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DWDM Link Design and Power Budget Calculation

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ABSTRACT: The aim of this paper is to give detailed description about Link design and optical Power budget calculation in a DWDM network. The DWDM system considered here is designed to carry 80 channels in 1550nm band. The amplifiers used to boost the signal power are fixed gain amplifiers. The power measurement at each component of DWDM system is calculated separately. Calculations are accounted to the 80 channel DWDM system and calculations are done with respect to the individual channels. Insertion loss of the network elements and attenuation through the fiber link are considered during calculation. The relationship between the optical power at input and output of each component in DWDM system is discussed, and is made feasible to carry all 80 channels without violating the power requirements and constraints for the amplifiers and other components used in the network.

KEYWORDS: Optical communication, DWDM, Link Design, Power budget, ROADM, Optical Power Meter (OPM), Erbium Doped Fiber Amplifier (EDFA).

I. INTRODUCTION

Advancement in Telecommunication sector has grown to a greater extent with high demand for internet and its related applications. High capacity network is needed to handle enormous amount of data transfer. Here comes the application of DWDM (Dense Wavelength Division Multiplexing) System which is an extension of Wavelength Division Multiplexing technique. DWDM is a cost efficient technique in optical network where multiple wavelengths carrying digital data are combined together and sent over a single fiber link efficiently. This provides 50 GHz spacing (approx. 0.4 nm), with 80 channels in a single mode fiber. More channels and higher capacity can be achieved using DWDM. DWDM channel spectrum has been defined in ITU-T recommendation G.694.1.

In this paper a detailed description of designing of DWDM link is given followed by the power budget calculation at each point of the link. The power management in a DWDM network is dependent on the number of channels which are supported by the setup [1]. This technique is described with per channel calculation for an 80 channel DWDM setup. Power budget analysis involves the description of gain accumulation in the signal due to EDFAs, attenuation calculation due to fiber and insertion losses caused due to ROADMs and DCMs.

II. LITERATURE SURVEY

Advancement in optical communication gave rise to WDM (Wavelength Division Multiplexing) as a bandwidth conservation scheme [1][2]. CWDM (Coarse WDM) was first introduced WDM type that had the capacity of carrying 8 channels with 20 nm spacing in 1550 nm window of C band. Then came DWDM which can carry up to 140 channels theoretically [3][4]. It became very much important to upgrade the capacity of optical network to carry data traffic along with voice traffic. This involved the need for intelligent optical networking capability, which was achieved by DWDM [5].

Power management is an important task to achieve optical receive power for better BER. Placement of DWDM components in a network requires analysis of the distance between two nodes, type of data rate, technical specifications of the component, their gain and insertion losses [7][8].

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DWDM network setup requires various network components to make the system work [9]. Optimal optical power requirements are the major constraints in these kinds of networks[10].

III. DWDM NETWORK COMPONENTS

A. Transponders

In DWDM system, multiple light signals (which may have same wavelength) client specific devices comes to DWDM system at input. Transponders are used to tune the incoming signal as per requirement of DWDM system which supports operation in C-Band. Tuning is done by first converting the optical signal to electrical and then again regenerated to optical signal with tuned λ. A transponder performs an O-E-O operation to convert wavelengths of light. Within the DWDM system a transponder converts the client optical signal back to an electrical signal (O-E) and then performs either 2R (reamplify, reshape) or 3R (reamplify, reshape, and retime) functions. As this optical signal is regenerated in transponder hence optical strength of output of light signal of each transponder is expected to be same or nearby.

B. Optical Multiplexer

DWDM Multiplexers (MUXs) are the units that combine multiple light signals exiting the multiple transponders which are tuned to the wavelength as per the system requirement. MUX is a passive device and is capable of multiplexing the multiple light signals and not strengthens the signal. There is a big insertion loss associated with DWDM MUX which is around 14 dB.

C. Erbium Doped Fiber Amplifier

Optical amplifiers (OAs) boost the amplitude or add gain to optical signals passing on a fiber by directly stimulating the photons of the signal with extra energy. Erbium-doped fiber amplifiers (EDFAs) are the most commonly used type of amplifiers in optical fibers. EDFAs amplify optical signals across a broad range of wavelengths. This is very important for DWDM system application. EDFAs are commercially available since early 1990’s. They work best in the wavelength range of 1530 to 1565 nm, and gain can be extended up to 30 dB (1000 photons out per photon in).

D. Single Mode Fiber

The characterization of different Single Mode Fibers are as follows:

- SMF (standard, 1310 nm optimized, G.652): These are the most widely deployed fibers, introduced in 1986. These give the characteristics of a single-mode optical fibre and cable with performance specified at 1310 nm, 1550 nm and 1625 nm but intended for use at 1310 nm region with chromatic dispersion slope in this region.
- DSF (Dispersion Shifted Fiber, G.653): Performance of this type of fiber is specified at 1310 nm and 1550 nm but with a zero chromatic dispersion slope in the 1550nm region. Support long-haul single mode transmission systems using erbium-doped fibre amplifiers (EDFA) that only operate in the third window.
- NZDSF(Non-Zero Dispersion Shifted Fiber, G.655): Performance of this fiber type is specified at 1550 nm and 1625 nm with a non-zero chromatic dispersion slope in these wavelength regions. Such optical fibres are developed to support long-haul systems that use Dense Wavelength Division Multiplexed (DWDM) transmission operating at 1530nm to 1625nm.

E. Dispersion Compensation Module (DCM)

Chromatic dispersion (CD) is one of the major concerns in the DWDM link design. It is the result of spreading of a pulse along the length of the fiber. It becomes very much important to recover the signal at the receiver, by reshaping the pulse. Most commonly incorporated method for the compensation of dispersion especially CD is the employment of specially designed optical fiber having negative dispersion. Their negative chromatic dispersion characteristics compensate for the transmission fiber’s positive dispersion. The modules are typically specified by what length, in km, of standard G.652 fiber will be compensated or by the total dispersion compensation over a specific wavelength range, in ps/nm. DCM components are used in order to compensate for the dispersion at the receiver. Typical residual dispersion value range is -510 to 1020 ps/nm.

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F. ROADM (Reconfigurable Optical Add/Drop Multiplexer)

ROADMs are the important components of a DWDM network. ROADM is a form of optical add-drop multiplexer that allows individual or multiple wavelengths channels carrying data information to be added or dropped from incoming fiber link. Main advantage of ROADM is it avoids the conversion of the signal on all the DWDM channels to electric signal & back again optical signals. Wavelength selective switching module is used to perform switching operation of the traffic from a wavelength-division multiplexing (WDM).

G. Link Power Budget

The key to network design is Optical Power Budget, which is the amount of light available to make a fiber optic connection. The allocation of power losses between optical source and detector is referred to as the power budget. The power budget with various losses in an optical fiber, as shown in figure 1, is obtained by first determining the optical power emitted by the source, usually expressed in dBm, and subtracting the power (expressed in same units, e.g., dBm) required by the detector to achieve the design quality of performance (Receiver Sensitivity).

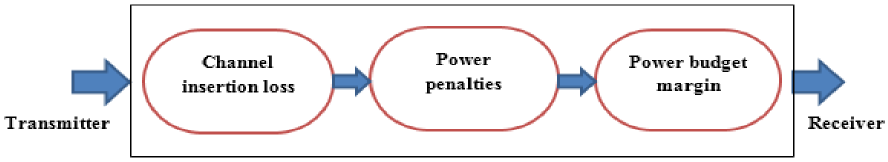

Fig.1: Link Power Budget

$$\text{Link Power Budget} = \text{Min Transmit Power} - \text{Min Receiver Sensitivity} \quad (1)$$

Equation (1) can be used to calculate the link power budget that can be used to decide length of the fiber span such that the loss through the span is manageable to have optimal power value at the receiver.

IV. DWDM LINK ENGINEERING

DWDM network evolution has contributed to deal with spectrum scarcity issues. Designing of DWDM network is a challenging task. DWDM Link Engineering deals with designing of a link with proper component placement and then making the link feasible with respect to power values at each point of the link[3][4]. A brief diagrammatic representation of component arrangement in a DWDM network span is shown in figure 2.

MDU (Mux- Demux Unit) at the transmitter end multiplexes multiple wavelengths () provided by the client node (i.e. Transponders). The composite signal is sent through a ROADM node which switches the wavelengths as per demand over the light path.

In ROADMs, number of network connections terminating or originating from the node is called "degree" of the node. Add/Drop ports of ROADM cards can be interconnected for pass through traffic from one direction to another direction OR can be connected to a local add/drop. For a ROADM node of N degree we must have N number ROADM cards for each degree and another ROADM in the local Add/Drop direction which provides Direction-Less functionality. A directionless ROADM card gives the ability to dynamically Add/Drop a channel in any of the directions (degrees). For example if we have a directionless ROADM node of degree 4 then we need 4+1(directionless) = 5 ROADMs to form the central optical cross connect. Directionless ROADM broadcast the signal form the MDU in all directions and degree ROADM can be provisioned to select channels towards the network[5][6].

Booster amplifiers are the EDFAs placed before every ROADM site to boost the signal power before sending it on the fiber link. Pre-Amplifiers are placed before ROADM nodes to strengthen the signal that has traversed through a long link and then is feed at the receiving ROADM node. The criteria fulfilling the amplifier limitations need to be take care of at the input and output of the signal.

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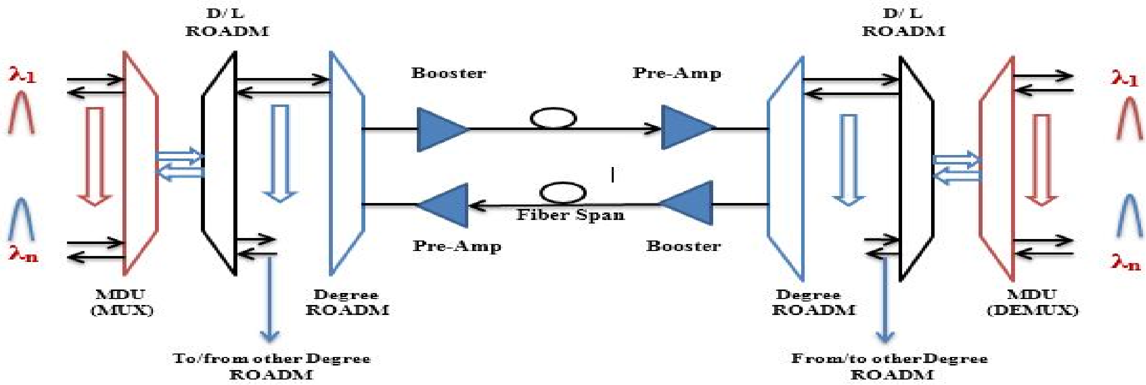

Fig 2. DWDM Link

Another important component in the link design is DCM, which has to be placed at ROADM or EDFA sites to manage dispersion of the signal travelling over longer distance through fiber. Preferable location of DCM placement is before the EDFA node, because DCMs also add up good amount of insertion loss and EDFAs after DCMs can take care of the losses. Finally at the receiver end the de-multiplexer part of MDU splits the incoming composite signal into individual wavelengths and feeds to the respective receivers.

A very important point in link power budget is that, the power received at the receiver should be well within the range of receiver sensitivity. So, MDU, ROADM, Fiber and CDMs are the major part of the network that adds up to the power loss through the link in the form of attenuation and insertion loss, whereas EDFAs are the gain components in the form of Boosters, Line and Pre amplifiers.

V. TECHNICAL SPECIFICATIONS

Below are the required specifications to design a DWDM link and perform link budgeting.

A. Operating wavelength band

The technicality of a DWDM system is mainly analysed with the wavelength specifications associated with it. The DWDM system discussed here works in C band on 1550 nm window, ranging from 1530 to 1565 nm. For 80 channel performance analysis the spacing is 50 GHz. In terms of frequency, the first channel considered is at 192 THz. The last channel frequency is;

F_{80} = 192 THz + 50 GHz x 79 = 195.95 THz

B. Fiber Specifications

Fiber characterization involves attenuation factor and the chromatic dispersion coefficient measured per kilometre of fiber length[7]. The common typical values of different fiber types are given in table 1.

Table 1. Fiber Specifications

Fiber type	**Attenuation ‘α’ (dB/km)**	**Dispersion coefficient (ps/nm-km)**
SMF	0.275	17
NZDSF		10
DSF		3.5

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C. ROADM Specifications

Table 2 and table 3 give typical specifications related to ROADM insertion losses that are used for the DWDM network design. Tables also include MDU insertion losses. Typical maximum multiplexer input is around 24 dBm.

- Add/Drop port to Common

Add/Drop to Common port specification involves insertion losses of the MDU, D/L ROADM and degree ROADM when the signal is passing from add/Drop port of each component to the common port at the other end of the component. The insertion loss values w.r.t degree is shown in figure. 3.3.1.

Table 2. Insertion Losses From Add/Drop Port to Common

ROADM Degree	Node Loss Parameters		
	MDU (dB)	Directionless ROADM (dB)	Degree ROADM (dB)
2	14	4	4
4	14	7	7
8	14	7	7

- Common to Add/Drop Port

Common to Add/Drop port specification involves insertion losses of the MDU, D/L ROADM and Degree ROADM for signal going from common to add/drop port direction, shown in table 3.

Table 3. Insertion Losses from Common to Add/Drop Port

ROADM Degree	Node Loss Parameters		
	MDU (dB)	Directionless ROADM (dB)	Degree ROADM (dB)
2	7	7	7
4	7	9	9
8	7	11	11

Other important specifications considered are:

- Attenuator range: 0-15 dB
- XFP receiver sensitivity : -15 dBm to -25 dBm
- Connector loss: 0.5 Db

D. Amplifier Specifications

Table 4. gives amplifier specifications which hold good for composite power values i.e. Total power values when all 80 channels passing through the EDFAs are combined. These are nominal values and care should be taken such that power should not go beyond these boundary conditions for betterment of the system. Output power of EDFA must be within output saturation value[8].

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Table 4. Amplifier Power Specifications

Amplifier Power types	Power Values
Flat Gain (FG)	22 dB
Gain Range (G)	15 to 30 dB
Noise Figure (NF)	5.5 dB
Maximum Input Power ($P_{in\ max}$)	5 dBm
Maximum Output Power ($P_{out\ max}$)	20 dBm
Minimum Input Power ($P_{in\ min}$)	-35 dBm
Minimum Output Power($P_{out\ min}$)	-5 dBm

E. DCM Specifications

DCM components are used in order to compensate for the dispersion at the receiver. Table 5. gives various DCM specifications available in market. Typical DCM loss that is being considered for the design is 4 dBm for every module used. Fiber used in DCM has a dispersion coefficient of 17 ps/nm-Km. The residual dispersion left after compensation must range from -510 to 1020 ps/nm.

Table 5. DCM Specifications

DCU Modules	Dispersion Compensation (ps/nm)	Insertion Loss (dB)
30 Km	-510	4
40 Km	-680	4
60 Km	-1020	4
80 Km	-1360	4
120 Km	-2040	4

VI. 80 CHANNEL DWDM LINK DESIGN

Link engineering involves placement of Optical amplifiers (OAs) and DCMs for each fiber link to ensure sufficient minimization of all optical impairments. A fiber link starts and ends at a central office containing a ROADM site with intermediate sequence of fiber spans with known losses and lengths. Intermediate endpoints of spans are pass through ROADMs, OAs and DCMs. The overall goal is to minimize equipment cost and power losses[9].

This paper focuses on DWDM network design for 80 channels with each channel carrying 10 Gbps of data. Considering per channel calculations, the output power of an amplifier per channel in an N channel DWDM network is obtained by considering below formula.

Pout (dBm) = Pin (dBm) + Gain (dB) (2)

P_{out}/ch = Maximum output power – $10*\log_{10}(N)$ (3)

With N = 80 channels:

$P_{out}/ch = 20 - 10*\log_{10}(80) = 1$ dBm

Per channel output power can be given as:

Pin (dBm) + Gain (dB) = 1 dBm

Therefore, in 80 channel DWDM link, for single channel calculation the maximum output should be 1 dBm. In order to maintain 1 dBm output power per channel, the gain has to be adjusted w.r.t the input power of the EDFAs. And gain should be in the range of 15 to 30 dB with a typical NF of 5.5 dB.

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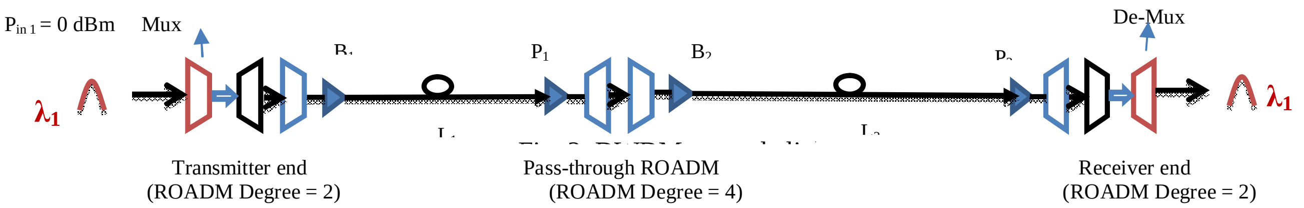
OSNR is an important parameter to be taken into consideration before deciding the placement of the amplifier and setting the gain. The minimum OSNR value for 10 Gbps transmission is 17 dB. Lower the input power of an amplifier stage, better is the OSNR. But this is a trade-off between OSNR improvement and number of amplifier components used throughout the link. If amplifier is place at a point to have less input power (i.e. at a lesser distance), this will increase the OSNR, but the distance covered will be less, and in order to compensate for the whole span, more amplifiers are needed, which will have reduced input power, but will increase the design cost. Formula used for OSNR calculation at (i + 1) stage of EDFA is:

$$OSNR_{(i+1)} = \frac{1}{\frac{1}{OSNR(i)} + \frac{NFh\nu\Delta f}{Pin}} \qquad (4)$$

In equation 4, "NF" is the noise figure of (i + 1th) amplifier. "ν" represents optical frequency (193 THz), "Δf" is the bandwidth (0.1 nm = 12.5 GHz) that measures the noise figure NF and "h" is the Planks Constant (6.626 x 10 $^{-34}$ J. s)
In this paper cost effective design is considered[10][11]. Thus the unnecessary placement of EDFAs is ignored. The detailed explanation of this scenario is carried out in next section with an example link.

A. DWDM network design with an Example link:

Consider a DWDM link with two ROADM sites at transmitter and receiver ends with an intermediate pass-through ROADM as shown in fig 3. ROADM sites at Tx and Rx are of degree 2 and pass-through ROADM had degree equal to 4. Link has two spans with fiber of type SMF having lengths L_1 and L_2 . As mentioned earlier, ROADMs are usually accompanied with Booster and Pre amplifiers. B_1 and B_2 are Booster amplifiers whereas P_1 and P_2 are Pre-amplifiers. Input given to Mux is 0 dBm which is given form the transponder.



Let L_1 = 80 Km and L_2 = 120 Km SMF fiber. Insertion losses w.r.t MDU, D/L ROADM and Degree ROADM are specified in table 2 and 3.
Fiber Attenuation loss = α x Length

L_1 Loss = 0.257 dB/km x 80 km = 22 dB
L_2 Loss = 0.275 dB/km x 120 km = 33 dB

B. Dispersion Compensation

Dispersion = Length x Dispersion coefficient
L_1 Dispersion = 80 Km x 17 ps/nm- km = 1360 ps/nm
L_2 Dispersion = 120 Km x 17 ps/nm- km = 2040 ps/nm
Total Link Dispersion = 1360 ps/nm + 2040 ps/nm = 3440 ps/nm (> 1020 ps/nm)

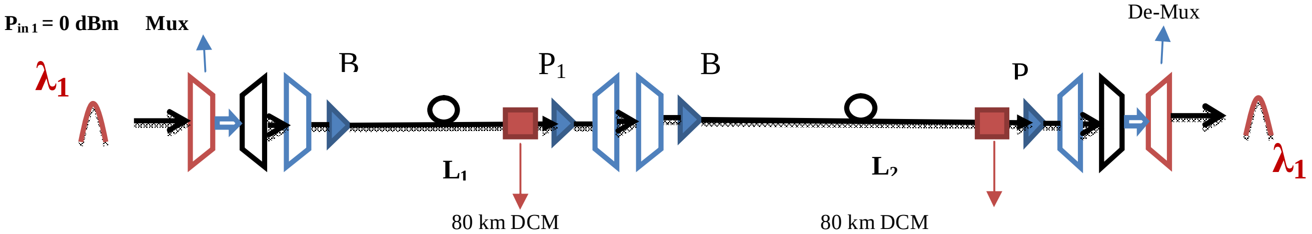


Fig.4: DWDM Link with DCM Placement

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To compensate for this high dispersion of 3440 ps/nm, an 80 Km DCMs are placed at the end of L_1 and. Fig.4. shows link with DCM placement at the end of L_1 and L_2. Therefore the dispersion now with DCMs at the receiver node is;
Residual Dispersion = 3440 ps/nm – (2 x 80 km x 17ps/nm-km)
= 680 ps/nm (-510 ps/nm < 680 ps/nm < 1020 ps/nm)

C. EDFA Placement

Placement of EDFA depends on the span loss. Maximum gain for an EDFA is 30 dB, i.e. to have an output power of 1 dBm per channel, minimum input power will be -29 dBm (-29 dBm + 30 dB = 1 dBm). Since B_1, B_2, P_1 and P_2 are all EDFAs, their outputs need to be maintained at 1 dBm / ch.

Gain calculation of B_1:

B_1 I/P power = (Pin_1 – MDU Loss – D/L ROADM Loss – Degree ROADM Loss) = 0 – 14 – 4 – 4
= -22 dBm
Therefore B_1 Gain = 23 dB (15 dB < 23 dB < 30 dB)

Gain calculation of P_1:

P_1 I/P power = B_1 O/P power – Span 1 Loss
Span 1 Loss = (L_1 Loss + (2 x Connector Loss) + DCM Loss) = 22 + 1 + 4 = 27 dB
P_1 I/P power = 1 – 27 = -26 dBm
Therefore P_1Gain = 27 dB (15 dB < 27 dB < 30 dB)

Gain calculation of B_2:

B_2 Input Power = (P_1 O/P power – Degree ROADM 1 – Degree ROADM 2) = 1 – 7 – 9 = -15dBm
Therefore B_2 Gain = 16 dB (15 dB < 16 dB < 30 dB)

Gain calculation of P_2:

P_2 I/P power = B_2 O/P power – Span 2 Loss
Span 2 Loss = L_2 Loss + (2 x connector Loss) = 33 + 1 = 34 dBm
P_2 I/P Power = 1 – 34 = -33 dBm
Therefore P_2 Gain = 34 dB (> 30 dB)
By observing the gain value needed for P_1 EDFA, it becomes clear that power budget exceeds the limit and an extra Line amplifier is necessary for second span of the link. Now it becomes important to decide at what point Line amplifier has to be placed. Placement of amplifier must be such that

- no more unnecessary line amplifiers must be needed further in the span, and
- OSNR value at the receiver must be good enough and within the limit.

Fig 5. represents second span of the DWDM link split into L_{11} and L_{22} on either sides of the Line Amplifier (LA) along with the 80 km DCM at the end of L_{22}.

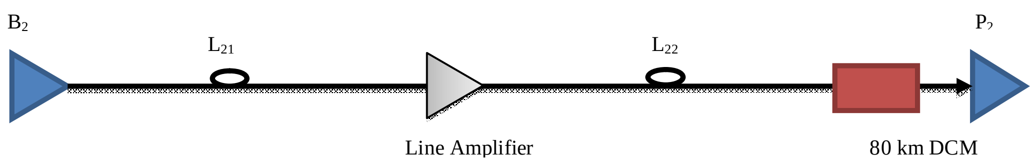

Fig. 5: Span 2 with Line Amplifier

Amplifier is placed at a point where minimum gain can be achieved i.e. 15 db. This implies;
Line Amp O/P power = Gain – Span Loss (Line Amp) = 1dBm
If Gain = 15 dB, then Line Amp I/P power = 14 dBm
L_{21} Loss = (LA I/P power – (2 x Connector Loss) + B_2 O/P power = 14 – 1 + 1 = 14 dB
Thus,
$L_{22} = L_2 – L_{21}$ = 120 – 50.9 = 69.1 km

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Therefore,
Length L_{21} = L_{21} Loss (dB) / α (dB/km) = 14 / 0.275 = 50.9 km
L_{22} Loss = 69.1 x 0.275 = 19 dB
Total span loss of L_{22} = L_{22} Loss + DCM Loss + (2 x Connector Loss) = 19 + 4 + 1 = 24 dB
P_2 I/P power = LA O/P power – Total Span Loss of L_{22} = 1 – 24 = -23 dBm
Thus Gain of P_2 = 24 dB (15dB < 24dB < 30dB)
After calculating I/P, O/P and gain power values for EDFA the last step remaining is calculating the input power at the receiving XFP connected to the De-Mux.
I/P to XFP = (P_2 O/P power – Degree ROADM Loss – D/L ROADM Loss – MDU Loss)
= 1 – 7 – 7 – 7
= -20 dBm (> -25 dBm)
Complete DWDM link design with the DCM and Line Amplifier placement is shown in figure 6. Numbers ranging from 1 to 19 are the node names at i/p and o/p of each component in the link

D. OSNR Measurements:
OSNR calculation is another important criteria to check for the network efficiency. OSNR should be above 17 dBm for 10 Gbps transmission data rate. The DWDM Link defined in figure 6 altogether includes 5 EDFAs and 2 DCMs after placement of DCMs and Line Amplifier. Using the formula from equation (4) OSNR at each amplifier stage has been calculated [12].

VII. RESULTS

With all the above work procedure, optimized DWDM link design is obtained with Link power budget calculation at all spans of the Link. The calculations considered here are calculated for ideal cases, without considering fiber non-linearities. Fig 2. represents a typical DWDM component set up for multiple wavelength propagation with ROADMs. Fig 2. is an example link considered to describe the DWDM network design and power budget analysis. Fig 4 and 5 show the placement of DCM and EDFAs in the link with proper compensation for dispersion and power loss respectively. Fig 6. gives a complete view of modified example link with all the required component placement. Table 6 gives detailed result values for Power, OSNR and Dispersion at each node point. The power calculation results are obtained for single channel. The design is optimized such that the system can be upgraded to support 80 number of wavelengths through a single fiber with a capacity of 10 Gbps/channel.

Complete DWDM link design with the DCM and Line Amplifier placement is shown in figure 4.1.2 Numbers ranging from 1 to 19 are the node names at i/p and o/p of each component in the link.

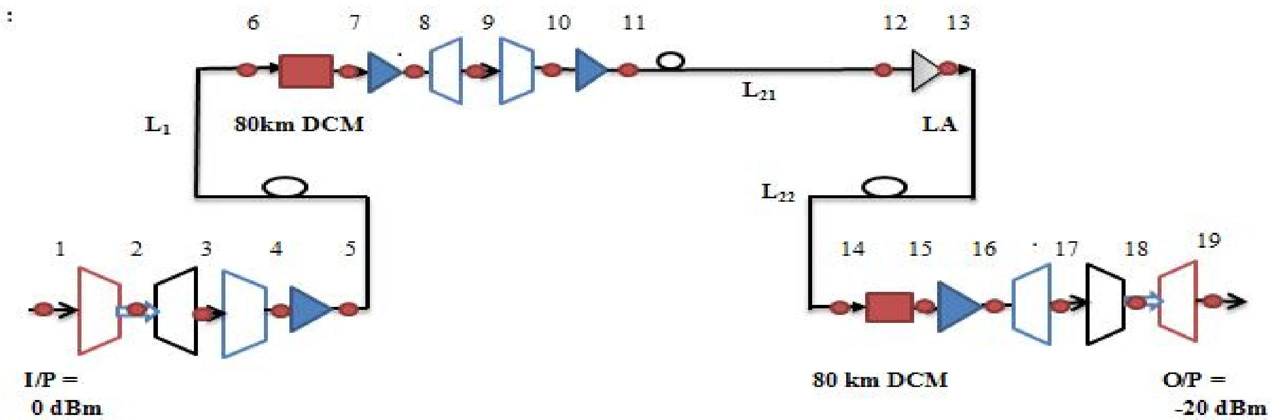

Fig 6: DWDM Link with DCM and EDFA Placement

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Table.6. Calculation Results For Example DWDM Link With Single Channel

Node Numbers	Power (dBm)	OSNR (dB)	Dispersion (ps/nm)
1	0	NA	0
2	-14	NA	0
3	-18	NA	0
4	-22	NA	0
5	1	30.4628	0
6	-22	30.4628	1360
7	-26	30.4628	0
8	1	25	0
9	-6	25	0
10	-15	25	0
11	1	24.766	0
12	-14	24.766	865.3
13	1	24.584	865.3
14	-19	24.584	2040
15	-23	24.584	680
16	1	23.361	680
17	-6	23.361	680
18	-13	23.361	680
19	-20	23.361	680

VI. CONCLUSION

For DWDM network design it is very necessary to obtain optimized power values at the EDFA nodes that are well within the range specified. Output power at the OAs should correlate to the number of channels passing through them. Dispersion compensation is also very much necessary so that signal is efficiently detectable at the receiver. OSNR has to be maintained above 17 dB to obtain improved BER at the receiver. The design procedure discussed in this paper gives the idea of DWDM link design and power budget calculation. Procedure followed here gives idealistic results that are independent of power penalties caused due to non-linear effects in the fiber. The DWDM System is capable of accommodating all the 80 wavelengths, thus upgrading the system capacity.

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