People’s Democratic Republic of Algeria
Ministry of Higher Education and Scientific research
M’hamed Bougara University, Boumerdes
Institute of Electrical and Electronic Engineering,
Laboratory of Signals and Systems (LSS)

ALGERIAN JOURNAL OF SIGNALS AND SYSTEMS

ISSN : 2543-3792

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Page range: **140- 148**

Volume : 2 Issue : 3 (September 2017)

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Design and Simulation of a WDM-OADM Optical Ring Communication System

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Abstract: The advent of nodal elements, such as Optical Add/Drop Multiplexers (OADM) for Wavelength Division Multiplexed (WDM) networks, has led to a myriad of possible network architectures for the optical layer. In this project we design and simulate a WDM-OADM optical ring system of four nodes, two wavelengths on unidirectional single mode fiber at data rates of up to 10 Gbps. We use a continuous wave laser as a source for each channel with external modulation. The performance of the system is reported on the basis of eye diagram, Bit Error Rate (BER) and Q-factor. Optisystem software is used to simulate the overall designed system.

Keywords: SMF, WDM, DWDM, OADM, EDFA, DCF, optical fiber network.

1. INTRODUCTION

Today's transport networks must cope with ever increasing traffic inflation by high capacity and reliable systems. The demand is increased by many different factors. The rapid growth of internet, voice, data, video conferencing, and private networking services consumes large amounts of bandwidth. Especially internet connections load the telephone network enormously. There are also increasing technological revolutions on the industry, finance, education, medicine, government and most business applications. All these factors increase the need for bandwidth in networks.

Due to this increase in bandwidth demand in the field of networking, the use of optical fiber is recommended. To achieve the higher data rate to support new multimedia application and services, different network providers are moving towards optical networks based on optical fibers which provide higher data rates or bandwidth and low signal degradation [1]. The potential bandwidth of a fiber is nearly 50 Tb/s, a speed that today's electronic processing capacity cannot match. Therefore, Wavelength Division Multiplexing (WDM) technology is developed to support tremendous bandwidth. WDM is a transmission system that enables more efficient utilization of optical fiber by multiplexing and simultaneously transmitting multiple optical signals of different wavelengths.

WDM communication networks require optical components which can separate closely spaced channels effectively and allow for the flexible addition and dropping of channels [2]. Add/drop multiplexers (OADMs) and filters that drop one channel of WDM signal, without disturbing other channels, are essential elements in all-optical networks [3, 4]. Ring resonators are promising devices for different applications in all-optical networks, such as filters, switches and optical delay lines[5-7]. Their small size allows for high density integration in optical photonic circuits by exploiting the availability of CMOS fabrication facilities [8]. Coupling a closed loop resonator with a bus waveguide leads to a new structure with a filter-like behaviour. Careful choice of the coupling coefficients between ring and bus waveguides has a great effect on the filter crosstalk performance.

In this work, we present a generalized procedure which can be used to design a WDM network system. As an application, a two channel basic optical ring communication network operating at 10 Gbps is designed. For testing purpose, simulation of the obtained system has been carried out by the OptiSystem software [9].

2. DESIGN PROCEDURE

The design approach of fiber links we have adopted is based on Q-factor (quality factor) and OSNR (optical signal to noise ratio). To design a network, it is imperative to comply with the system design with the BER (Bit Error Rate) requirement of the network.

The absolute quality of an optical signal is given by the Q-factor. The Q-factor provides a qualitative description of the receiver performance because it is a function of the optical signal to noise ratio (OSNR). The Q-factor suggests the minimum SNR required to obtain a specific BER for a given signal. The higher the Q factor of the signal, the better the BER will be.
The Q-factor of an optical signal can be expressed as:

$$Q=\frac{I_1-I_0}{\sigma_1-\sigma_0} \tag{1}$$

Where, is the value of the 1-bit current, is the value of the 0-bit current, is the standard deviation of the 1-bit current, and is the standard deviation of the 0-bit current.
The BER can be calculated from the Q-factor as:

$$BER=\frac{1}{2}erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{2}$$

Where, *erfc(x)* is the error function:

$$erfc(x)=\frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-y^2}dy \tag{3}$$

For a given optical signal, among these three design parameters, the OSNR is a measurable quantity and hence is certainly the most important parameter from practical point of view. Further, the Q-factor can be determined directly from the OSNR as [9]:

$$Q_{dB}=OSNR_{dB}+10\log\left(\frac{BW_O}{BW_E}\right) \tag{4}$$

Where, BW_O and BW_E are respectively the optical and the electrical bandwidths.
Typically, while designing a high-bit rate system, the margin at the receiver is approximately 2 dB, such that Q is about 2 dB smaller than OSNR (dB) [9]. This practical margin sets therefore the practical constraints on the ratio BW_O/BW_E.
Consider a physical link AB, as shown in figure 1. Assume this to be a long-haul fiber WDM link. Amplifiers are placed periodically at repeated intervals to boost signal power. Therefore, the signal can reach much farther than the maximum allowable accumulated loss. However, in doing so, each amplifier stage adds its own component of amplified spontaneous emission (ASE) noise and degrades the OSNR further. Moreover, every amplifier amplifies the already present noise. Noise is present throughout the spectra and almost impossible to be removed. Therefore, it is imperative to devise a method to calculate the OSNR (output) at the end of an N stage-amplified system and see if the value N is still valid.

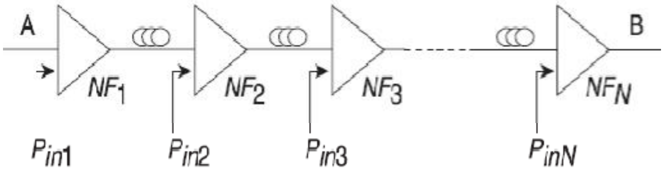

Figure 1. A Multiple Stage Amplified WDM System Deployed between two nodes

The OSNR of the kth stage is given by [9]:

$$OSNR_k=\frac{Pin_k}{NF_k\, h\nu\Delta f} \tag{5}$$

Where: Pin_k is the input optical power at stage k, NF_k is the noise figure of the stage, *h* is the Plank's constant (6.626 × 10-34 Js), *v* is the optical frequency and *Δf* is the bandwidth that measures the NF_k (usually 0.1 nm)
The total OSNR for the N stage system can be considered by a reciprocal method as shown below [9]:

$$\frac{1}{OSNR_{Total}}=\sum_{k=1}^{N}\frac{1}{OSNR_k} \tag{6}$$

For an N amplifier stage system, with each amplifier compensating for the loss of the previous span where the span loss in dB is *Γ*, taking the logarithm to the common base (10), and substituting *Δf*=0.1nm, or 12.5 GHz, we get the following equation for OSNR [9]:

$$OSNR_{dB} = 58 + P_{in_1} - \Gamma_{dB} - NF_{dB} - 10\log(N) \quad (7)$$

In equation (7), the following has been assumed:

- The NF of every amplifier is the same. We assume thus uniformity of products which is highly recommended in practical implementation.
- The span loss *Γ* is constant. (This assumption can change.)

Equation (7) provides the actual mathematical calculation of OSNR. This calculation method has quite a few approximations in which we can still find the system OSNR to a great degree of accuracy. In a multichannel WDM system, the design should consider OSNR for the worst channel (the one that has the worst impairment). Figure 2 shows the basic flowchart which can be used to design an optical network based on this approach.

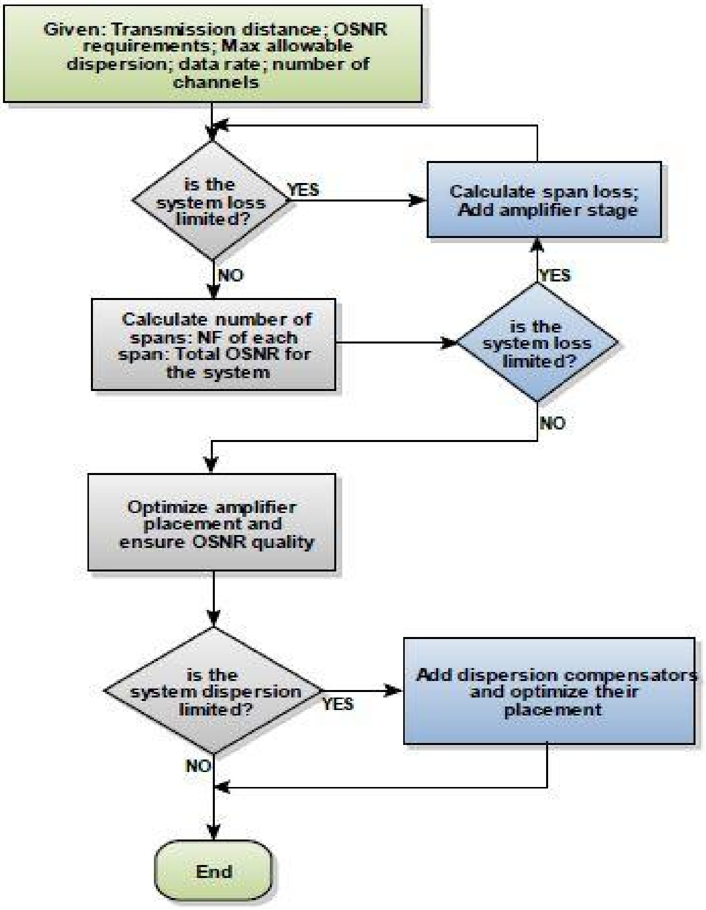

Figure 2. Flow Diagram of a Generic WDM Design case

3. CASE STUDY: DESIGN OF A BASIC RING WDM NETWORK

A basic transparent two channel WDM metro ring network operating at 10 Gbps with 200 km in circumference with four OADMs as shown in figure 3 is to be designed. In this network node 1 communicates with node 3 on channel 1 at 193.2 THz and node 2 communicates with node 4 on channel 2 at 193.1 THz.

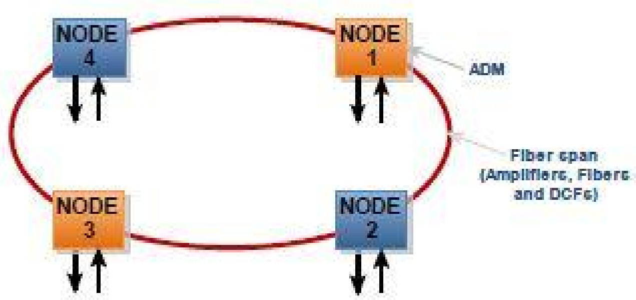

Figure 3. Basic Ring Topology with four Nodes

The above network has the following specifications:

Transmission window	**Data rate**	**BER**	**Dispersion tolerance**	**Power margin at receiver**
1550 nm	10 Gbit/s	< 10^{-12}	1600 ps/km	2dB

The characteristics of the different components of the network are indicated in the following tables:

(a) **Transmitter:** CW Laser diode

Parameter	**Value**
1st channel frequency	193.2 THz
2nd channel	193.1 THz
Data rate (NRZ)	10 Gbps
Launch power per channel	+7 dBm

(b) **Receiver:** PIN photodiode detector

Parameter	**Value**
Receiver sensitivity	-18 dBm

(c) **Optical amplifier:** EDFA

Parameter	**Value**
Optical amplification band	1530 nm – 1560 nm
Gain	23 dB
Noise figure	5 dB
Maximum output power	10 dBm
Input power	-13 dBm

(d) **Transmission line:** Single mode fiber

Parameter	**Value**
Attenuation at 1550 nm	
Chromatic linear Dispersion at 1550 nm	

(e) **connectors, splices and OADM**

Symbol	**Description**	**Loss value**
L_{conn}	Loss of a connector	0.15 dB
L_{splice}	Loss of a splice	0.25 dB
L_{oadm}	Loss of a OADM	2.00 dB

4. SIMULATION MODEL

The simulation of the designed network was carried out using the OptiSim software [10]. The overall layout is shown on figure 4. Each node of the network gathers a transmitter, an ADM and receiver as shown in figure 5. Each optical receiver consists of a PIN photodetector, a fourth order low-pass Bessel electric filter with 0.75 * Bit rate cut-off frequency. The performance of a digital lightwave system is characterized through the bit-error rate (BER). In OptisyStem, the BER analyzer is used to analyze the received signal and thus it's connected after the filter as shown in figure 6. Single Mode Fiber (SMF) is applicable for high-capacity, long-distance optical fiber communications due to its tremendous bandwidth. In optical fibers, after a long haul, the signal's intensity is greatly attenuated and therefore needs to be enlarged by a relay optical in order to be received or continue transmission. At present, the EDFA is used. The most fundamental reason that restricts the transmission of high-speed signals on the 1550nm optical fiber is linear dispersion [11]. The dispersion of SMF in the 1550nm window is 17ps/(nm·km), therefore dispersion compensators are used for compensating their dispersion performance. DCFs are used and have a negative chromatic dispersion coefficient of –85 ps/(nm·km). EDFAs are added to compensate linear loss after the DCF and near to the receiver because the attenuation of DCF is large. The span design in OptiSystem is shown in figure 7. Metro networks using ring topology are expected to have more dynamic traffic pattern compared to most long-haul networks, and are expected to have optically transparent nodes. Thus, we need to consider all optical degradations that accumulate along the links until the optical termination. There are several factors that may limit system design and these include nonlinear effects, receiver sensitivity, and losses in fibers, OADMs etc.

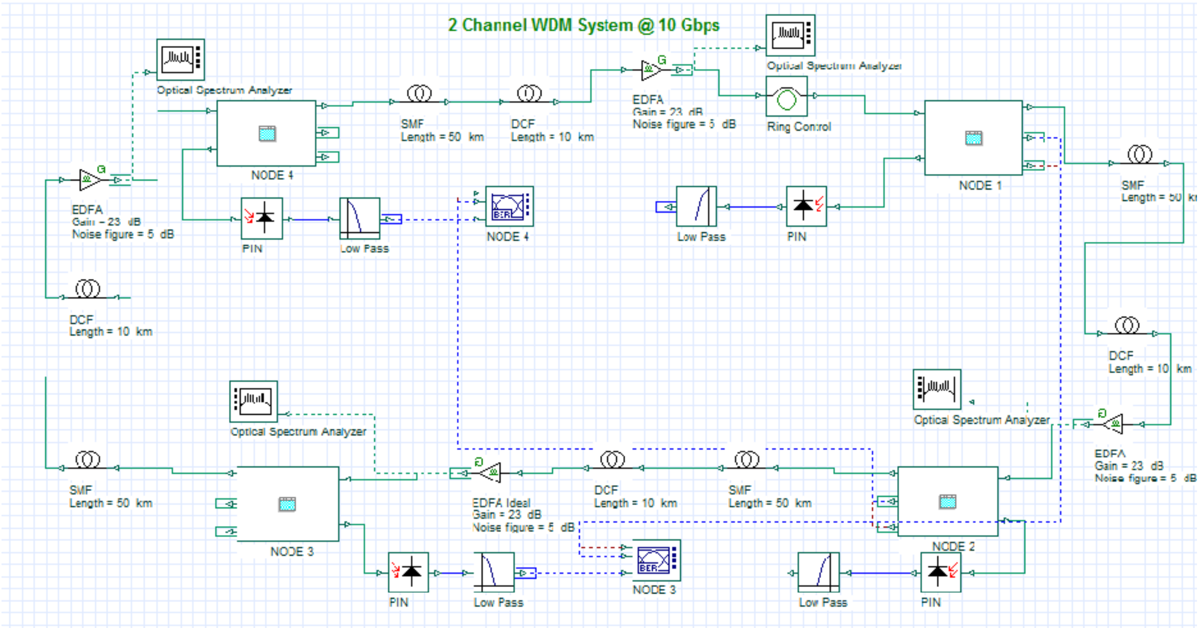

Figure 4. The general network model

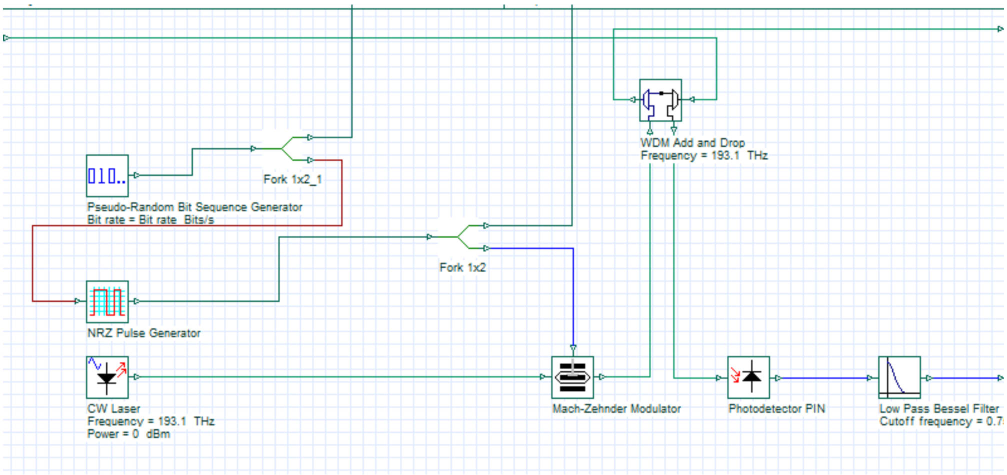

Figure 5. Node details

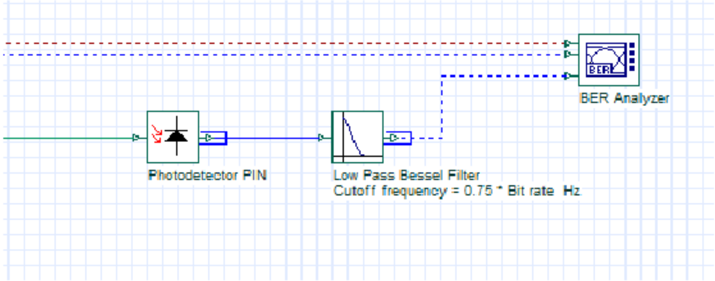

Figure 6. The receiver model

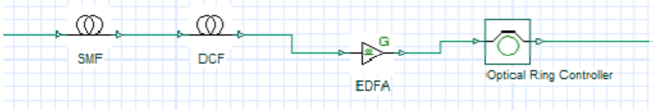

Figure 7. The transmission line model

5. RESULTS AND DISCUSSIONS

Appropriate lengths of DCFS were used and EDFAs with a gain of 23 dB were used for compensating the system losses and dispersion accumulated in the system. The resulting Q-factor and eye diagrams for node 3 are shown in figure 8a and 8b. Table 1 shows the measure of the signal power and OSNR for channel 2 as given by the WDM analyzer.

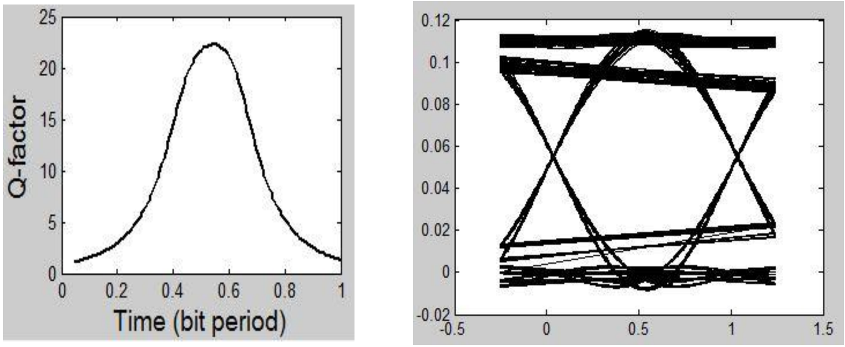

Fig.8.a. Q-factor at node 3

Fig.8.b. Eye diagram at node 3

Using the appropriate compensations, wide open eye diagrams were obtained as well as Q factors greater than 6 dB and BERs less than 10^{-12} , which means that the performance of the system are Excellent and the received signal is well determined by the receiver. The effect of varying the launch power of the laser on the system was also investigated. The different power levels used and the obtained results for node 4 are shown in figures 9a and 9b.

As shown on the figures, for small launch powers, the received signal has a low Q factor (Q< 6) and a high BER ($>10^{-9}$) this is below what is required by the communication standards. However, as the power is gradually increased, optimal power is achieved at around 3 dBm. But as the power is further increased, the signal starts to degrade. This is due to nonlinear effects in the fiber which are significant at high power rates.

Finally, the maximum distance our system can reach keeping a good Q factor and BER within the required range was investigated, and the obtained results are presented in figure 10.

Table 1. Simulation results for channel 2

Frequency (THz)	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
193.1	5.008	-29.967	34.975
193.2	1.456	-26.208	27.664

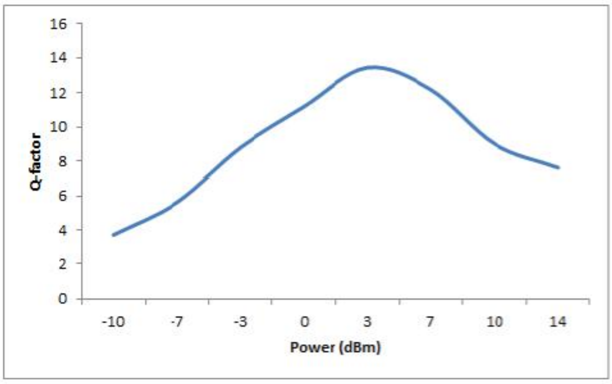

Figure 9a. Q-factor as function of optical power

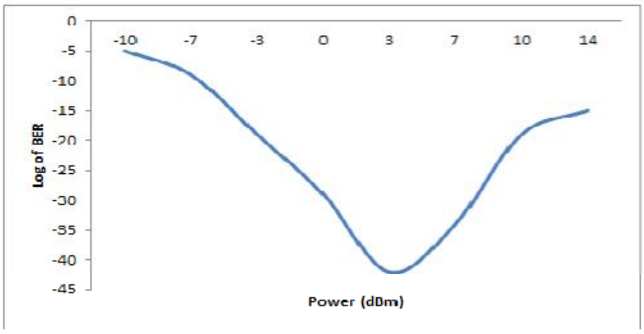

Figure 9b. BER as function of optical power

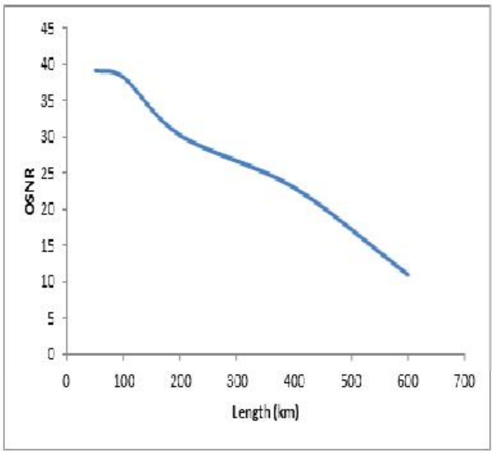

Figure 10. OSNR as function of optical link length

The results show that for data rate of 10 Gbps per wavelength channel good performance in terms of OSNR is achieved for distances up to 400 km.

6. CONCLUSION

A design approach for WDN networks has been presented. As an application, a WDM-OADM optical ring communication system, operating at 10Gbps was designed and tested using Optisystem software. It has been found that EDFAs and DCFs must be used to respectively compensate the system losses and dispersion along the optical link to ensure good communication quality. It was also found that optimum powers should be used to achieve better results, the transmit power should be high enough so that it can maintain signal power greater than the Receiver sensitivity (R) at the receiver end, despite the attenuation along the transmission line. That does not mean that if we increase the transmit power to a high level, we can send bits across greater distances. High input power is also a breeding ground for impairments (nonlinearities such as cross-phase modulation (XPM), self-phase modulation (SPM), four-wave mixing (FWM) and so on).

After varying the length of the fiber, it was noticed that for a certain number of transmitted channels, the BER increases while the Q-factor decreases with increasing distance which results in poor system performance. Our simulation model can be used to determine the maximum allowable distance between two nodes taking the OSNR as the basic criterion for system performance.

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