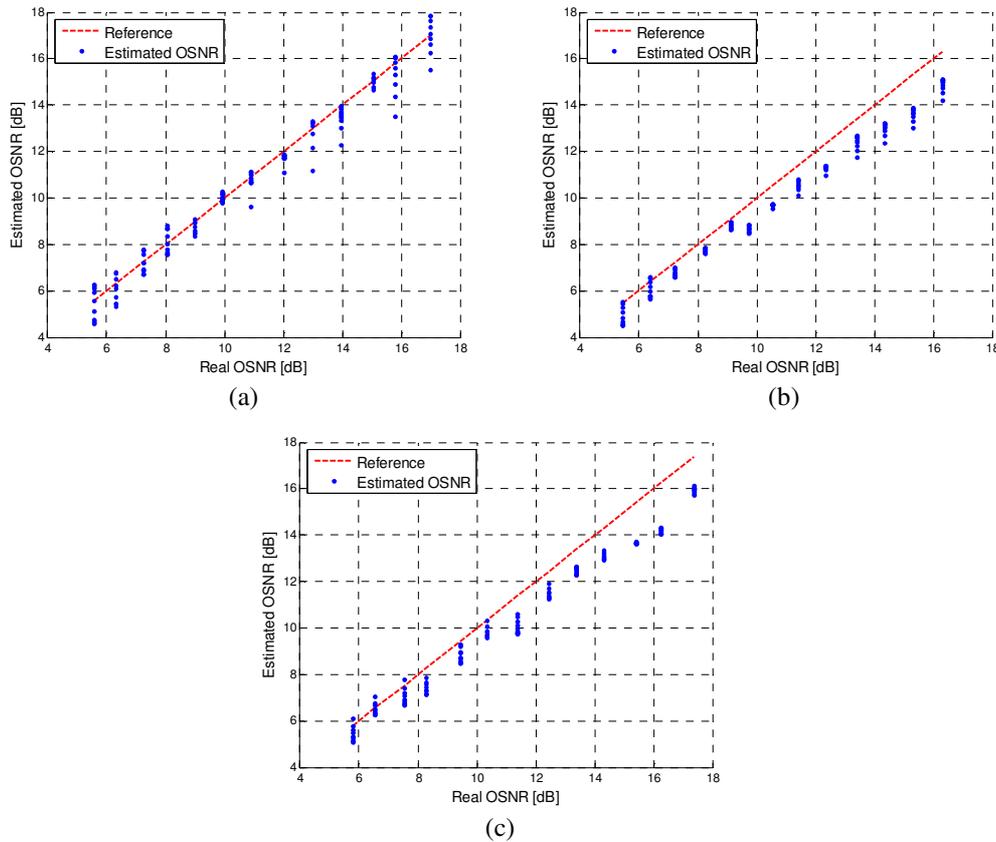


Fig 11 – OSNR estimation with the effects of variation in the state of polarization corrected by the use of polarization controller and error characterization. Input Power of (a) - 7.9dBm; (b) - 9.9dBm; (c) - 12.5dBm.

Through the error characterization it is possible to achieve an error estimation below 2dB, what is less compared with the error from fig. 3 where this error is close to 8dB, as can be viewed in fig. 9.

IV. Results

At the simulation environment (Optisystem®), one signal modulated at 10Gbps NRZ-OOK was used together with the ASE noise to build the setup shown in fig. 1. In this scenario, to compensate the dependence on state of polarization of the input signal, the estimation error was characterized to define its pattern and to mitigate the signal to noise beating effect in the OSNR monitoring. This characterization allows compensating the error for different values of the factor r , improving the estimation. The fig.12 shows two situations, the first one with the estimation error influenced by the signal noise beating, and the second one with this influence compensated by the characterization of the estimated error.

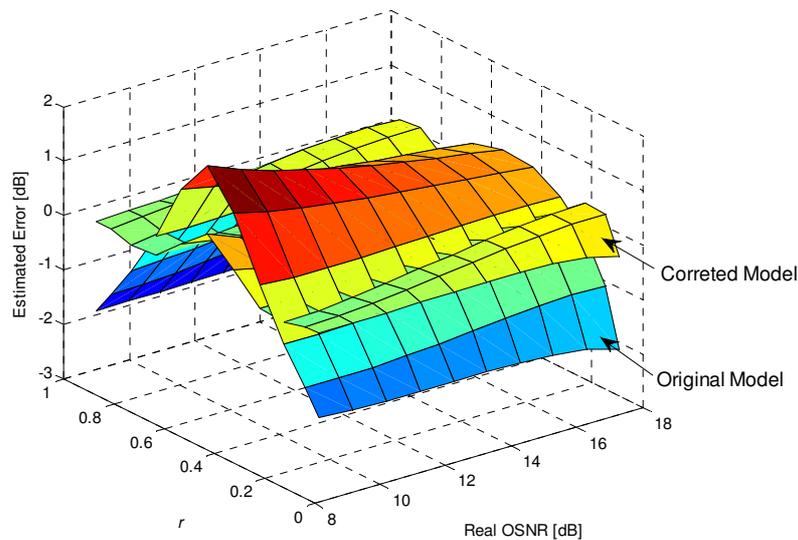


Fig. 12 - OSNR estimation error by the variation of input signal state of polarization for two models analyzed.

As can be seen by fig. 12, the estimated error only converges to the minimum value if the factor r , which represents the distribution of power between the PBS arms, is equal to 0.5. When the factor r is far away from this situation the error rises, because the noise at one PBS arm will be different from the other one due to signal to noise beating effect. Also, in fig. 12 can be seen after error characterization the decrease of the error estimation, which goes from 2dB to 0.5dB for all range of

the OSNR analyzed. This characterization is supported by the error behavior, which has a well defined pattern in all OSNR range analyzed, so, the quality of estimation will be guaranteed.

At experimental setup, through the calibration of the estimated OSNR to consider the electrical impairments at the PCB and the error characterization due to the state of polarization in the input signal, the performance of the OSNR monitor reaches an estimation quality as shown in fig. 13, however, these results are only achieved because of the polarization controller presents in the experimental setup, which gets possible to have a well defined pattern for the estimated error.

In the fig. 13 there are three different conditions of the input power, the first one with - 7.9dBm and the other with - 9.9dBm and - 12.5dBm, respectively.

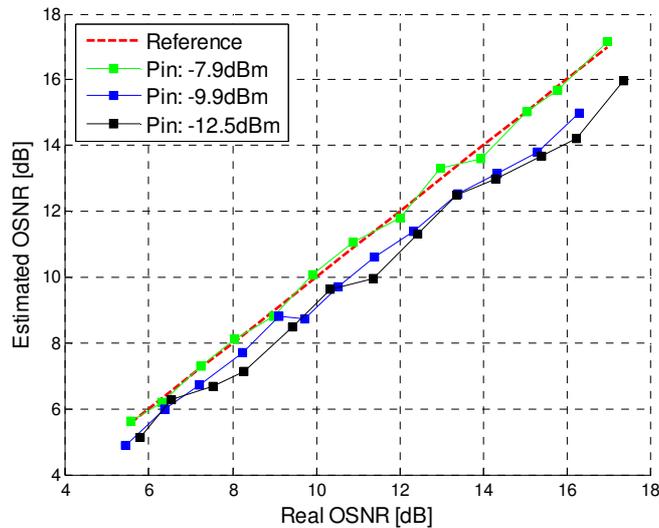


Fig.13 – Experimental OSNR estimation device performance for a defined state of polarization.

Besides the set of calibration and error characterization, the PCB built to monitor OSNR presents electrical issues that become the quality of estimation higher dependence on the calibration process and the control of signal state of polarization. The hardware components at PCB insert electrical noise in the input signal, and this noise decrease the acquisition quality required to OSNR estimation with a low error. In this way, it is important to consider the performance of the front end circuit, mainly the transimpedance amplifier used to guarantee the appropriate level to the analog to digital converts, because in the amplification process is inserted electrical noise in the signal, what may surpass the improvements in the OSNR estimation given by the calibration and compensation of variation in the state of polarization.

V. Conclusion

Through the gotten results, the influence of the signal to noise beating from the photodetector was observed, which proves the dependence on input signal polarization in the OSNR estimation. At the Simulation environment the estimation error increases with the difference between the powers in each

orthogonal polarization component presents in the PBS arms, so, when the ratio of these powers runs away from 0.5, the OSNR estimate error increases. Once the simulation is considered, the OSNR estimation error was lower than 2 dB for an OSNR range from 8 dB to 17 dB. With the error characterization the monitoring quality increases and the error becomes lower than 0.5 dB for the same OSNR range.

For the experimental setup, the quality of estimation is dependent on the calibration process and the control of variation in the state of polarization, which is required due to the noise inserted by the electronic circuit used to condition the signal into PCB. Also, the PCB front end circuit must guarantee the precision of the signal acquisition, but the amount of noise from the electrical amplifiers in this circuit influence the quality of estimation. However, besides all issues presented the experimental setup showed an estimated error lower than 2dB for an OSNR range from 5.5 dB to 17 dB.

Another point that needs to be considered in the experimental analysis is the behavior pattern of the estimated error related to variation in the state of polarization, because the error pattern only is observed for a little range of this variation, what becomes harder to characterize that. The alternate is inserting one more optical component in the experimental setup, a polarization controller, whose function is to ensure that the ratio power between each PBC arms always will be around to the best input polarization performance for measuring the OSNR, which in the experimental analysis was indicate by the factor r close to 0.4. Besides the difference between the simulation and experimental results, the last one has perspective of a high quality of OSNR estimation, which will require improving in the quality of front end at PCB and putting a polarization controller between the band pass filter and the PBS.

The OSNR monitoring based on polarization diversity between signal and noise, as the one has already described here, does not work for the coherent signals because for this kind of signals its two orthogonal polarization states have approximately the same amplitudes and hence appear unpolarized to a polarization-sensitive optical spectrum analyzer [9], so, consequently, the signal is not readily distinguishable from the superposed ASE noise. However if the sample frequency is faster than signal speed instead of get the time-averaged polarization state, which is unpolarized, we get instantaneous polarization distribution of the optical signal through the PBS [10], which remains the polarization diversity property used to monitor the OSNR. Although it will solve the problem for the coherent monitoring, the solution will be more expensive.

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