A Novel Computer Aided Approach to Fiber Optic Communication link Design

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Abstract: A generalised and comprehensive flowchart is developed for designing optical fiber communication links, taking into consideration most design factors and component parameters. The flowchart, which is implemented into a web page using ASP.net web programming and C#, is tested on several existing optical fiber links. A general computer-aided approach is developed to assist the designer in selecting suitable combination(s) of Transmitter, Fiber, Detector and number of repeaters to satisfy the link specifications. The capability of this program to minimize the number of repeaters is also demonstrated. With the proper choice of parameters, the program also determines the various cost involved and finally the Cost Estimation relationships. Also an experimental investigation is carried out on an existing long-haul optical fiber link.

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1. Introduction

In modern communications, fiber optics has established itself as a quantum leap forward. It is rapidly becoming a better alternative to copper based transmission systems in a large variety of application areas. The broader bandwidth, higher degree of security and immunity from electromagnetic interference (EMI) offer technical advantages over copper based systems. The design of fiber optic communication link is based on a variety of considerations starting with the desired link specifications. The selection of any of the three main components i.e. the source (transmitter), fiber type and the detector, affect the other two because of their interdependence. Moreover any component of inferior characteristics will increase the required number of repeaters which in turn will affect the cost of the system.

At present the design procedures are virtually dictated by the manufactures of the components. They provide some sort of design charts based on their own products and thus leave a little choice to the designer to select and mix components from a number of manufacturers [1]. The design process discussed in this paper has been developed into a computer program which incorporates the basic and exact design equations rather than depend upon the manufacturer`s charts. This therefore, provides flexibility mentioned earlier [2].

2. Link Design Process

The usual specifications given to an optical fiber link designer are data rate (bit rate), link length and acceptable bit error rate (BER). The digital nature of signals requires that intensity modulation be used.

Given these requirements, the designer must try various combinations of the optical sources, fiber and detector to meet the power budget, bandwidth budget and cost budget.

2.1 Power Budget

The power budget is determined from source output power, source-to-fiber coupling loss, fiber`s attenuation, joint and connector losses, detector sensitivity and power margin. These are related by the following equation [3]:

$$P_t = P_c + \alpha L + P_j + P_k + P_r + P_m \text{ (in dB's) .... (1)}$$

where

P_t = the source transmitted power,
P_c = the coupling loss,
α = the attenuation coefficient of fiber,
L = the fiber length,
P_j = the joint loss,
P_k = the connector loss,
P_r = the minimum detected power (sensitivity) of the receiver,
P_m = the system power margin.

Depending upon the beam pattern and the transmitting area of the source, numerical aperture of the fiber and its core cross-sectional area, the source to fiber coupling loss varies between 1 and 14 dB's. The coupling loss increases with increasing transmitting area and beam width. P_c decreases with increasing numerical aperture and receiving area [3].

The coupling loss is smaller for directional sources such as edge-emitting diodes and laser diodes than for surface-emitting diodes. The exact estimation of the joint loss is difficult because it depends on mechanical adjustment and preparation of fiber ends to be joined. Mechanical misalignments could take place at a joint [4].

Techniques for slicing have been improved in order to reduce the misalignments that occur. Splice losses in the order of 0.1 dB's have been achieved [5].

Generally the sensitivity of the detector is known from the manufacturer`s data. If it is not supplied it can be calculated using the following equation [8]:

P=I(min)/p …... (2)

where

I(min) is detected current,

p is the responsivity of the detector which in turn is given by:

p=nλe/hc …………............................ (3)

where

n is quantum efficiency,

λ is the wavelength,

e is the electron charge,

h is the Planck's constant,

c is the speed of light.

I(min) is given by:

$$\overline{I_m}=\frac{k^2eFB}{4}\left[1+\left[1+\frac{2}{k^2e^2M^2F^2}\left[\frac{\pi^2}{3}(CV_A)B+\frac{[(I_A)^2]}{B}\right]\right]^{\frac{1}{2}}\right] \quad \text{... (4)}$$

where

I_A^* is the equivalent amplifier noise current density,

V_A^* is the equivalent amplifier noise voltage density,

C is the input capacitance,

M is avalanche gain,

F is the noise factor associated with the avalanche process,

K is the signal to noise ration which is related to the Bit-Error-Rate (BER) according to the following error function:

$$\text{BER}=\text{erfc}\left(\frac{K}{2}\right) \quad \text{……………................................ (5)}$$

where

$$erfc(x)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}dt \quad \text{……..…………….......... (6)}$$

The value of error complementary function (erfc(x)) is given in mathematical tables [6]. The relationship between BER and K equally probable 1's and 0's is illustrated in Figure 2.1.

The relationship (4) is valid assuming that the receiver is designed in such a way that the noise contributed by the input resistance in the case f input impedance preamplifier or the feedback preamplifier is negligible compared to the amplifier and shot noise.

The system margin is a safety margin which is added to take care of the degradation of the system with time and due to temperature variations. It is not intended to cover any degradation during installation such as cable breaks and during ordinary maintenance. This is usually set between 6 and 7 dB's.

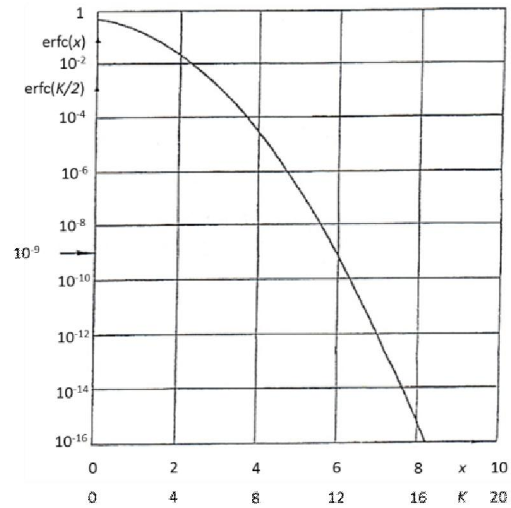


Fig. 2.1. Plot of erfc(x)

2.2 Bandwidth Budget

The bandwidth budget can be calculated from the following relationship [1]:

$$T_t = 1.1*\sqrt{T_s^{\,2}+T_f^{\,2}+T_d^{\,2}} \quad \text{…………..…............... (7)}$$

Where

T_t is the system's risetime,

T_s is the source risetime,

T_f is the fiber risetime,

T_d is the detector risetime.

The risetimes of the source and the detector are generally supplied by the manufacturers. However, the fiber's risetime is calculated by evaluating the fiber dispersion.

Material dispersion is given by [3]:

$$D_{mat} = |DL \;\; \Delta\lambda| \quad \text{...……………..….................... (8)}$$

Where

D is material dispersion coefficient,

Δλ is the source spectral width,

L is the fiber length.

Modal dispersion is given by:

$$D_{\text{mod}} = (L/c)n \;\; \Delta_n \quad \text{(for step-index fibers) …... (9a)}$$

$$D_{\text{mod}} = (L/8c)n \;\; \Delta_n \quad \text{(for graded-index fibers)... (9b)}$$

where

Δn is the relative refractive index difference.

Waveguide dispersion is normally small compared to other types of dispersion, so it can be neglected. The equivalent dispersion of the fiber is then given by:

$$D_{eff} = \sqrt{D_{mat}^2 + D_{\text{mod}}^2} \quad \text{...……….…...................... (10)}$$

The fiber risetime can be computed from the fiber dispersion using the relationship:

$$T_f = 1.1D_{eff} \quad \text{…………………...……............ (11)}$$

In case the fiber`s bandwidth factor is given instead of the dispersion, then the risetime is calculated from the relationship:

$$T_f = 0.44B_u \quad \text{......................................} (12)$$

where

B_u is the bandwidth factor.

In case of concatenated lengths of fiber, the bandwidth of the fiber follows the relationship [3]:

$$B_s = B_u \left[\frac{L_u}{L_s}\right]^{\gamma} \quad \text{..................................} (13)$$

where

B_s is the system`s bandwidth factor,
L_u is the unit length of the fiber,
L_s is the link length,
γ is the concatenation factor which has a value between 0.5 and 1.

2.3 Cost Budge

A designer must consider the economic factor related to the selection of optical components. The following are the short and long term considerations:

a) An LED is favored over a laser diode because it is less expensive.
b) Similarly a PIN diode is preferred over the more expensive and complex APD.
c) If future expansion is not planned, then step-index fibers are less expensive and therefore preferred over the graded-index fibers. This fact is becoming less and less true because of the increased tendency towards the use of graded-index fibers, which in turn is making it less expensive. Similarly graded-index fibers are less expensive than single-mode fibers. Moreover low-attenuation fibers are more expensive than the high-attenuation fibers. However if future expansion is expected, it is good investment in the long run to use a high quality fiber because the cost of laying the fibers cable would be paid once only. This is an addition to the fact that a high quality fiber would result in longer transmission section lengths, which means fewer of repeaters and consequently more reliable and economical link. This will also reduce the constraints on the choice of high quality and expensive electronic components.

2.3.1 Fiber Optics Economical Issues:

To design the system economically, various cost components have to be calculated, based on experience and prevailing service charges [10]. The following is a description of method to calculate these in steps (The flowchart of cost shown in Figure 2.2).

i) Total Engineering cost:

$$C_t = \sum C(i)[B+1] \quad \text{..................................} (14)$$

Where

$C(i)$ is the engineering cost of element i,
B is the burden rate.

ii) Unit cost of material:

$$C_{mat} = \sum\left(\left(C_m(i) * Q_m(i)\right)/Q_u\right) \quad \text{..................} (15)$$

Where

$C_m(i)$ is the cost of material,
$Q_m(i)$ is the quantity of material,
Q_u is the number of units.

iii) Waste cost per manufacture unit:

$$C_w = \sum\left[\left(Q_m(i) - U_m(i)\right) * C_m(i)\right]/Q_u \quad \text{..........} (16)$$

Where

$U_m(i)$ is the actual quantity used.

iv) Cost of special processes and handing:

$$C_{sp} = \left(H_h * R_h + C_{ce} * U_R\right)/Q_u \quad \text{.........................} (17)$$

Where

H_h is the specialized skill hours,
R_h is the specialized skilled labor rate,
C_{ce} is the cost of special support equipment,
U_R is the utilization of equipment during production.

v) Assembly cost per manufactured unit:

$$C_{as} = \left(H_a(i) * R_a(i)\right)/Q_u \quad \text{...............................} (18)$$

Where

$H_a(i)$ is the number of work hour per assembly,
$R_a(i)$ is the assembly labor rate per hour.

vi) Cost of support and test equipment:

$$C_{se} = \sum\left(Q_e(i) * C_e(i)\right)/Q_u \quad \text{...........................} (19)$$

Where

$Q_e(i)$ is the total quantity of equipment,
$C_e(i)$ is the cost of support and test equipment.

vii) Cost of quality control per manufactured unit:

$$Q_{qc} = \left(H_i * R_i + H_{te} * R_{te} + C_{eq} * U_{qu}\right)/Q_u \quad \text{............} (20)$$

Where

H_i is the number of inspection hours,
R_i is the inspection labor rate,
H_{te} is the number of test hours,
R_{te} is the test labor rate,
C_{eq} is the equipment utilization in hours,
U_{qu} is the equipment utilization cost per hour.

viii) Cost of manufacture:

$$C_{ma} = \left(H_f * R_f + H_a * R_a\right)/Q_u \quad \text{.........................} (21)$$

Where

H_f is the number of manufacture units,
R_f is the manufacture labor rate,
H_a is the assembly hours,
R_a is the assembly labor rate.

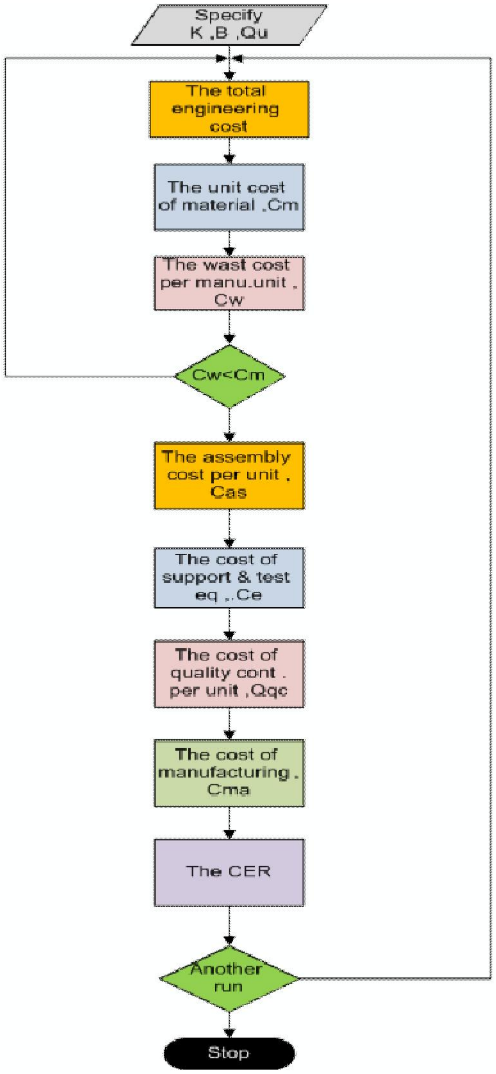


Fig. 2.2. Cost flowchart

The input form of the cost program is shown below in Figure 2.3.

The designer should fill all fields that are described on the form, then by pressing Calculate button will give the summary of the fiber optics system design cost. Figure 2.4 illustrates the output form of the cost estimation program.

2.3.2 Cost Estimation Relationships (CER)

The following Cost Estimation Relationship was developed [10] for long haul fiber optic data transmission systems;

$$C_{fo} = 425(20 - L_r)\,\mathrm{L}\left(\mathrm{B}/5\right)^{\frac{1}{3}} \quad \ldots\ldots\ldots\ldots\ldots\text{.....} \ (22)$$

where

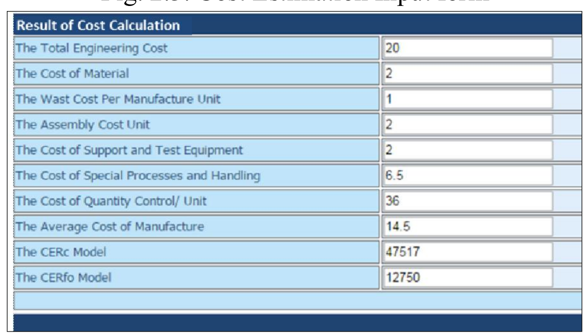
L_r is the repeater spacing (in Km),
L is the total system distance (in Km),
B is the bandwidth (in MHz).

Fiber Optics Economical Issues

No. of Elements *	2
The Burden Rate *	4
The Number of Units *	4
The Engineering Cost of Element #2 *	2
The quantity of Materialt #2 *	2
The Cost of Material #2 *	2
The Actual Used Quantity #2 *	1
The Assembly Labor Rate #2 *	2
The Work-Hours For Assembly #2 *	2
The Quantity of Equipment #2 *	2
The Cost of Equipment #2 *	2
The Specialized Skill Hours *	2
The Special Skill Labor Rate *	3
The Cost of Special Support *	4
The Utilization of Equipment During Production *	5
The Inspection Hours *	6
The Inspection Labor Rate *	8
The Test Hours *	9
The Test Labor Rate *	10
The Equipment Utilization Hours *	2
The Equipment Utilization Cost/hours *	3
The Hours To Manufacture *	6
The Manufacture Labor Rate *	9
The Repeater Spacing in km *	5
The Total System Length of Cable in km *	2
The Band-Width in MHz *	5

Calculate

Fig. 2.3. Cost Estimation Input form



Result of Cost Calculation	
The Total Engineering Cost	20
The Cost of Material	2
The Wast Cost Per Manufacture Unit	1
The Assembly Cost Unit	2
The Cost of Support and Test Equipment	2
The Cost of Special Processes and Handling	6.5
The Cost of Quantity Control/ Unit	36
The Average Cost of Manufacture	14.5
The CERc Model	47517
The CERfo Model	12750

Fig. 2.4. Cost Estimation Output form

Since this relationship was developed in 1970, the figures are no more valid. Since then the cost of components has decreased the components performance has improved and the cost of labor has increased. The general form of the relationship is, however, still valid and is

$$CER = K_1(K_2 - L_r)L\left(B/5\right)^{\frac{1}{3}} \quad \ldots\ldots\ldots\ldots\text{.....} \ (23)$$

Where K_1 has changed because of different cost factors of components and labor and K_2 has changed due to improvement of characteristics of the system components. Both K_1 and K_2 have increased and any realistic cost estimate can only be based upon first estimating the values K_1 and K_2.

3. Design Procedures

3.1 Graph And Chart Assisted Design

Manufacturers have devised graphs and charts to simplify the design process [1]. However, this method is limited in use, since it is applicable only to the system components made by the manufacture by whom those graphs and charts have been devised.

3.2 Flowchart Assisted Design

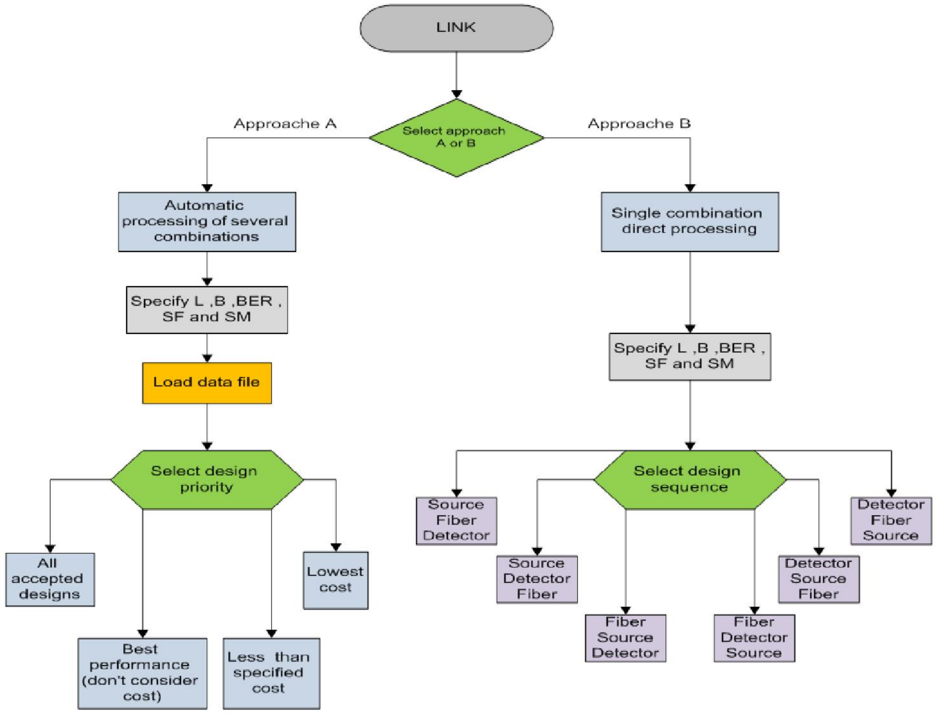


Fig. 3.1. General Flowchart

Table 3.1. Design priority parameter

Priority Parameter	Program Behavior
Lowest Cost	The program looks for the combination of source, fiber link, and detector, which achieves the design specification and has the lowest material cost. (Figure 3.1 illustrates flowchart for this part).
Less than [user specified cost]	The program takes the cost entered by the designer as a maximum cost and looks for the best combination (highest performance) of source, fiber link, and detector which meets the specification and has a cost lower than the maximum. (Figure 3.2 illustrates flowchart for this part).
Do not consider cost [highest performance]	The program, if this selection is made, looks for the best combination (highest system performance) ignoring the cost. (Figure 3.3 illustrates flowchart for this part).
All accepted design [no priority]	This selection lets the program lists all combination meets the specification and the designer could choose the desired design manually. (Figure 3.4 illustrates flowchart for this part).

This flowchart assisted design method has been developed by many authors [7, 9]. The flowcharts are useful and can be utilized as a guide to the design of each subsystem independently of others. However, a major drawback of those flowcharts is that some of the design parameters in one subsystem are dependent on parameters in another subsystem. As an example, the selection of the spectral width and wavelength for the source affects the dispersion and the attenuation of the fiber link as well as the spectral response of the detector. For this reason a comprehensive flowchart has been developed.

Fiber optics system consists of three parts; source, fiber link (cable), and detector the selection process of these three parts is not a simple task, because the parts work together to build up the desired system at the required specification. So, a change in one part specification should be followed by another change in the other two parts to compensate the system and keep it running. According to this dependency between parts, a selection process of any part should not be separated from the selection of the other two parts, and the whole system should be taken as one module. Figure 3.1 illustrate a general flowchart of selection process. The flowchart consists of two main approaches named, Automatic Processing of Several Combination, and Single Combination Direct Processing.

The program implementing the Automatic Processing of Several Combination approach extracts the best combination of source, fiber link, and detector from the database according to design specification and priority parameter given by the designer. Table 3.1 shows priority parameters and describes the behavior of the program at every selection. Once the program has succeeded to find the combination, which meets the specification, the output form will show the result of the design and allow the designer to save the design data to file and then print it out if needed. If the automatic design process fails to find a combination meets the design specification, the program gives the designer the ability to use one or more repeater(s) and redesign again.

The designer is requested to enter the link length, data rate, bit error rate (BER), signal format, and system margin as well as choosing a desired design approach such as lowest cost, less than a specified number, do not consider cost (best performance), or all accepted design. Once these requirements are filled, the Calculate button will be activated allowing the designer to execute the design and get the results as shown in Figure 3.7. The repeater part shown in Figure 3.6 is used only if the program fails to find an accepted combination of source, link, and detector.

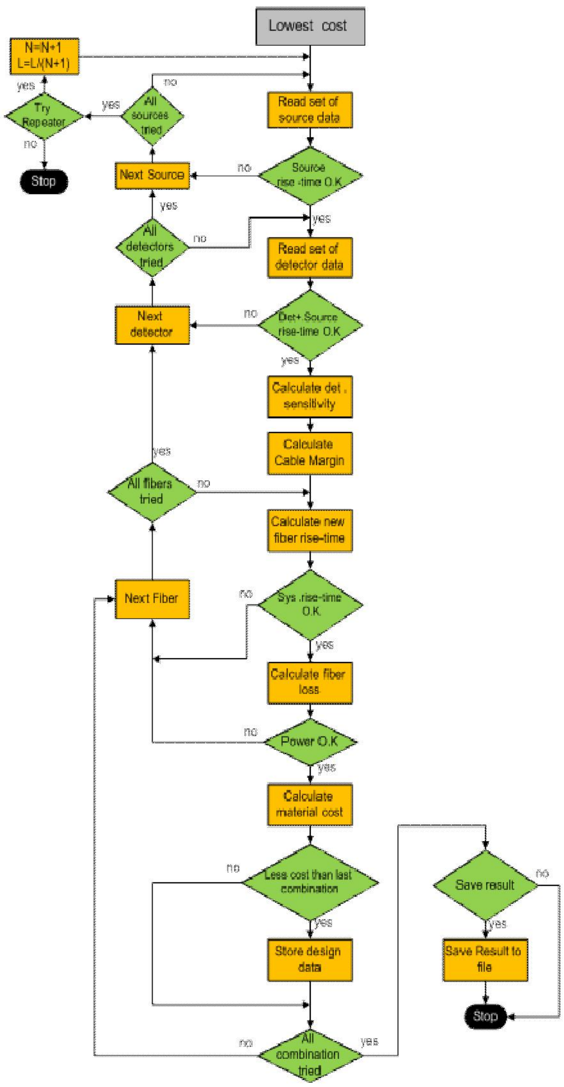


Fig.3.2. Lowest Cost Flowchart.

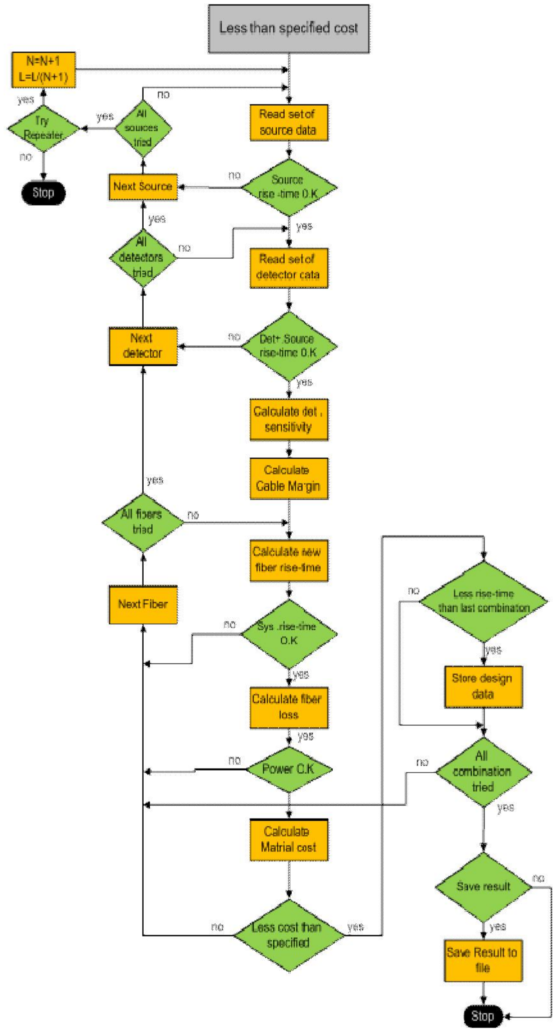


Fig.3.3. Less Than Specified Cost Flowchart

The second approach implementing program is a manual process, this means that the data of source, fiber link, and detector is given manually to the system. The output form shows the result of the design and allows the designer to save his design to a file and then get a print out if required. If the design fails to meet the design specification, the program gives the designer the ability to upgrade any part of the system or use one or more repeater(s) and then redesign again. One of the choices available is Source/Fiber/Detector, if it is selected then it will go through select source type, input source data, select fiber type, select detector type, calculate system risetime, calculate system power and many more steps before saving the result. The complete flowchart is shown in Figure 3.6. All others combinations is available in program.

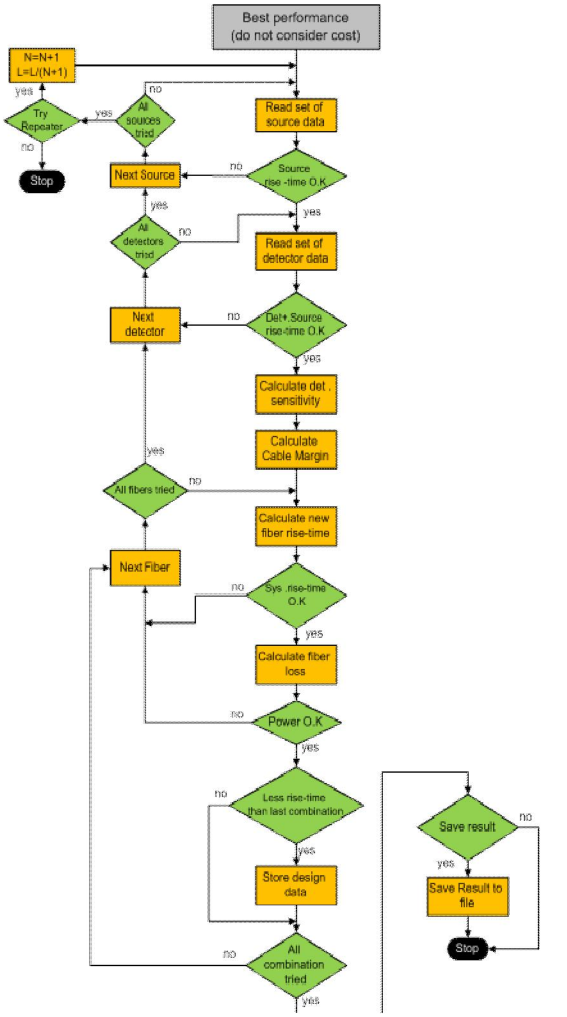
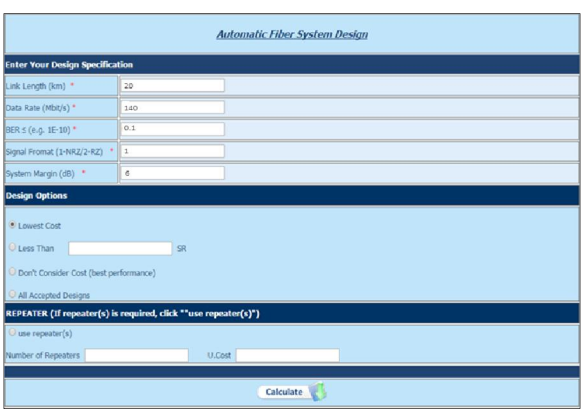


Fig. 3.4. Best Performance (Do not consider cost) Flowchart

Automatic Approach Input Program shown in Figure 3.6:


Automatic Fiber System Design

Enter Your Design Specification	
Link Length (km) *	20
Data Rate (Mbit/s) *	140
BER ≤ (e.g. 1E-10) *	0.1
Signal Fromat (1-NRZ/2-RZ) *	1
System Margin (dB) *	6

Design Options

- Lowest Cost
- Less Than SR
- Don't Consider Cost (best performance)
- All Accepted Designs

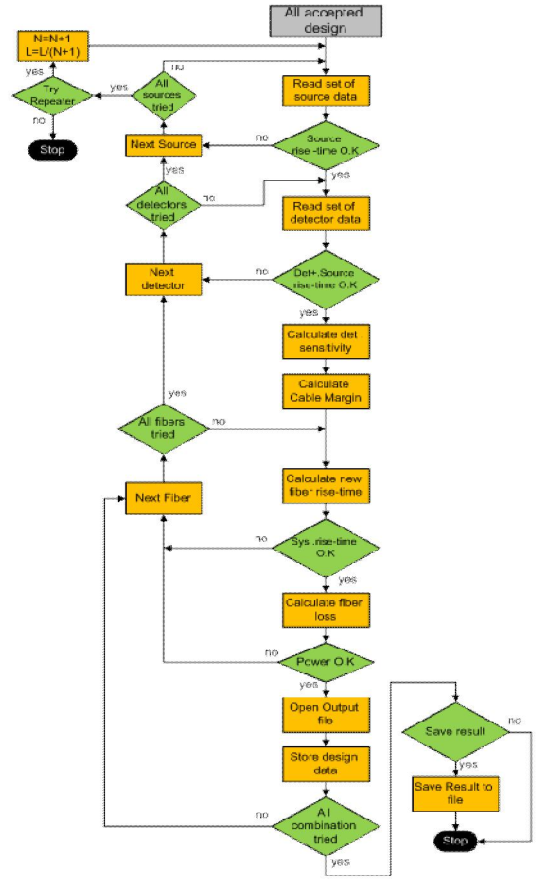
REPEATER (If repeater(s) is required, click "use repeater(s)")

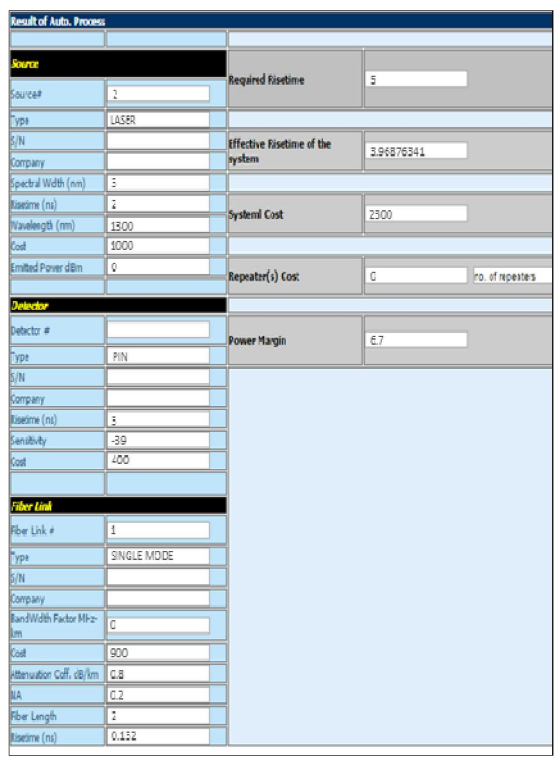
- use repeater(s)

Number of Repeaters U.Cost

Calculate

Fig. 3.6. Automatic Approach Program




Result of Auto. Process

Source		Required Risetime	5
Source#	2		
Type	LASER		
S/N		Effective Risetime of the system	3.96876341
Company			
Spectral Width (nm)	3		
Risetime (ns)	2	System Cost	2300
Wavelength (nm)	1300		
Cost	1000		
Emitted Power dBm	0	Repeater(s) Cost	0 no. of repeaters
Detector			
Detector #		Power Margin	6.7
Type	PIN		
S/N			
Company			
Risetime (ns)	3		
Sensitivity	-39		
Cost	400		
Fiber Link			
Fiber Link #	1		
Type	SINGLE MODE		
S/N			
Company			
BandWidth Factor MHz-km	0		
Cost	900		
Attenuation Coff. dB/km	0.8		
NA	0.2		
Fiber Length	2		
Risetime (ns)	0.132		

Fig. 3.7. Result Form of Automatic Approach Program

4. Sample Design

The transmitter program output result can be checked easily by applying the equations on the input data and compare the result with that given by the program. By doing this shows that the program is very accurate. The cable, receiver, and the cost programs were dealt similar to the transmitter program and output results of these programs are also accurate.

The fiber optics system program is very flexible, because the program includes a lot of decisions and calculations. Testing the program is also more complicated specially the automatic design process because it uses the database.

4.1 Fiber Optics System Program Evaluation

We enter two sources, fiber links, and two detectors to the database and we could then start the automatic design and check if the output result fit with what is expected. The database data are listed in table 4.1.

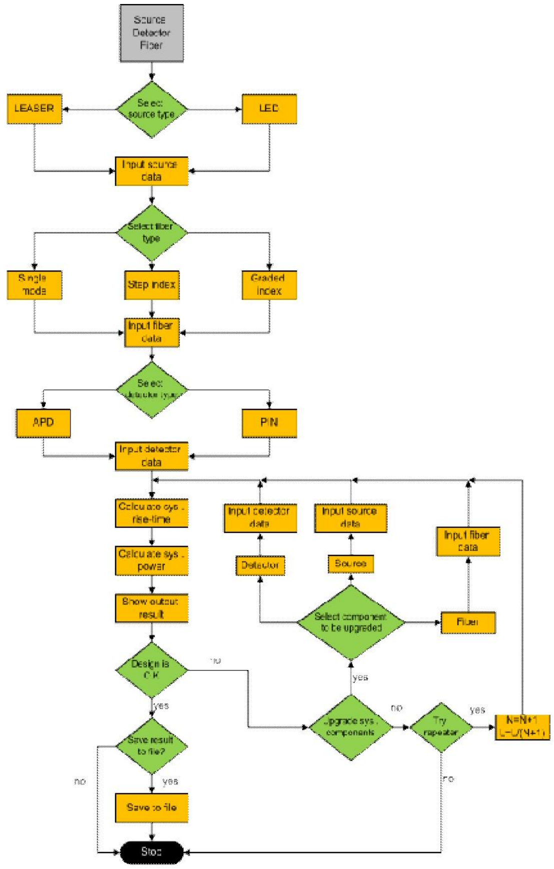


Fig.3.6. Source/Fiber /Detector Flowchart

The design specification plays a big role in determination of the system limitations that can be designed using the above listed elements. For example, if the designer specify a long distance, the program may fail to reach to a proper design without using a repeater.

Table (4.1) Sample Link Component Data

Source Parameters	Source #1	Source #2
Type	LED	LD
Pigtail Power (dBm)	-10	-6
Wavelength (nm)	1300	1300
Risetime (ns)	5	2
Spectral Width (nm)	10	3
Fiber Link Parameters	**Fiber #1**	**Fiber #2**
Type	Single Mode	Graded Index
Atten. Coeff. (dBlkm)	0.8	0.7
Bandwidth Factor (MHz-km)	-	1250
Mat. Dispersion Coeff. (ps/nm-km)	2	-
NA	0.2	0.2
Piece Length (km)	2.0	2.1
Joint Loss (dB)	0.4	0.3
Connector Loss (dB)	0.7	0.6
Receiver Parameters	**Receiver #1**	**Receiver #2**
Type	PIN	APD
Risetime (ns)	3	2.5
Sensitivity (dBm)	-39	-
Quantum Efficiency	-	0.7
Avalanche Gain	-	32
Noise Factor	-	10
Input Capacitance (pF)	-	4
Equiv. Noise Volt. (nv/Hz)	-	3.5
Equiv. Noise Current. (pv/Hz)	-	5

Design result #1:
------------------ Result summary -----
Required Rise Time = 5 ns
Repeater Spacing = 20km
Effective rise time of the system = 3.96876341446552ns
System Cost = 2300SR
Number of Repeaters =
Repeater(s) Cost = SR
Power Margin = 6.7 dBm

--Source Data--------------------------
ID = 2
Type = LEASER
Spectral Width = 3nm
Rise Time = 2ns
Wave Length = 1300nm
Emitted power = 0 dBm
Pigtail Output Power = -6 dBm
Lambertian/Directional Source =
Cost = 1000SR
S/N =
Company =
Comments =

--Fiber Link Data-----------------------
ID = 1
Type = SINGLE MODE
Attenuation Coeff. = 0.8 dB/km
BandWidth Factor = 0 MHz-km
Concatenation Factor = 0
Rise Time = 0.132 ns
Fiber Piece Length = 2km
Numerical Aperture = 0.2
Material Dispersion Coeff. = 2 ps-nm/km
Material Dispersion = 0.006 nm/km
Modal Dispersion = 0 nm/km
Refractive Index = 0
Relative Refractive Index Difference= 0
Joint Loss = 0.4 dB
Connector Loss = 0.7 dB
Cost = 900 SR
S/N =
Company =
Comments =

--Detector Data--
Type = 1
Rise Time = PIN
Sensitivity = 3ns
Responsivity = -39 dBm
Quantum Efficiency = 0 A/W
Avalanche Gain =
Noise Factor = 0
Equivalent Voltage Noise Source= 0 nV/sqr(Hz)
of Receiver Amplifier
Equivalent Current Noise Source= 0 pA/sqr(Hz)
of Receiver Amplifier
Total Input Capacitance of Detector= 0 pF
Cost = 400 SR
S/N =
Company =
Comments =

End of Design

Fig.4.1. Design Results #1

To simplify the program result evaluation process, the data rate, bit error rate, signal format and the power margin are fixed and the link. length will be varied to check all program options.

First Design:

```
Design result #2:
-------------------- Result summary -----
Required Rise Time                 = 5 ns
Repeater Spacing                   = 20km
Effective rise time of the system  = 3.96876341446552ns
System Cost                        = 2300SR
Number of Repeaters                =
Repeater(s) Cost                   = SR
Power Margin                       = 10 dBm

--Source Data--------------------------
ID                                 = 2
Type                               = LEASER
Spectral Width                     = 3nm
Rise Time                          = 2ns
Wave Length                        = 1300nm
Emitted power                      = 0 dBm
Pigtail Output Power               = -6 dBm
Lambertian/Directional Source      =
Cost                               = 1000SR
S/N                                =
Company                            =
Comments                           =

--Fiber Link Data-----------------------
ID                                 = 2
Type                               = GRADED INDEX
Attenuation Coeff.                 = 0.7 dB/km
BandWidth Factor                   = 1250 MHz-km
Concatenation Factor               = 0.7
Rise Time                          = 2.27970697660666E-03 ns
Fiber Piece Length                 = 2.1 km
Numerical Aperture                 = 0.2
Material Dispersion Coeff.         = 0 ps-nm/km
Material Dispersion                = 0.006 nm/km
Modal Dispersion                   = 0 nm/km
Refractive Index                   = 0
Relative Refractive Index Difference= 0
Joint Loss                         = 0.3 dB
Connector Loss                     = 0.6 dB
Cost                               = 1000 SR
S/N                                =
Company                            =
Comments                           =

--Detector Data----------------------------------------------
Type                               = 1
Rise Time                          = PIN
Sensitivity                        = 3ns
Responsivity                       = -39 dBm
Quantum Efficiency                 = 0 A/W
Avalanche Gain                     =
Noise Factor                       = 0
Equivalent Voltage Noise Source= 0 nV/sqr(Hz)
of Receiver Amplifier
Equivalent Current Noise Source= 0 pA/sqr(Hz)
of Receiver Amplifier
Total Input Capacitance of Detector= 0 pF
Cost                               = 400 SR
S/N                                =
Company                            =
Comments                           =
------------------------------------------------------------------------

                                                          End of Design
```

Fig.4.2. Design Results #2

Specification: Link length = 20 km,

Data rate = 140 Mbit/s,

Bit error rate = 1E-10,

Signal format = NRZ,

System margin = 6 dB,

If "All Accepted Design" option is selected, then the program lists all designs meet the bandwidth budget and power budget conditions. This option will be used first, and once the program offered the accepted designs, the designer can then add more restrictions to the program such as "lowest cost".

The program gives the following design results (as.pdf file as shown in Figures 4.1, 4.2).

As shown above two designs were accepted and in the following the two designs will be checked if they meet the specification or not.

Design result #1:

Bandwidth budget: the system rise time should be less than or equal to maximum allowed rise time

The maximum allowed risetime could be calculated as follows:

In our case NRT signal format is used so;

$risetime_{max}$ = 5ns

$risetime_{sys}$ = 0.132ns

Power budget: if the excess power is greater than or equal to zero, then the power budget condition is met.

Excess Power = 6.7 dBm

The bandwidth budget condition is met and the calculated risetime and excess power are fit to the program result.

Power Margin = 6.7 dB, which fits with that calculated by the program.

Design result #2:

Rise $time_{sys}$ = 3.9661ns

Excess Power = 10 dB

The bandwidth budget condition is met and the calculated risetime and excess power are fit to the program result.

Power Margin = 10 dB, which fits with that calculated by the program.

Table (4.2) below shows why the other combination of source, fiber link, and the detector are discarded by the program.

Table (4.2) All possible combination

Source#	Detector#	Fiber Link#	Risetime	Excess power	Accepted/ Discarded	Condition Violated
1	1	1	5.521	8.7	D	BW Budget
1	1	2	5.5	12	D	BW Budget
1	2	1	5.211	-10.78	D	BW Budget &Power Budget
1	2	2	5.188	-7.4793	D	BW Budget &Power Budget
2	1	1	3.968	6.7	A	
2	1	2	3.966	10	A	
2	2	1	3.525	-12.78	D	Power Budget
2	2	2	3.522	-9.4793	D	Power Budget

If the "Lowest Cost" option is used, then the program should select the second accepted design because of its cheapest cost. Note that the costs of parts are not the real costs, they are selected for illustration only.

If four repeaters are used, the program will accept two additional designs. The result summaries of accepted designs are shown in Figures 4.3, 4.4, 4.5 and 4.6.

Design result #1: [source#2, Fiber Link#1, Detector#1]
------------------ Result summary -----
Required Rise Time = 5 ns
Repeater Spacing = 5km
Effective rise time of the system = 3.9687634144655 2ns
System Cost = 2300SR
Number of Repeaters = 4
Repeater(s) Cost = 5000SR
Power Margin = 21.9 dBm

Fig.4.3. Design Results #1

Design result #2: [source#2, Fiber Link#2, Detector#1]
------------------ Result summary -----
Required Rise Time = 5 ns
Repeater Spacing = 5km
Effective rise time of the system = 3.9661065168425 7ns
System Cost = 2400SR
Number of Repeaters = 4
Repeater(s) Cost = 5000SR
Power Margin = 22.6 dBm

Fig.4.4. Design Results #2

Design result #3: [source#2, Fiber Link#2, Detector#1]
------------------ Result summary -----
Required Rise Time = 5 ns
Repeater Spacing = 5km
Effective rise time of the system = 3.5219054061686 6ns
System Cost = 2700SR
Number of Repeaters = 4
Repeater(s) Cost = 5000SR
Power Margin = 2.42074 dBm

Fig.4.5. Design Results #3

Design result #4: [source#2, Fiber Link#2, Detector#2]
------------------ Result summary -----
Required Rise Time = 5 ns
Repeater Spacing = 5km
Effective rise time of the system = 3.5217184587841 7ns
System Cost = 2800SR
Number of Repeaters = 4
Repeater(s) Cost = 5000SR
Power Margin = 3.12074 dBm

Fig.4.6. Design Results #4

Now, if "Less than specified cost" option is selected and the maximum accepted cost is set to 2400, then it expected that the program will select design # 1 because it has the lowest risetime and a cost less than specified.

The program execution summary result (Figures 4.7) with mentioned above specification.

------------------ Result summary -----
Required Rise Time = 5 ns
Repeater Spacing = 5km
Effective rise time of the system = 3.9687634144655 2ns
System Cost = 2300SR
Number of Repeaters = 4
Repeater(s) Cost = 5000SR
Power Margin = 21.9 dBm

Fig.4.7. Summary Result ("Less than specified cost ")

The last option is "Don't consider cost". If this option is selected, the program should select only one design that has the lowest risetime ignoring the cost. The program selects the following design (Figures 4.8):

------------------ Result summary -----
Required Rise Time = 5 ns
Repeater Spacing = 5km
Effective rise time of the system = 3.5217184587841 7ns
System Cost = 2800SR
Number of Repeaters = 4
Repeater(s) Cost = 5000SR
Power Margin = 3.12074 dBm

Fig.4.8. Summary Result ("Don't consider cost")

5. Experimental Investigation Of A Long –Haul Optical Fiber Link

5.1 System Description

The system design was based on the Philips 140 Mbit/s Optical Line Equipment (Type 8TR 684) and on the Graded-Index optical fiber cable (Type NKF-NM) which consists of 8 fibers. The link, as shown in Figure 5.1, provides two way transmission paths between city A and B; one being standby to the other thus having 100 % redundancy [7].

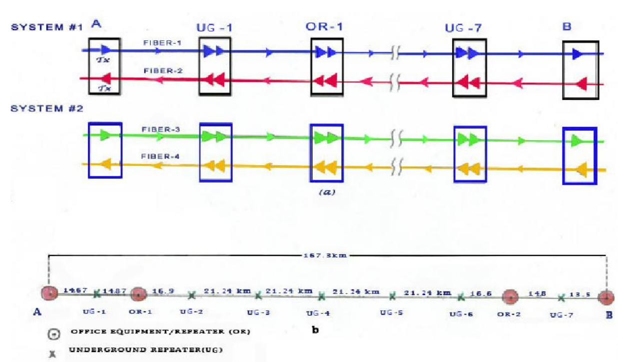


Fig.5.1 (a) Block Diagram of System-1 & System-2. (b) Link route plan indicating link sections.

5.2 Link Design

The link design was carried out by the contractor who was given the responsibility to execute this link. The following is the initial calculations of power and bandwidth budgets.

5.3 Bandwidth Budget

Considering that the system is required to transmit the 140 Mbit/s signal without distortion; then the required system band-width should not be less than 100 MHz.

The Bandwidth Factor of the fiber cables measured at the factory has an average value of 1.250 GHz-KM and an average concatenation factor of 0.5 which is quite small. This would produce a high fiber bandwidth using the concatenation formula of eq.(24). The repeater spacing, considering just the bandwidth of the fiber only, can be calculated using the same formula as follows:

$L = (BWF/B_S)\ 1/y$ ………………………..... (24)

Where,

L	is the repeater spacing,
BWF	is the bandwidth factor of the fiber,
B_s	is the system's bandwidth.

Therefore

repeater spacing = L

= (1850/100) 2

= (18.5) 2

= 342.25 KM

Which is quite high. Consequently it can be concluded that there is no bandwidth limitation for the fiber used in this link.

5.4 Power Budget

The nominal transmitter power has three settings: 0, -3 & -6 dBm. In order to extend the life of the laser -6 dBm level has been used. The parameters affecting power budget are:

Transmitter Power (nominal)	-6 dBm
Minimum Receiver Sensitivity	39.0dBm
Free System Margin	4 dB
Fiber Attenuation Coefficient	0.95 dB/km
Splice Loss (avg.)	0.3 dB
Connector Loss	0.8 dB

5.5 System Testing And Evaluation

Three types of tests were performed to test and evaluate the link:

1. Fiber splice loss measurement (Figure 5.2).
2. Power measurements (Figure 5.3).
3. Power margin (or Bit-error-rate) measurement (Figure 5.4).

The first test was carried out to measure the power loss due to various fiber splices. The second test was carried out to measure the power transmitted from the different optical transmitters and the power received by the different optical receivers in the link. The third test was carried to evaluate the link performance by measuring the received power, and the error-rate while physically degrading various sections of the link by inserting an attenuation which was increased in steps.

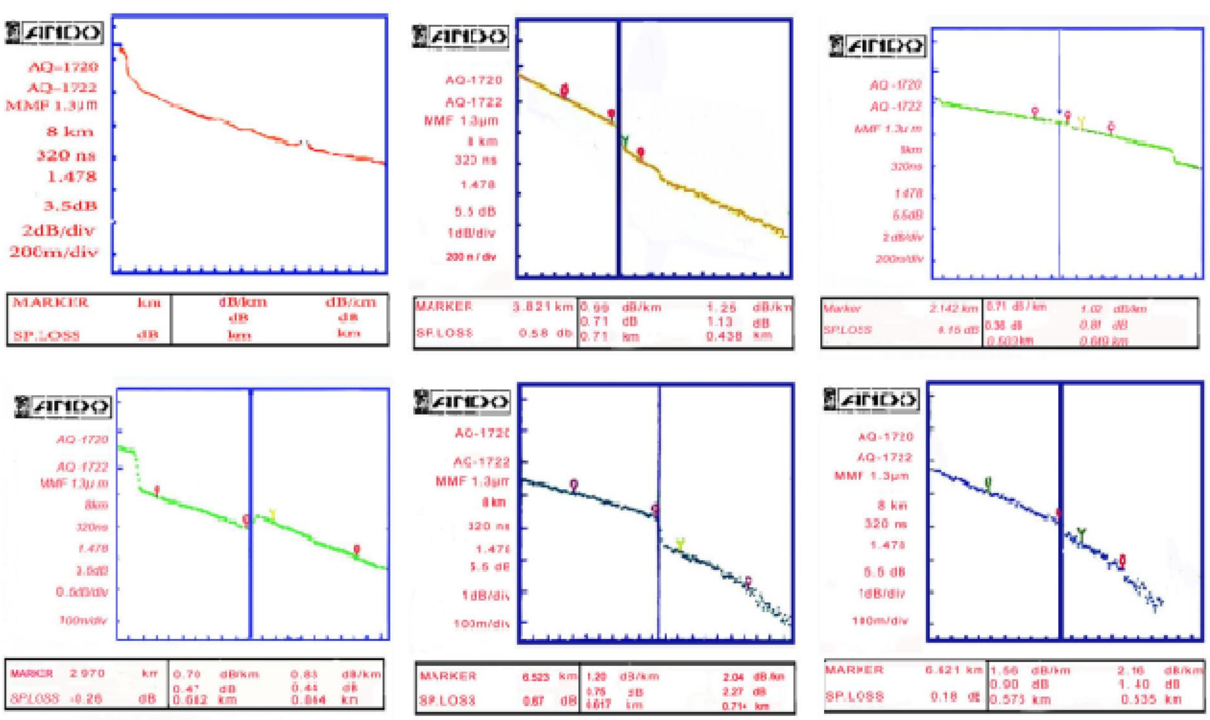


Fig. 5.2. (Loss Measurement of Random Splices on Fibers)

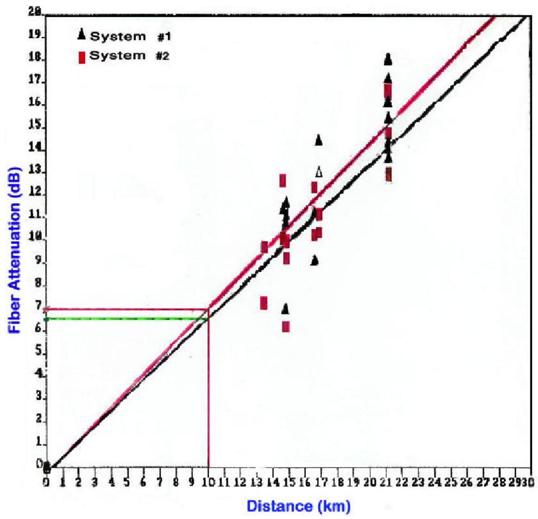


Fig. 5.3. (Plot of fiber attenuation vs. Distance for the two link systems)

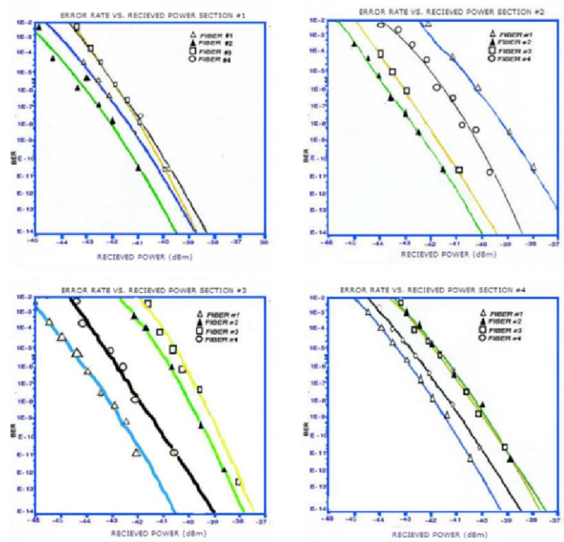


Fig.5.4. (Plot of BER vs. Received Power)

6. Results & Discussion

The fiber splices have an average splice loss of about 0.3dB which is in agreement with the assumed value at the design stage. Fiber attenuation is different from one fiber to another in the same section, having the same length. This can be attributed to the following factors:

1. During fiber manufacturing, impurity level variation exist in the fiber material as well as tolerances allowed for the core diameter and refractive index profiles. These factors have an impact on the value of the attenuation coefficient, and fiber diameter making identical fibers difficult to produce.

2. Splicing conditions and mechanical misalignments which occur during splicing are difficult to control.

Plots of BER against received power show a difference between the various curves corresponding to the different fibers. The optical fiber cable has an average attenuation coefficient of 0.664 dB/km for system-1 and 0.708 dB/km for system-2. These values are lower than the assumed value of 0.95 dB/km. This reduction in fiber attenuation has resulted in improvement of performance. Values of excess power margins, as in Figure 6.1 are so great that average repeater spacing can be increased to around 30 kilometers. Although, power margins of some sections fall below the average line, as in figure, they can be improved. Since transmitters are operated six db's below their nominal values, the transmitter output power for those sections can be increased in order to extend the repeater spacing of all sections to 30 km.

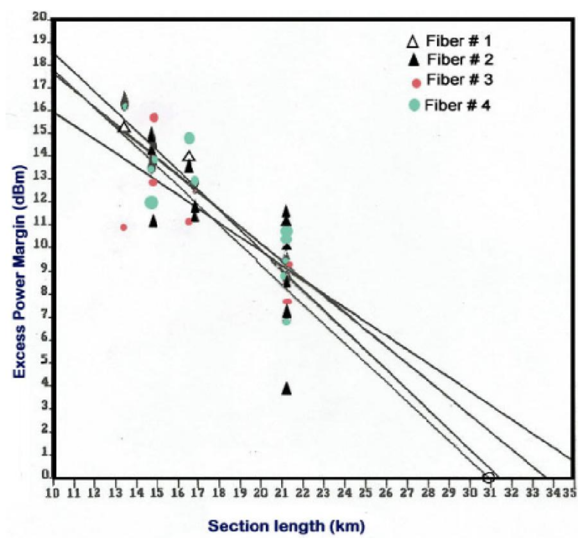


Fig. 6.1. (Excess Power Margin vs. Section Length)

Conclusion

The different aspects of the design process of optical fiber links have been discussed, starting at the optical source and ending at the optical detector. The factors contributing to the power budget and bandwidth budget have been successfully analyzed. The elements contributing to the power budget are the optical power transmitted from the source, the source-to-fiber coupling loss, the fiber attenuation, the splice and connector losses and the sensitivity of the optical receiver. Whereas the elements contributing to the bandwidth budget are the risetimes of the optical source, optical fiber and optical detector. The formulas relating those factors have been presented.

The methods that are currently being employed in the design procedures have been reviewed.

The drawbacks that make those methods limited in application have been highlighted. They are related to the fact that those methods are either inflexible or inadequate to take into consideration all the design factors. The charts and graphs devised by manufacturers can be applied only to a particular range of components provided by them. On the other hand, flowcharts developed for subsystem design are inadequate since they neglect the interdependence of different system parameters.

A novel method has been developed to ease and simplify the design procedure through the use of computer processing. A generalized and comprehensive flowchart has been devised taking into consideration most design factors and component parameters. The flowchart, which has been implemented into a computer program in ASP.net and C#, overcome the problem of interdependence of component parameters through the application of iterative processes. Furthermore, any number of components of differing ranges can be processed together to come up with a combination that meet some given link performance criteria. The information required for the design is the link length, the data rate, the bit error rate, and the digital signal format. The computer program is the advantage of transforming the cumbersome optical fiber link design process into ab easy and simple operation. In order to test its reliability, this method has been applied to some existing links. The resulting design has been found to be in agreement with the published design.

In addition, an experimental investigation has been carried out on a long-haul optical fiber link which consists of ten sections, connected through nine repeaters. The system tests performed, cover measurement of power loss of several randomly selected fiber splices. Analysis of the results indicate that the average splice loss is in agreement with the value estimated at the design stage. Also, power measurements have been carried out on the optical power transmitted and received for each section in the link. Evaluation of the results show an average fiber attenuation coefficient of 0.664 dB/km, and 0.708 dB/km for system-1 and system-2, respectively. These values are lower than the 0.95 dB/km included in the design calculations.

A third set of measurements has been taken for the power margin of each section by physically degrading the system and measuring the Bit Error Rate. Analysis of the excess power margin for each section shows that section length or repeater spacing could have been made thirty kilometers, which is longer than the actual value. Consequently, all repeater spacings could have been made longer or even doubled at some sections without affecting the link performance. This means that the link had been overdesigned.

With the improvement in the attenuation coefficient and the new repeater spacing value, the link can be redesigned. Furthermore, they provide power for the underground repeaters. It can be seen from the new link schematic, that the number of repeaters has decreased to only five instead of the nine actually used in the link. Naturally, there are significant benefits obtained by reducing the number of repeaters. Equipment cost would be greatly reduced. There is also the added advantage of less maintenance effort, since system reliability would be improved.

Acknowledgment

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