FIBER OPTIC COMMUNICATION LINK DESIGN

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Abstract: *In all-optical networks, traffic is carried end-to-end in the optical domain, without any intermediate optical-electrical-optical conversion. The promise of such networks is the elimination of a significant amount of electronic equipment, as well as added capabilities, such as the ability to transport any type of data format through the network. Fiber optic communications has been growing at a phenomenal pace over the past twenty years, so rapidly, in fact, that its impact is increasingly felt in nearly all aspects of communications technology. The design of such a system involves many aspects such as the type of source to be used (LED, LASER), the kind of fiber to be employed (multimode or single mode), and the detector (PIN or APD). This work emphasizes the basic requirements and design approaches of an optical fiber communication link. For designing such system the main concern is the optimization of cost, maximum link length and stability of performance characteristics. For a given bit rate, link length and typical bit error rate, the cost effective design is chosen here with software implementation.*

Key Words: *Bit Error Rate (BER), Light Amplification Stimulated Emission of Radiation (LASER), Power Budget, Time Budget, Graded Index (GI) Fiber, and Avalanche Photo Diode (APD).*

1. INTRODUCTION

The information Age is in a stage of rapid growth. As quick as new technologies are introduced, users demand more capability, more speed, and greater flexibility. Users demand more capabilities from every kind of electronic device: more processing power, more features, and better connectivity. Fiber optic transmission medium is first emerging as an alternative and strong competitor to coaxial cables in telecommunication networks. The communication engineers have always dreamt of higher information bandwidth with low attenuation and cost. For this reason they preferred optical fiber for network purposes as transmission medium and over the high bit rate point to point communication link. In word, for higher speeds and longer distance communication the transmission link must be made based on optical fiber. Therefore, they are used as a preferred transmission medium in current communication systems. Ease of communication in any country is the prerequisite for development. Communication is not just building roads, railway and bridges only. To foster and sustain all round advancement, a robust, efficient and widespread telecom infrastructure is as integral and essential component of development as any other. Research and development efforts have led to commercial realization of low cost, low loss optical fibers. The optical fiber communication system must be in cost effective which are sensitive to the proper selections of source, optical fiber and detector. So, before going to implementation of optical communication system it must take a hand in the software analysis in the link design such that it would be cost effective and meet the availability of the components.

2. OPTICAL FIBER COMMUNICATION

Technologies used in wireless broadband systems are typically data-driven and require a very high processing speed. So, before designing such a long–haul high speed link one must have knowledge about optical fiber communication system. An optical fiber is a dielectric waveguide made by ultra thin fiber of glass that operates at optical frequencies i.e., in which the signal is transmitted by the virtue of visible of light. To guide light, optical fiber contains of two concentric layers called the core and the cladding. A basic optical fiber communication system consists of an optical transmitter (Modulator, Channel coupler and optical source e.g., LED, LASER), a transmission channel (optical fiber), and an optical receiver (optical amplifier, electronic processing circuitry and optical detector e.g., PIN, APD). Fig. 1 shows a representative fiber optic communication link.

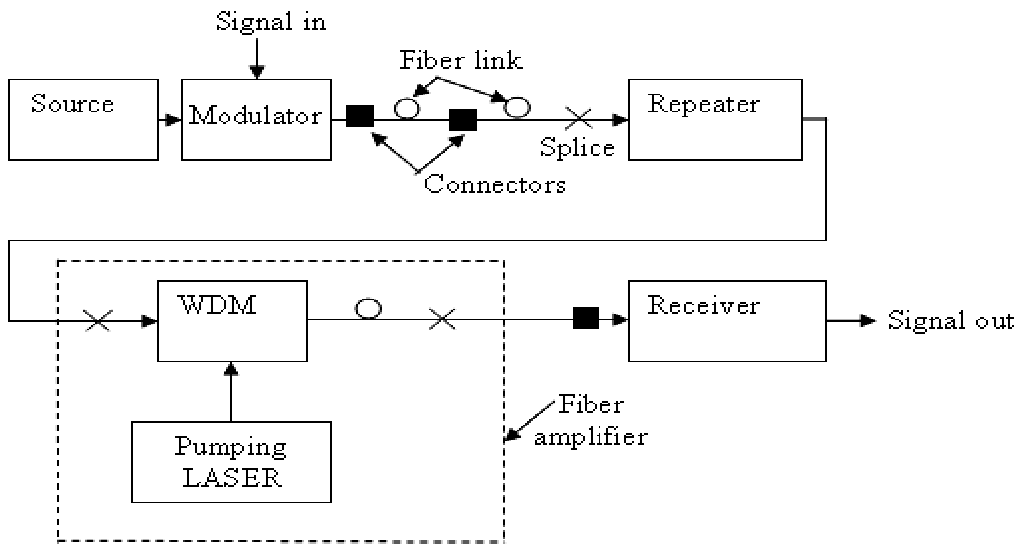

Fig. 1 A typical optical fiber communication system

In Fig. 1 an optical source such as a semiconductor LASER or LED is modulated by a signal. The output light is introduced into the fiber link through a set of connectors or through a permanent fiber splice. If the link is long, the light intensity diminishes because of attenuation in the fiber, and the optical signal may need to be regenerated by an optical repeater. The optical repeater consists of an optical detector that converts the light into an electrical signal, then amplifies it by means of an electronic processing circuits and finally coverts the electrical signal into an optical signal by an optical source. An alternative to repeating the signal is to optically amplify the light by means of an optical amplifier. The WDM combines the signal beam and a pump laser beam (at two different wavelengths) in an optical fiber amplifier. The fiber amplifier strengthens the signal beam using the power from the pump laser beam without requiring optical/electronic and electronic/optical conversion. Finally, the optical signal arrives as its destination and the information is recovered and converted back into its original format.

The main objective of fiber optic cable is to support greater bandwidth and high transmission rate. But, incase of short distance transmission the use of optical cable may not be cost effective as compared to another procedures. In that case one may prefer another procedure for data transmission. One option for a data transmission line is traditional metal cable, such as a twisted-pair cable and a coaxial cable. It is suitable for many applications, but is not suitable where noise immunity is required or for long-distance data transmission. Instead of metal cable, optical-fiber cable has been developed to overcome these limitations. For digital audio applications, all-plastic fiber is already well known and widely used for data transmission lines. Fiber optic cable is more efficient for interconnecting cable TV or phone companies that are consolidating with geographically adjacent companies.

3. FIBER LINK

To provide the communication through optical fiber must need a procedure to design a usable optical fiber link to meet the desired specifications such as coupling losses, bit error rate, data rate, etc. The procedure is iterative, that is certain assumptions are made and the design is carried out based on those assumptions. The design is not finished at that point; however the designer must verify that it meets the objectives and represents economical and technical solutions. If not, it is required to pass to another combination through procedure. In particular, the assumptions need to be inspected to determine if changes might provide a simpler or cheaper alternative.

Flow Chart of Link Design

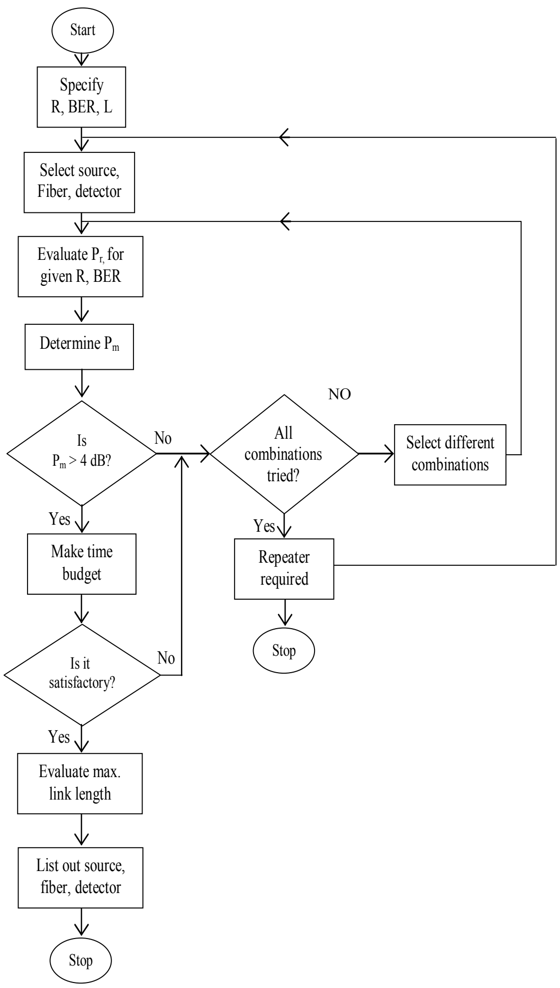

Fig. 2 Flow chart showing the steps involved in a fiber optic link design

The starting point for optical fiber communication link design is choosing the operating wavelength, the type of source (i.e., LED or LASER), and whether a single mode or multimode fiber is required. In a link design, one usually knows (or estimates) the data rate required to meet the objectives. From this data rate and an estimate of link length, one chooses the wavelength, the type of source, and the fiber type. Also, the requirements for the link design must be chosen in such a way that the losses (e.g., source to fiber coupling loss, fiber to fiber coupling loss, fiber to detector coupling loss, dispersion, attenuation etc.) involved in those requirements should be maintained to a minimum. The optical fiber link design simulator flow chart is given below Fig. 2[1]:

3.1 Requirements in the Link Design

The key system requirements needed in the link design are:

(a) Data or bit rate/bandwidth;
(b) Bit error rate/signal to noise ratio and
(c) Transmission distance or link length.

In the optical fiber communication link design the basic issues are:

(a) Attenuation which determines the power available at the photodetector input for given source power (known as power budget) and
(b) Dispersion which determines the limiting data rate usable bandwidth (known as time budget) [2].

3.2 Power Budget

In a fiber-optic communication link, the allocation of available optical power (launched into a given fiber by a given source) among various loss-producing mechanisms such as launch coupling loss, fiber attenuation, splice losses, and connector losses, in order to ensure that adequate signal strength (optical power) is available at the receiver. The amount of optical power launched into a given fiber by a given transmitter depends on the nature of its active optical source (LED or laser diode) and the type of fiber, including such parameters as core diameter and numerical aperture. Manufacturers sometimes specify an optical power budget only for a fiber that is optimum for their equipment--or specify only that their equipment will operate over a given distance, without mentioning the fiber characteristics. The purpose of the power budget is to ensure that enough power will reach the receiver to maintain reliable performance during the entire system lifetime. Performance of the system is evaluated by analyzing the link power budget of the system and the cost is kept minimum by carefully selecting the system components from a variety of available choices [2].

In the preparation of link power budget, certain parameters like required optical power level P_r at the receiver to meet the system requirements, coupling losses etc. are required. In any practical design, an allowance has to be made for the degradation of components with ageing, replacement, variations due to temperature fluctuations, manufacturing spreads, imperfect repeatability on reconnection, field repairs, maintenance, and variations in drive conditions and so on. In an optical communications link, power margin is the minimum optical power that is required by the receiver for a specified level of performance. The amount of optical power launched into a given fiber by a given transmitter depends on the nature of its active optical source (LED or laser diode) and the type of fiber, including such parameters as core diameter and numerical aperture. After computing various losses and fixing safety margin, power budget of the link is calculated by the following equations [2]:

Power margin in dB, $P_m = (P_t - P_r(\text{min}) - L_{sf} - NL_{ff} - \alpha_L - L_{fd})$……………………………(1)

Where, P_t= Source output power...…..dBm
P_r (min) = Minimum receiver power….dB
L_{sf} = Source to fiber coupling loss……dB
L_{fd} = Fiber to detector coupling loss… dB
L_{ff} = Fiber to fiber coupling loss……..dB
N=Number of splice = Integer part of $[L/L_0]$
L = Fiber link length………………… km
L_0 = Factory unit length of fiber…... …km
α = Attenuation coefficient of fiber... dB/km
α_L = Fiber loss……………………… dB
N_α = Total splice loss………………...dB

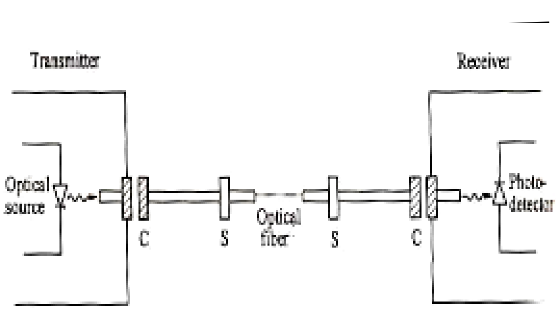

Fig. 3 Loss model of point to point optical fiber link (C; connector and S; splice)

A power margin $P_m \geq$ 4dB is acceptable otherwise some components need to be upgraded. With $P_m \leq$ 4dB, system will become less reliable. A typical losses involved in the calculation of power budget: The loss model for a point to point optical fiber link is shown in Fig. 3 [2]. From the above figure optical power loss occurs due to

(a) Coupling losse (L_{sf}, L_{ff} and L_{fd})
(b) Connector loss
(c) Splice loss
(d) Fiber attenuation and
(e) Fiber bend loss

The typical values of L_{sf}, L_{ff} and L_{fd} are about 2 dB, 0.5 dB and 0.2 dB respectively. But they also vary with wave length [2]. The source to fiber coupling loss is largely dependent on the numerical aperture, source, fiber size (core diameter/cladding diameter) and can be calculated as follows which is listed in Table 1 [7].

Table 1 Coupling efficiencies calculation

Lambertian emitter			Nonlambertian emitter
Coupling efficiency (η) $r_s \leq a$	Coupling efficiency (η) $r_s > a$	Fiber	Coupling efficiency (η) $r_s < a$
NA^2	$NA^2(a/r_s)^2$	Step index	$(m+1/2)\ NA^2$
$NA^2[1-(2/(g+2))\ (r_s/a)^g]$	$NA^2(a/r_s)^2\ (g/(g+2))$	Not assigned	Not assigned

where, r_s = radius of the source
a = the fiber core radius
g = the refractive index profile;
m = a constant has a value larger than 1 (typically in the range 14 to 34).

Now the source to fiber coupling loss L_{sf} can be calculated (in dB) from the table (Table 1) as follows:

$L_{sf} = -10 \log_{10} \eta$ (dB)…………………….(2)

After specifications all the terms mentioned above one can simply estimate the power budget calculation. For example the power budget of a 0.85 μm lightwave system is listed in Table 2 [5].

Table 2 Power budget of a 0.85 μm light wave system

Quantity	Symbol	LASER	LED
Transmitter power	P_t	0 dBm	-13 dBm
Receiver sensitivity	P_r (min)	-42 dBm	-42 dBm
Power margin	P_m	6 dB	6 dB
Available channel loss	C_L=-L_{sf}+ NL_{ff} + αL+ L_{fd}	36 dB	23 dB
Maximum fiber length	L	9.7 km	6 km

3. 3 Time Budget

The objective of the time budget is to ensure that the system is able to operate properly at the desired data rate. Sometimes, it may happen that the total system is not able to operate at the desired data rate even if the bandwidth of the individual system exceeds the data rate. The root means square (RMS) width of pulses propagating in nonlinear, dispersive fibers is useful for predicting how far a pulse can travel before it suffers significant distortion due to the combined influence of the nonlinearity of the refractive index and the dispersive properties of the fiber. This theory applies to pulses operating near the zero-dispersion wavelength where dispersion alone has a negligible influence, but where the combined influence of nonlinear self-phase modulation and dispersion can produce a significant effect. It is demonstrated that for an optical pulse propagating along an optical fiber the rms pulse width varies parabolically with distance, irrespective of initial pulse form and frequency chirp variation. Furthermore, the result is true to arbitrary dispersive order and should prove a very useful tool in determining the information-carrying capability of long-distance optical-fiber transmission systems. If the transmitter, fiber and receiver are considered to have the rms pulse widths σ_{tx} , σ_f and σ_{rx} respectively , then rms pulse width of the overall system response will be [2]:

$\sigma_{sys} = \sqrt{(\sigma_{tx}^2 + \sigma_f^2 + \sigma^2_{rx})}$ ………………..(3)

System time budget is considered to be satisfactory if σ_{sys} does not exceed (1/4R); where R is the data rate in Mbps.

3.4 Transmitter and Receiver Rise Time

The time taken for a signal to rise from silence to full intensity is called rise time. The rise time of transmitter primarily depends on the electronic components of driving circuit and electrical parasitic associated with the optical source. It is few nanoseconds for LED based transmitter, but can be as short as 0.1 ns for a LASER based transmitter. Presuming an exponential rise and decay, σ_{tx} is nearly equal to half of the rise time [2]. The receiver rise time is determined as follows:

t_{rx} = 350/B (ns) ………..…………………(4)

where, B is the receiver bandwidth in MHz.

3.5 Dispersion

Dispersion is the phenomenon that the phase velocity of a wave depends on its frequency. There are generally two sources of dispersion: material dispersion, which comes from a frequency dependent response of a material to waves and a modal dispersion that results from the different transit lengths of different propagating modes in a multimode optical fiber. Considering both the modal and material dispersions in fiber optic the rms pulse width of the fiber σ_f is determined as follows:

$\sigma_f = \sqrt{(\sigma^2_{mod} + \sigma^2_{mat})}$ ………………………(5)

Where, σ_{mod} and σ_{mat} are the rms pulse widths due to modal and material dispersion (and usually expressed in ps/km-nm) of the fiber respectively. For SM fiber, modal dispersion does not contribute and therefore, σ_f becomes same as σ_{mat}.

The optical fiber link may consist of several concatenated sections and the fiber in each section may have different dispersion characteristics. Further, there may be mode mixing at the splices and the connectors. As a consequence, propagation delay associated with different modes tends to average out. In the absence of mode mixing, σ_{mod} for SI fiber is [2]:

$\sigma_{mod}=(n_1\Delta L)/(2\sqrt{3}c)$……………….………(6)

Where, c is the velocity of light and the parameter Δ depends on the core and cladding refraction indices. For GI fibers, delay time is a function of the refractive index profile (g). The minimum intermodal rms pulse broadening with an optimum g is [2]:

$\sigma_{mod}=(n_1\Delta^2L)/(20\sqrt{3}c)$……………………….(7)

The rms pulse width due to material dispersion is determined as follows:

$\sigma_{mat} = | D_{mat} |\sigma_\lambda L$……………..…………..(8)

Where, σ_λ is the rms spectral width of the source and D_{mat} is the dispersion parameter.

3.6 Link Length

The design of fiber optic communication systems requires a clear understanding of the limitations imposed by the loss, dispersion and nonlinearity of the fiber. Since fiber properties are wavelength dependent, the choice of the operating wavelength is a major design issue. When a particular set of components meets the design requirements, one would like to know the maximum distance up to which these components could be used. Further, if the link length is quite large, it will help in determining the repeater location. The maximum link length is determined presuming that link is attenuation limited and there is no dispersion effect. And again when the link is dispersion limited and there is no attenuation effect. Minimum of the two is taken as the maximum practicable link length. For dispersion limited link, maximum data rate that can be transmitted over an optical fiber system is given by [2]:

$R= (1/4\ \sigma_{sys})$………………………………(9)

Where, R is data rate in Mbps.

The maximum allowable fiber dispersion will be:

$\sigma_{al}=\sqrt{((1/4R)^2- \sigma^2_{tx} -\sigma^2_{rx})}$ns……………...(10)

Now we can easily determine fiber dispersion per unit length as (σ_f/L). Therefore, the maximum link length under dispersion limited condition is determined as [2]:

$L_d\ (max) = (L*\sigma_{al})/\sigma_f$ (km)…………(11)

For comparison purposes we frequently want to calculate the maximum link distance for a system limited only by the fiber attenuation. Therefore, the formula for maximum link length under attenuation limited condition is:

$L_a\ (max) = [P_t\,(dBm) – P_r\,(dBm)]/\alpha\ (dB/km)$ (km) ....(12)

4 Simulation Results

For the combination of LASER-GI-APD (Fig.4), it is clearly observed that both the attenuation limited distance and dispersion limited distance are decreased with data rate (Mbps). As the total dispersion is approximately zero and a significant amount of attenuation around the 1300nm operating wavelength which is a common phenomenon [4][6-7] so, the dispersion limited distance is quiet high as compared to attenuation limited distance before their intersection point. For considering the optimum and reliable link design both the attenuation limited distance and dispersion limited distance are equal at the desired data rate with suitable selection of fiber, source and detector. From this curve (Fig.4) it is observed that both the attenuation limited maximum distance and dispersion limited maximum distance are equal (12km) at a data rate of 60Mbps. This 60Mbps data rate is not desired for proposed link design however, GI fiber is expensive as compared to the SI fiber. So, we ignore this combination as it is not suitable for the optimum and reliable link design.

For the combination of LASER-SI-APD as shown in Fig.5, It is observed that at optimum point (i.e. certainly the intersection point) the data rate is 45.65Mbps and the maximum link length is 17km. As the detector APD is quiet expensive and this proposed link design is considered for 10km. So, again this combination is not suitable for the optimum and reliable link design.

Finally, it is described sharply that the combination of LASER-SI-PIN as shown in Fig.6 which clearly states that for the same data rate 45.65Mbps the desired maximum link length is 12km. And these optimum values are obtained at a lowest cost combination of fiber and detector. But in the combination of LASER-GI-APD maximum link length is 10 Km which is lower than LASER-SI-PIN combination. So, the lowest cost combination of source, fiber and detector for the broadband optical link design is LASER-SI-PIN.

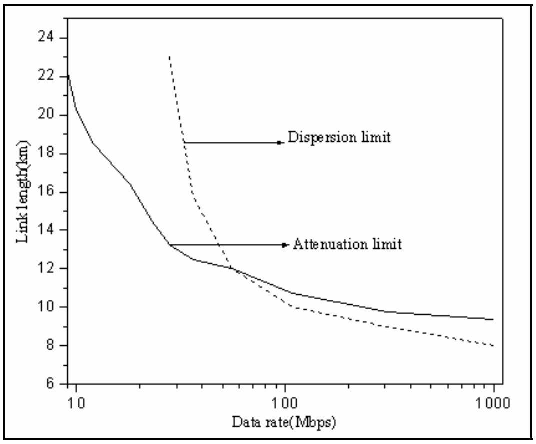

Fig. 4 Maximum transmission distance vs. data rate for the combination of LASER-GI-APD

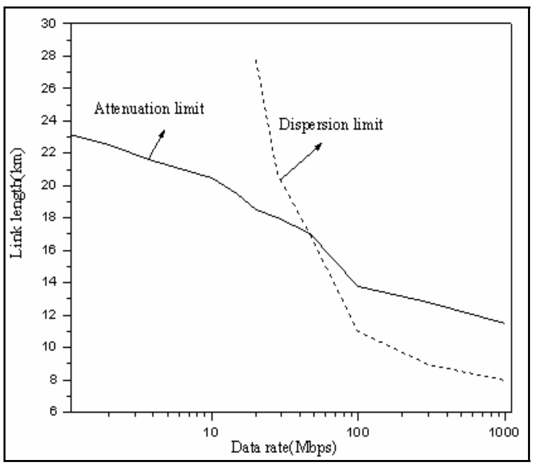

Fig. 5 Maximum transmission distance vs. data rate for the combination of LASER-SI-APD

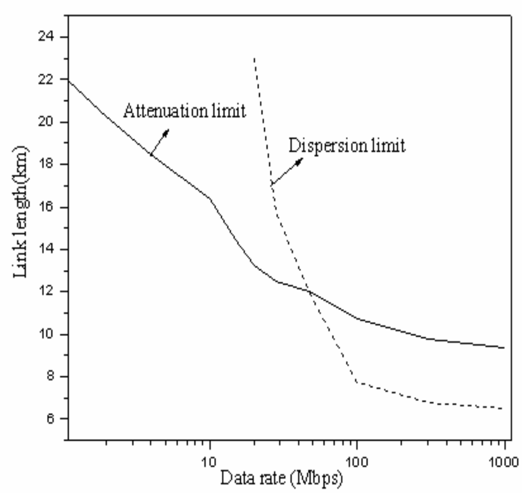

Fig. 6 Maximum transmission distance vs. data rate for the combination of LASER-SI-PIN

5 Conclusion

The optical reach of today's ultra-long-haul system is clearly shorter than the length of the longest demands. We have looked at network design in today's realistic backbone networks. The key system requirement for a fiber optic link design is power budget and time budget, in general. If these two basic issues are satisfied then easily calculate the maximum link length. These are tried to be satisfied in such a way that we have moderate data rates and moderate distance transmission. For this the link design reduces to the selection of commercially available transmitter and receiver modules. The user design is only in the selection of the power modules and in the design of the electronic interface circuitry. Depending upon these issues; the LED is tried to be selected first as an optical source because it is commercially available and low cost but for long distance link design (in which LED can not meet the key system requirement) LASER is used. The other components such as fiber (SI-SM, SI-MM and GI-MM), detector are also chosen.The results over a range of real networks have demonstrate that treating routing and wavelength assignment as separate steps can produce cost-eeffective, efficient designs.

Finally we may conclude that for this proposed link design lowest cost combination of source-fiber and detector is LASER-SI (SM)-PIN. The design of a fiber optic communication system involves the optimization of a large number of parameters associated with transmitters, optical fibers, optical amplifiers and receivers. The aspects are too simple to provide the optimized values for all system parameters. Since economic considerations often play a more important role than technical consideration in the design of optical link. For this design we have made an approach that uses computer simulations and provides a much more realistic modeling of fiber optic communication systems. The computer aided design techniques are capable of optimizing the whole system and can provide the optimum values of various system parameters such that the design objectives are met at a minimum cost combination.

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