The 2012 2nd International Conference on Circuits, System and Simulation (ICCSS 2012)
IPCSIT vol. 46 (2012) © (2012) IACSIT Press, Singapore

Performance of Optical Network with Lower Bit Error Rate (BER)

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Abstract. Bit error rate always exists in the optical Network. Lower BER which is at 10^{-12} with the best performance is practicable .Under certain conditions, optical network which includes one wavelength is setup with the longest possible reach. The properties of optical devices play a crucial role in the network. This design has chosen the cheapest components to build up practical optical links with PIN receiver.

Keywords: Bit Error Rate (BER), Crosstalk, Noise, Optical network.

1. Introduction

As we can see nowadays, the optical communication system has changed the communication industry and human lifestyle dramatically. The optical communication systems are structured by some optical components, such as optical transmitters, amplifiers, optical receivers, WDM systems, filters, attenuators and, of course optical fiber. By using some of these components to build up an optical link to transmit information data and keep the data uncorrupted are the engineers' basic task, which is also challenging. The purpose of this paper is to design an optical network at the BER less than 10^{-12} with the best performance, and the design is also to choose the cheapest components to build up practical optical links.

2. Components

2.1. Transmitters (TX)

Transmitter generates an optical signal from an electronic input and input the signal to the communication channel. Laser with high resolution or narrowband are the main devices of the transmitter. The electrical signal will be transmitted and modulated to optical signal for transmission. The optical carrier EM wave field E can be expressed as below [1]:

$$E = A\sin(2\pi ft + \phi) \tag{1}$$

Where f denotes the frequency; ϕ is the phase and A is amplitude of the signal. Hence the intensity of the light is proportional to A^2 .

The On-Off Keying (OOK) modulation scheme has been used in the optical network. Obviously, p_0 represents the low power or "Off" and p_1 stands for the high power or "On". It is obtained by varying the signal current. One of the characteristic is the Extinction Ratio r which is defined by the high power p_1 to the low power p_0 .

$$r = p_1 / p_0 \tag{2}$$

In theory, within an ideal transmitter, p_0 would be zero and r would be infinite. However, the laser must be biased and p_0 is around the laser threshold. It means that a small amount of the optical power is

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emitted at a low level. Hence, $p_0 > 0$. In practice, it is useful to bring the average optical power p_{av} in optical transmitter and in the DWDM system. p_0 and p_1 can be represented by the Extinction Ratio and the average power[2].

$$p_0 = \frac{2}{r+1} p_{av} \qquad\qquad p_1 = \frac{2r}{r+1} p_{av} \tag{3}$$

For an optical transmitter, the Extinction Ratio must be high enough. Typically it is 10 or even greater. Otherwise, the signal cannot be distinguished easily at the receiver, or the transmission power is required much larger.

2.2. Optical Receiver (RX)

An optical receiver is a device that detects optical signal and converts it to electrical signal. Because the noises exist in the receiver, the power level at the input of the receiver differs to the original one. Not all signals can be detected correctly by the receiver. The Bit Error Rate is normally used as the fundamental performance measurement for binary digital communications over optical fiber links. It is determined by Optical Signal to Noise Ratio (OSNR), crosstalk and dispersion eye penalty. The nonlinearity and polarization mode dispersion are neglected in this work. The BER in this project is no more than 10^{-12} which is the commercial requirement.

2.3. Variable Optical Attenuators (VOA)

VOAs are the most important devices used in the DWDM system. Optical attenuators reduce the optical signal power to satisfy the system commanding. Some of them are employed before the multiplexer to keep the power in different wavelengths more or less the same. Be placed before the optical amplifiers to match transmitter power levels to the amplifier gain. In the system, it ensures power into fiber is below eye safety and nonlinear limits.

2.4. Optical Amplifier (OA)

The term “amplifiers” refer to boost the transmission of information along the fiber. It can be said that the amplifier provides optical gain because fiber attenuation limits the strength of optical signal. There are three areas to use optical amplifiers in a modern communication system. As power amplifiers they employ to enlarge the power of the signal before it reaches into the fiber transmission link and it can extend the transmission distance. Line amplifiers are set at designed points to restore or compensate a signal to its initial level. Finally, preamplifiers serve at the input of an optical receiver to boost the signal level which improves the signal detection performance. In each these three types of amplifiers has different properties. Power amplifier has high gain, preamplifier needs lower noise value and the line amplifier requires both of them.

A few materials which are semiconductor optical amplifiers (SOAs) and Erbium-doped fiber amplifier (EDFAs) can be made as optical amplifiers. EDFAs become common and popular now, because Erbium atoms provide light amplification over the range of wavelength 1525—1610 nm. It has a gain bandwidth of about 35nm in the 1550nm. The SOAs are cheaper and can be integrated with semiconductor lasers, modulators. Compare with EDFAs, the SOAs have higher noise, lower gain, moderate polarization dependence and high nonlinearity with fast transient time. The amplifiers in optical systems not only amplify the signal power, but also enlarge the noise. Amplifiers induce Amplified Spontaneous Emission (ASE) noise which results in reduced detected optical Signal-to-noise ratio (OSNR). The ASE has power spectral density (PSD) in W/Hz

$$N_0 = n_{sp}(G-1)h\nu \qquad \text{or} \qquad N_0 = \frac{1}{2}(NFG-1)h\nu \tag{4}$$

Here NF is the noise figure of the optical amplifier. It is related to the spontaneous emission or inversion factor n_{sp} [3].

2.5. Wavlength Multiplexer and Demultiplexer (MULT / DEM)

In the optical communication network, the wavelength multiplexer and demultiplexer are the core devices of a DWDM system. The multiplexer can be used to mix all the wavelengths into a single fiber. And the demultiplexer can separate the wavelengths at the detect stage. Specifically, channel spacing of 100 GHz or 50 GHz is often exploited in multiplexing and demultiplexing. This is the ITU-T frequency grid using in industry. Since the EDFAs have a narrow band of 35 nm, the forty channels are possible for DWDM system at 100 GHz separation.

3. Mathematics

3.1. Dispersion in DWDM System

There is another factor which is the dispersion will limit the signal transmission in optical DWDM systems. When the optical signal propagates along the optical fiber, the energy will be broadening by the separation of the light wave. Therefore, the power level to the present signal "1" will be lowered. The Extinction Ratio will be reduced significantly. We will use the Dispersion Penalty and Eye Penalty [3] to describe this phenomenon.

$$D_{pen}(dB) = D_0 \frac{L}{150} r_{wc} \quad (5)$$

where D_{pen} (dB) is the dispersion penalty. L is distance (in Km). D_0 is the dispersion penalty which is measured using APD receivers at BER of 10^{-12} after 150 Km of G.652 fiber.

The eye penalty is defined as the ratio of the unimpaired eye opening to the impaired eye opening while the average power at the detector is the same with and without the dispersion impairment. If we consider the crosstalk as well, then

$$E_{pen} = \frac{i_1 - i_0}{i_{1wc} - i_{0wc}} = \frac{p_1 - p_0}{p_{1wc} - p_{0wc}} \quad (6)$$

Cleary, this is the clean eye penalty because when the eye is wide open no noise is being taken. The dispersion penalty can be expressed by a worst case received extinction ratio. This Worst Case Extinction Ratio is:

$$r_{wc} = p_{1wc} / p_{0wc} \quad (7)$$

And

$$p_{0wc} = \frac{2}{r_{wc}+1} p_{av} \qquad p_{1wc} = \frac{2r_{wc}}{r_{wc}+1} p_{av} \quad (8)$$

The Worst Case Extinction Ratio r_{wc} is the power in a "1" surrounded by zeroes to the power in a "0" surrounded by ones. If the transmitter using a PIN (and no EDFAs), then the dispersion power penalty D_{pen} (linear) is the same as the eye penalty E_{pen} .Typically signal dependent noise dominates will include that and

$$D_{pen} = A^2 E_{pen}^2 \quad (9)$$

Where

$$E_{pen} = \frac{D_{pen}(\sqrt{r}+1)^2}{\sqrt{2(r+1)(\sqrt{r}+1)^2 D_{pen} - (r-1)^2}} \quad (10)$$

3.2. Noise in DWDM System

The aim to design a communication network is to minimize the noise and keep the best performance during the transmission. There are three main types of noises in a DWDM system. They are therrmal noise, shot noise and amplified spontaneous emission noise (ASE)[2].

(1) Thermal Noise

The thermal noise can be calculated by

$$\sigma_{th}^2 = \frac{4K_B T}{R_L} NFB_e \quad (11)$$

Here, B_e is electrical bandwidth, NF is the noise Figure and R_L is the load resistor.

(2) Shot Noise

Shot noise occurs when the finite number of particles that carry energy. Shot noise can be considered as white noise or flatness. Its variance for a single incident on a PIN is:

$$\sigma_{sh}^2 = 2qRP_{opt}B_e \tag{12}$$

For APD

$$\sigma_{sh}^2 = 2qRM^2F(M)P_{opt}B_e \tag{13}$$

where $R = \frac{\eta q}{h\nu}$ is the responsivity for the primary detection/photoelectron generation process. F(M) is the excess noise factor of the APD.

(3). ASE Noise

In our project, ASE noise have been taken account. They are signal-spontaneous beat noise and spontaneous-spontaneous beat noise. The formulas to calculate these ASE noise (for PIN) are shown below:

$$\sigma_{sig(n)-sp}^2 = 4R^2R_{ASE}P_nB_e \qquad \sigma_{sp-sp}^2 = 2M_tR^2B_{opt}R_{ASE}^2B_e \tag{14}$$

Where Mt is the number of polarization states of noise (1 or 2). B_{opt} is optical bandwidth. The ASE noise power spectral can be calculated to obtain the noise variances [3]. It is known as:

$$R_{ASE} = \frac{P_{av}}{M_tB_{OSNR}OSNR} \qquad OSNR = \frac{P_{av}}{M_tB_{OSNR}R_{ASE}} \tag{`15}$$

3.3. Analysis and Calculations of BER

3.3.1. The Simple BER Model

Assume that all the noises are to be Gaussian[4], the BER can be written as:

$$BER = \frac{1}{2}erfc(\frac{Q}{\sqrt{2}}) \quad \text{and} \quad erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-y^2}dy \tag{16}$$

Hence

$$BER = \frac{1}{Q\sqrt{2\pi}}e^{\frac{Q^2}{2}} \tag{17}$$

3.3.2. BER Model with Crosstalk

Crosstalk will increase the Bit Error Rate in the DWDM system [5]. The signal and two adjacent wavelengths have been considered in this paper. Therefore there are eight cases when a crosstalk happens, When considering the adjacent channel (signal to) crosstalk ratio, we use $R_{XT} = \frac{P_{av}}{P_{XTav}}$, a ratio typically expressed in dB. We can obtain the power in a crosstalk 1 and crosstalk 0 from this, and from assuming a value for the extinction ratio for the crosstalk. Worst case calculations would generally assume that the crosstalk has a good Extinction Ratio – most of the damage caused by the crosstalk arises from it's 1, so the worst case occurs if that 1 is as big as possible for a particular power.

With crosstalk[2]

$$Q = \frac{i_1 - i_0}{\sigma_1 + \sigma_0} \qquad i_D = \frac{i_1\sigma_0 + i_0\sigma_1}{\sigma_1 + \sigma_0} \tag{18}$$

$$i_1 = RP_1 \qquad i_0 = RP_0 \tag{19}$$

Where i_1, i_0 are the signal currents and σ_1, σ_0 are the noise variances. So:

$$\sigma_1^2 = \sigma_{th}^2 + \sigma_{sig(1)-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{sh,1}^2 \qquad \sigma_0^2 = \sigma_{th}^2 + \sigma_{sig(0)-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{sh,0}^2 \tag{20}$$

In the presence of the dispersion, the BER is

$$BER = \frac{1}{2}erfc\left[\frac{(P_{1wc} - P_{0wc})D_{pen}}{k\sqrt{D_{pen}P_{1wc}} + \sqrt{D_{pen}P_{0wc}}}\right] \tag{21}$$

where $k = 2\sqrt{2}\sqrt{N_0B_e}$.

$$BER = \frac{1}{8}\left[P_{(1/0,0,0)} + P_{(1/0,0,1)} + P_{(1/0,1,0)} + P_{(1/0,1,1)} + P_{(0/0,0,0)} + P_{(0/0,0,1)} + P_{(0/0,1,0)} + P_{(0/0,1,1)}\right] \quad (22)$$

4. Solutions

In this target, it will be designed an optical network, which is included one wavelength, and this system is setup with longest possible reach, using the best components and irrespective of cost. It should be taken into account sensible worst case modeling of gain, loss, OSNR and adjacent channel crosstalk. Assume equal lengths of fiber between nodes. Here is shown the system structure diagram below.

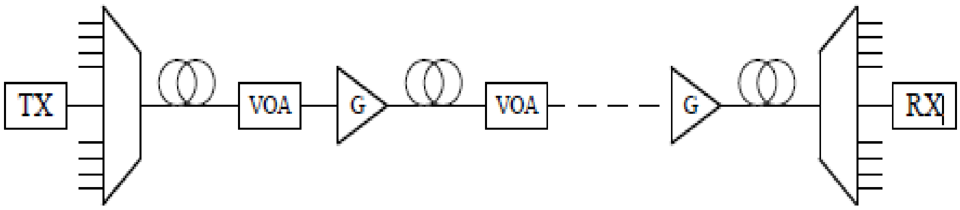

Figure 1, PIN Receiver Network Structure with Dispersion

As shown in Fig 1, it can be seen that, it is setup by one TX, one RX, one MULT, one DEM, 10 OAs, 11 VOAs, and fibers. The broken line hides the other OAs and VOAs. For the fibers, there are 11 segments equal length fibers in this system, so the total length of distance is equal to 11 x each segment length of fiber (31.694km). The following table 1 is shown the details of the chosen components [6]:

Table. 1: Parameters of Components in Network for PIN Receiver

Components Properties:		
Transmitters:	TX (cost)	4
	Av. Output Power (dBm)	-2
	Extinction ratio (dB)	13
	Dispersion penalty (dB)	1
Optical Amplifiers:	EDFA (cost)	9
	Gnom (dB)	20
	Nfmax (dB)	5.5
	Gctrl (dB) (±0.5)	N/A
	Gflat (dB) (±0.3)	N/A
Receivers:	RX (PIN) (cost)	0.7
	Sensitivity (dBm)	-22
	Overload (dBm)	-3
MULT/DEM:	Type (cost)	5
	Insertion loss (dB) (±0.1)	2
	Adjacent channel rejection (dB)	35
	Effective bandwidth (Hz)	4.00E+10
VOA:	Type (cost)	0.6
	Insertion loss (dB)	1
	Dynamic range (dB) (Adjusted 0~30 dB)	6
	Loss non-flatness (dB)	0.15

These BERs calculations are dependent on the signal power and three-channel crosstalk effect. In this case, on the achievable distances (as long as possible), from the table 2, the system will obtain a good performance. it can be seen that, when the signal reached to the RX, the signal power is equal to -21.4dBm; for the range of signal power, who can be accepted by the PIN receiver, is larger than sensitivity (-22 dBm) and smaller than overload (-3dBm), so this signal power is in safe range and acceptable. And the BER value, 3.50456E-13, also is in the safe range, where is $10^{-15} < BER < 10^{-12}$, so it's acceptable.

Table. 2: Numeric Properties in Network for PIN Receiver with Dispersion

	Power (dBm)	OSNR (dB)	BER
TX	-2		
OA1 in	-25.9	#NUM!	6.90E-04
OA1 out	-5.9	2.66E+01	0.00E+00
OA2 in	-25.85	2.66E+01	6.35E-04
OA2 out	-5.85	2.3578E+01	0.00E+00
OA3 in	-25.8	2.3578E+01	5.84E-04
OA3 out	-5.8	2.1842E+01	0.00E+00
OA4 in	-25.75	2.1842E+01	5.37E-04
OA4 out	-5.75	2.0617E+01	0.00E+00
OA5 in	-25.7	2.0617E+01	4.94E-04
OA5 out	-5.7	1.9673E+01	0.00E+00
OA6 in	-25.65	1.9673E+01	4.55E-04
OA6 out	-5.65	1.8906E+01	0.00E+00
OA7 in	-25.6	1.8906E+01	4.20E-04
OA7 out	-5.6	1.8261E+01	0.00E+00
OA8 in	-25.55	1.8261E+01	3.87E-04
OA8 out	-5.55	1.7706E+01	0.00E+00
OA9 in	-25.5	1.7706E+01	3.57E-04
OA9 out	-5.5	1.7219E+01	0.00E+00
OA10 in	-25.45	1.7219E+01	3.30E-04
OA10 out	-5.45	1.6786E+01	0.00E+00
RX	-21.4	1.68E+01	3.50456E-13
Total Distance(km):	374.924		

5. Conclusion

In summary, this work performed an optical network with lower BER which is at 10^{-12}, and it is practicable. Under certain conditions, the link which includes one wavelength is setup with the longest possible reach. The design has chosen the cheapest components to build up practical optical links with PIN receiver. Crosstalk is the main problem of the link.

6. References

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