Experimental Investigation of Power and Bandwidth Budgets for a Long-Haul Fiber Optic Link

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Abstract
This paper describes the results of an experimental investigation performed on a long-haul digital optical fiber link between two cities. The link is 176.3 km long and carries 140 Mbit/s digitally formatted signal. The link components have been explained in details. Power and bandwidth budgets are calculated to make sure there are no limitations. The system tests performed cover splice loss measurements, power measurements, and bit-error-rate measurement to test and evaluate the link. The test results are analyzed and compared to the design parameters, and several conclusions are drawn.

Keywords: *Fiber optic, Long-haul, Link design, power budget bandwidth budget*

1. Introduction

The potential of fiber optics in long-distance transmission of digital data is becoming more apparent. It is superior to conventional transmission media. Optical fibers offer higher bandwidth capacity, and long repeater sections [1]. Hence they represent a more economical means of long distance transmission.

The design of fiber optics 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 optics cable type and the detector (receiver), affect the other two because of their interdependence that illustrated in Figure 1. Moreover, any component of inferior characteristics will increase the required number of repeaters which will affect the cost of the system [2].

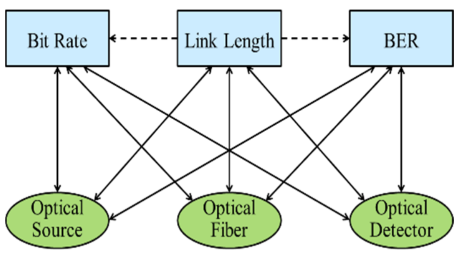

Fig. 1. Design factors interdependence

The available fiber optic link described here has the following overall performance specifications are reported in Table 1:

Table 1: Fiber optic link described performance specifications

Data Rate	140 Mbit/s
Length	176.3 km
Bit Error Rate	< 10-10
Signal Type	NRZ

This link is to carry voice and other digitally formatted signals such as video, data, etc., between city A and city B.

The experimental investigation was done for available fiber optic link, but it should be applicable to the latest fiber optics system taking into consideration new developed fiber optics system.

2. System Descriptions

The system design was based on the Philips 140 Mbit/s optical line equipment (Type 8TR 684) and on the graded-index fiber optic cable (Type NKF-NM) which consists of 8 fibers [3]. The link, as shown in Figure 2, provides two-way transmission paths between city A and B; one being standby to the other thus having 100 % redundancy.

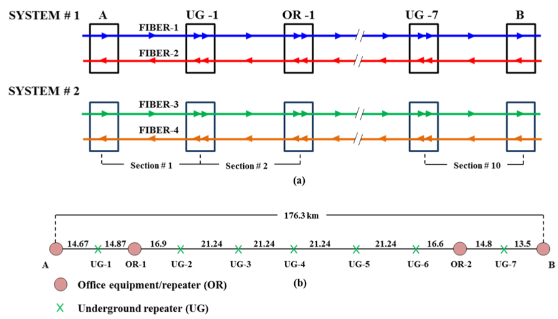

Fig. 2. (a) Block diagram of system-1 & system-2. (b) Link route plan indicating link sections

3. 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 [4,5].

A. Bandwidth budget

The purpose of bandwidth budget (risetime budget) to make sure each element of link is fast enough to meet the given bit rate. The system bandwidth should be big enough to allow the input signal to pass through it without any distortion, one must consider the effects of the different

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system components on the system's bandwidth. These effects are conveniently analyzed in terms of rise/fall times. So, optical source rise time, fiber rise time, and detector rise time must be considered [6].

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

The bandwidth factor of the fiber cables measured at the factory has an average value of 1.850 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 Equation (1). The repeater spacing, considering just the bandwidth of the fiber only, can be calculated using the following relationship:

$$Lr = (BWF/ Bs)^{1/\delta} \quad (1)$$

Where Lr is repeater spacing, BWF is bandwidth factor of the fiber, Bs is system's bandwidth and δ is concatenation factor.

Therefore

Repeater spacing $= (1850/100)^2$

$= 342.25$ km

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

B. Power budget

The purpose of power budgeting is to identify the optical power performance of each link component, then through calculations and estimation, deduce whether the system meets the requirements or not. 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 [7].

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 reported in Table 2:

Table 2: Parameters affecting power budget

Transmitter power (nominal)	-6 dBm
Minimum receiver sensitivity	-39 dBm
System degradation	4 dB
Free system margin	3 dB
Fiber attenuation coefficient	0.95 dB/km
Splice loss (avg.)	0.3 dB
Connector loss	0.8 dB

The available margin for cable section (P_f) is given by the following relationship:

$$P_f = P_t - P_m - P_r \quad (2)$$

Where P_t is transmitted power, P_m is system margin and P_r is receiver sensitivity.

Therefore, the available power margin for the fiber is:

$$P_f = -6 - 4 - 3 - (-39) = 26 \text{ dB}$$

Using this available margin the repeater spacing is approximately 22.5 km. Therefore the system is power limited.

4. System Testing and Evaluation

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

1. Fiber splices loss measurement.
2. Power measurements.
3. Power margin (or Bit-error-rate) measurement.

A. Splices loss measurement

The fiber splice loss measurement was performed using Ando OTDR (model AQ-1720) [8,9]; typical fiber splice measurement printout is shown in Figure 3.

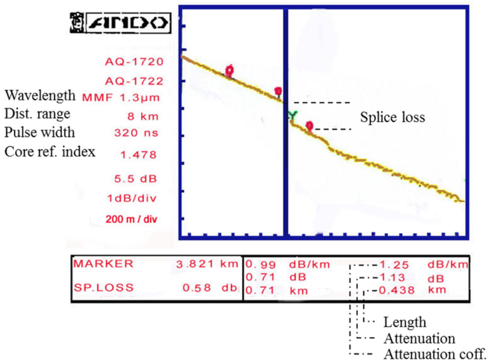

Fig. 3. Typical fiber splice measurement printout

The vertical axis represents the attenuation of the signal in dB's; whereas the horizontal axis represents the distance from the end where light is injected.

The power losses of some randomly selected splices are given in Table 3.

Table 3: Splice loss readings

Section No.	Splice No.	Fiber No.	Splice loss (dB)
1	2	2	0.23
1	2	3	0.31
1	2	4	0.18
1	5	1	0.15
1	5	2	0.58
1	3	3	0.67
3	2	2	0.45
3	5	2	0.28
3	5	3	0.05
3	8	1	0.26
10	1	3	0.19
10	2	1	0.96
10	3	1	0.01
10	4	1	0.08
10	5	1	0.05
Total number of sample splice = 15 Total splice loss = 4.45 Average splice loss = 4.45/15 = 0.2966 dB			

The average splice loss = 0.2966 dB (approx. 0.3 dB) therefore the average measured value is the same as the value assumed at the design stages.

B. Power measurement

The optical power transmitted from each transmitter in the link was measured using the Anritsu power meter. The point where power was measured is at the transmitter module output connector. Also, the optical power received by each receiver was measured using the same power meter at the fiber connector where power is received at the distant end. For each fiber in the ten sections making up the link the power lost during transmission on the fiber has been computed. It is equal to the power transmitted minus the power received. Furthermore, the losses due to splices have been calculated based on the average splice loss derived previously which is about 0.3 dB per splice. The net fiber attenuation has been calculated for each section, and the results along with the other parameters measured and computed are illustrated in Table 4. Moreover, the average fiber attenuation coefficient has been computed and included in the same table. A plot of the fiber attenuation calculated for each section has been plotted against distance (or section length). The plot is shown in Figure 4.

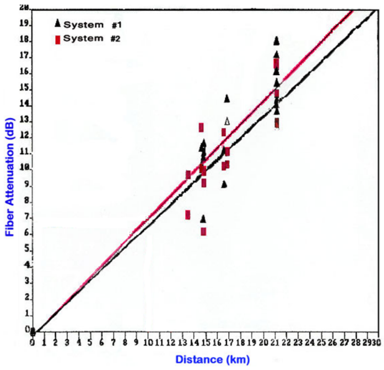

Fig. 4. Plot of fiber attenuation vs. distance for the two link systems

The resulting line has a slope that represents the average attenuation coefficient of the fibers employed in the link. The value of this coefficient is about 0.740 dB/km for system-1 and 0.711 dB/km for system-2 which is lower than the value assumed at the design stage, which is 0.95 dB/km. This means that the value assumed initially is higher than the actual value by about 28 to 33%. This improvement in the attenuation coefficient is reflected on the overall performance of the link.

Another type of power measurement was carried out on the transmitters at two time intervals differing by twenty six days of continuous operation. The two sets of random readings and the difference are given in Table 5. The total variation is around 2.13 dB. This variation in the power of the transmitter can be attributed to variations over time. Threshold current varies over time and temperature and consequently radiated power changes.

C. Bit-error rate (power margin) test

The bitstream generation and the analysis of the received signal was done through the Anritsu digital analyzer. 140 Mbit/s digital signal was sent down the link on one fiber (e.g. fiber number 1) and then looped back through onto another fiber, so that the signal would be received in the same station from which it was sent. An optical attenuator, type Anritsu, was situated on the route of the signal at the receiving end just before the optical receiver. This signal was measured using the optical power meter type Anritsu. The signal then was analyzed on the digital receiver, measuring the error rate inflicted during transmission.

The same test arrangement was used for all sections with this optical power meter, and attenuator placed just before the receiver of the section. The digital analyzer, which measures the error-rate was fixed at the station (A). Since each section has two operational fibers, two sets of readings were taken for each section. For each set of readings, the received power and the error-rate were measured for each attenuator setting.

A plot has been made for each set of readings showing the variation of BER rate versus the received power in dBm. These plots are illustrated in Figure 5.

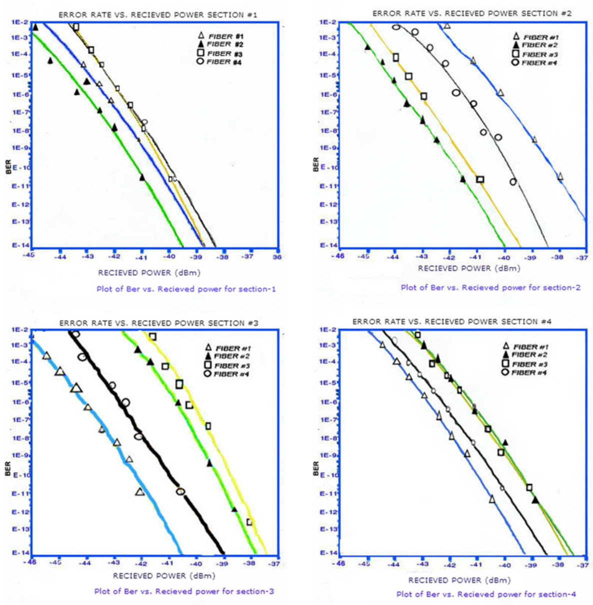

Fig. 5. Plot of BER vs. received power

It is clear from the plots that there is a difference between the various curves in each section. The reasoning behind this variation is explained in the next section.

Analysis of the power margin test readings was done by computing the excess power margin for each section. This excess power margin (P_X) was calculated as follows:

$$P_X = P_R - P_A + P_B - P_M \quad (3)$$

Where P_A is actual power received before attenuation is introduced, P_B is built-in insertion loss, P_R is power received and P_M is system degradation margin.

The excess power margin was calculated for each fiber in each section. The results are illustrated in Table 6.

It can be seen from the table that excess power margins have values which range between 3.65 to 16.14 dB's. This means that repeater spacing between all sections could have been made larger by some amount which varies from one section to another. This is in addition to the margin already set for the laser power output which is 6 dB for each transmitter.

The excess power margins have been plotted versus section lengths (or distances) for the different fibers. The plot is illustrated in Figure 6 where linear regression is done over the different points. The resulting lines indicate that the excess power margins decrease as the distance increases, as is expected.

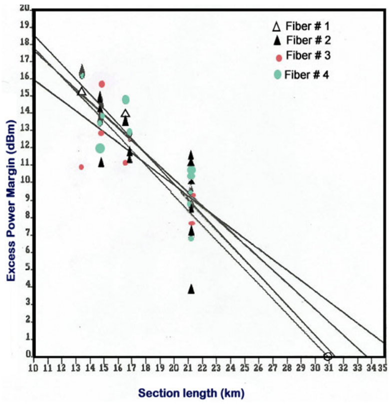

Fig. 6. Excess power margin vs. section length

5. Results and Discussion

From the preceding performance test result, the following points can be deduced:

1) The fiber splices have an average splice loss of about 0.3dB which agrees with the assumed value at the design stage.

2) 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:

a) During fiber manufacturing, impurity level variation exists 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.

b) Splicing conditions and mechanical misalignments which occur during splicing are difficult to control. Hence, it is quite usual to have variations in splice losses.

3) Plots of BER against received power show a difference between the various curves corresponding to the different fibers.

4) The fiber optic cable has an average attenuation coefficient of 0.740 dB/km for system-1 and 0.711 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 illustrated in the graph of Figure 6 are so great that average repeater spacing can be increased to around 30 km. Although, power margins of some sections fall below the average line, as illustrated in that figure, they can be improved. Since transmitters are operated 6 dB’s below their nominal values, the transmitter output power for those sections can be increased to extend the repeater spacing of all sections to 30 km.

6. Conclusion

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 indicates 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 shows an average fiber attenuation coefficient of 0.740 dB/km, and 0.711 dB/km for system-1 and system-2, respectively. These values are lower than the 0.95 dB/km included in the design calculations. The 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 spacing 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.

References

[1] A. S. Tanenbaum, *Computer networks*, 4th ed.: Prentice Hall PTR, 2002.

[2] S. Deb, L. Ni, H. Yu, and A. Chattopadhyay, "Racetrack memory-based encoder/decoder for low-power interconnect architectures," in *2016 International Conference on Embedded Computer Systems: Architectures, Modeling and Simulation (SAMOS)*, 2016, pp. 281-287: IEEE.

[3] "140 Mbit/s optical line equipment," Philips equipment manual PR-L 570e.

[4] S. Pachnicke, "Fiber Optical Transmission Systems," in *Fiber-Optic Transmission Networks*: Springer, 2012, pp. 11-29.

[5] A. Affandi and O. AL-Rusaini, "A Novel Computer Aided Approach to Fiber Optic Communication link Design," *Life Science Journal*, vol. 12, pp. 69-81, 2015.

[6] P. K. Cheo, *Fiber optics: devices and systems*: Prentice-Hall, Inc., 1985.

[7] G. Keiser, *Optical fiber communications*. McGraw-Hill New York, 2000.

[8] T. Chu and A. McCormick, "Measurements of loss due to offset, end separation, and angular misalignment in graded index fibers excited by an incoherent source," *Bell System Technical Journal,* vol. 57, no. 3, pp. 595-602, 1978.

[9] P. Melman and W. Carlsen, "Elastic tube splice performance with single-mode and multimode fibres," *Electronics Letters*, vol. 8, pp. 320-321, 1982.

[10] M. Altmann, J. Caia, R. Morle, M. Dunsmore, Y. Xie, and N. Kocaman, "A low-power CMOS 155 Mb/s transceiver for SONET/SDH over co-ax and fibre," in *Proceedings of the IEEE 2001 Custom Integrated Circuits Conference (Cat. No. 01CH37169)*, 2001, pp. 127-130: IEEE.

[11] H. C. Casey and M. B. Panish, *Heterostructure lasers*. Academic press, 1978.

[12] F. Laforce, "Low noise optical receiver using Si APD," in *Optical Components and Materials VI*, 2009, vol. 7212, p. 721210: International Society for Optics and Photonics.

[13] M. Romeiser, *Optical Fibers and RF: A Natural Combination*. IET, 2004.

J. Gowar, *Optical communication systems*: Prentice-Hall, Inc., 1993.

Power measurement reading and evaluation of fiber attenuation coefficient

Section No.	Sys. No.	D (km)	P_t (dBm)	P_r (dBm)	L_t (dB)	N	L_s (dB)	L_f (dB)	α (dB/km)
1	1	14.67	-6.00	-18.35	12.35	6	2.10	10.55	0.719
1	2	14.67	-6.93	-20.30	13.37	6	2.10	11.57	0.789
2	1	14.87	-6.58	-20.26	13.68	6	2.10	11.88	0.794
2	2	14.87	-7.24	-20.36	13.12	6	2.10	11.32	0.761
3	1	16.90	-6.60	-23.34	16.74	7	2.40	14.64	0.866
3	2	16.90	-5.40	-20.75	15.35	7	2.40	13.25	0.784
4	1	21.24	-6.57	-26.60	20.03	9	3.00	17.33	0.816
4	2	21.24	-7.60	-28.55	20.95	9	3.00	18.25	0.859
5	1	21.24	-6.44	-25.50	19.06	9	3.00	16.36	0.770
5	2	21.24	-6.37	-23.37	17.00	9	3.00	14.30	0.673
6	1	21.24	-6.52	-24.85	18.33	9	3.00	15.63	0.736
6	2	21.24	-6.00	-23.27	17.27	9	3.00	14.57	0.686
7	1	21.24	-6.52	-23.13	16.61	9	3.00	13.91	0.655
7	2	21.24	-5.68	-22.28	16.60	9	3.00	13.90	0.654
8	1	16.60	-7.00	-18.45	11.45	7	2.40	9.35	0.563
8	2	16.60	-7.30	-20.80	13.50	7	2.40	11.40	0.687
9	1	14.80	-7.62	-20.44	12.82	6	2.10	11.02	0.745
9	2	14.80	-6.45	-15.45	9.00	6	2.10	7.20	0.486
10	1	13.50	-6.65	-18.06	11.41	5	1.80	9.91	0.734
10	2	13.50	-6.76	-18.05	11.29	5	1.80	9.79	0.725

Average attenuation coeff. = 0.708, D is the section length, P_t is the transmitted power, P_r is the received power, L_t is the total attenuation = $P_t – P_r$, N is the no. of splices = round [D/2.1 – 1], L_s is the total splice losses = 0.3 * N, L_f is the net fiber attenuation= $L_t – L_s$, α is the fiber attenuation coeff. = L_f/D

Table 4: Power measurement reading and evaluation of fiber attenuation coefficient

Transmitter Designation	P_t (dBm) (first time)	P_t (dBm) (26 days later)	Difference (dBm)
ATCC-FBR1	-6.00	-7.40	-1.40
ATCC-FBR3	-7.03	-7.10	-0.07
OR-1-FBR1	-6.60	-7.00	-0.40
OR-1-FBR2	-7.24	-6.70	0.54
OR-1-FBR3	-6.35	-7.00	-0.65
OR-1-FBR4	-6.89	-6.60	0.29
UG-2-FBR1	-6.57	-6.60	-0.03
OR-2-FBR1	-7.62	-6.30	1.32
OR-2-FBR2	-7.30	-6.10	1.20
BTCC-FER2	-6.76	-6.10	0.66
BTCC-FER1	-6.27	-5.60	0.67

Power variation = ±1.4 dBm , Total variation = 2.13 dBm

Table 5: Excess power margin for BER = 10^{-10}

Section No.	Fiber No.	Power margin (dB) = $P_R - P_A$	P_B (dB)	P_M (dB)	P_X (dB)
1	1	40.25-24.35=15.90	6	7	14.90
	2	40.90-26.30=14.60	6	7	13.60
2	1	38.26-26.26=12.00	6	7	11.00
	2	41.70-26.36=15.34	6	7	14.34
3	1	42.00-29.34=12.66	6	7	11.66
	2	39.00-26.75=12.25	6	7	11.25
4	1	40.80-26.60=14.20	0	7	07.20
	2	39.20-28.55=10.65	0	7	03.65
5	1	39.60-25.50=14.10	0	7	07.10
	2	41.55-23.43=18.12	0	7	11.12
6	1	40.70-24.85=15.85	0	7	08.85
	2	41.77-23.27=18.50	0	7	11.50
7	1	40.20-23.13=17.07	0	7	10.07
	2	38.80-22.28=16.52	0	7	09.52
8	1	39.25-24.45=14.80	6	7	13.80
	2	41.30-26.80=14.50	6	7	13.50
9	1	41.60-26.44=15.16	6	7	14.16
	2	32.15-27.40=15.75	6	7	13.75
10	1	40.20-24.07=16.13	6	7	15.13
	2	41.19-24.05=17.14	6	7	16.14