Design and Analysis of Optical Fiber Network for Railway Communication Lines

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***Abstract*—The development of the railroad industry in Indonesia by P.T. Kereta Api Indonesia (KAI) is one of the strategic development programs for the transportation of passengers and goods. The system should also guarantee the function of the entire signaling and telecommunications equipment system. Replacement of current communication lines from coaxial with fiber-optic networks is an improvement step to obtain a reliable communication system. Fiber optic networks offer high data rates and high levels of security to meet the ever-increasing bandwidth requirements. This paper reviews and proposes the north coast route of Java as the main route on the Java island, especially from the Bojonegoro Station to Surabaya Pasar Turi Station. The replacement design from the use of coaxial to the optical fiber is a ring configuration and one station jump in each hop. This ring configuration is anticipation if the channel has broken at one of the stations. Therefore, communication is remain guaranteed with the path in the opposite direction. From the proposed arrangement, the power link budget in this optical network design shows that the received power ranges from -13.56 ~ -17.89 dBm, which is still above the detector sensitivity level of -24 dBm. The rise time system at each station ranges from 39.91 ~ 44.55 ps with a maximum rise time system of 4501.03 ps. The Bit Error Rate analysis is 2.31 x 10-13. Based on the obtained values of those parameters, the proposed network design can guarantee that the entire signaling and telecommunications equipment system will function well.**

Keywords*— *Railway optical network, power link budget, rise time budget, bit-error-rate

I. INTRODUCTION

Railways are one of the transportation modes having the characteristics and advantages to transport both passengers and goods in large quantities [1][2]. To maintain the sustainability of benefits and in line with the continued increase in the flow of passengers and goods, the railroad services need to be continuously improved to develop an integrated national transportation system.

The supply and construction of railway infrastructure and the procurement of railways facilities must be based on predetermined requirements to guarantee the safety, comfort, security, smoothness, and order of railroad operations [3]. One of them is the technical requirements related to signaling and telecommunications equipment systems. A reliable system will support safe, comfortable, and sustainable railroad operations [4][5]. Railway signaling equipment functions give instructions or cues in the form of color, light, or other information with a particular meaning. Railway telecommunications equipment functions to convey information and or communicate for the benefit of railroad operations in the form of voice communication systems and data communication systems.

Limitation of the track becomes a challenge when the number of trips increases, so a double-track development solution is needed [6]. A double-track is a two-track railroad to use each track in a different direction. The Directorate General of Railways is currently carrying out double-track construction on the Bojonegoro Station line to Surabaya Pasar Turi Station in the VIII Operational Area (DAOP) Surabaya [7][8]. The addition of the dual-rail purposes is increasing frequency and capacity. At the same time, the development program can also enhance the reliability of signaling and telecommunications systems by applying optical fiber-based communication systems on these lines. This optical transmission system can become the primary transmission medium for the railroad signaling and telecommunication equipment system, where previously there had been a coaxial cable in the transmission system on the line.

Some researchers have conducted researches on the optical fiber communication system for railway communication lines. Previous research proposed a proposal to build a fiber-optic network on a railroad that aims to connect remote cities in Sudan [9]. The study also analyzed the socioeconomic impact, potential problems, and obstacles faced. Another research made an alternative to the settlement of disturbances on Surodadi and Pemalang Station block equipment to improve the safety of Surodadi-Pemalang Station train travel [10]. The research also recommends the replacement of the physical cable with optical fiber cables. However, those studies have not yet carried out the calculation and feasibility analysis of the proposed fiber-optic network system.

This paper reviews and proposes the design of the deployment and feasibility analysis of fiber optic communication systems on the aspects of the tracks and transceiver device components on the railroad by reviewing

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the implementation locations on the line from Bojonegoro Station to Surabaya Pasar Turi Station. The feasibility parameters are by calculating the power link budget, rise time budget, bit error rate (BER), needs of the leading equipment and estimated costs needed, as well as potential problems and impacts of the proposed fiber-optic network architecture.

II. Optical Network Design

A. Architectural Design

Figure 1 shows a flow diagram of the proposed design plan in deploying optical networks across Bojonegoro-Surabaya Pasar Turi. By starting with the literature survey, the next step is designing the planned routes. After determining paths and considered parameters, examining the route plans are the next steps until obtaining the desired condition.

The proposed design forms an uninterrupted ring configuration with a single-mode inter-hop optical fiber capacity of 24 cores. The selection of these specifications refers to references [7][8]. The hop system in this design is by jumping one station between a hop. Suppose the first hop is station A; the next destination hop is station C by skipping station B. Therefore, the communication can continue even if one of the links broken. If the initial setup uses clockwise, when an interrupted connection occurs, it can be overcome by diverting the flow of communication in a counter-clockwise direction.

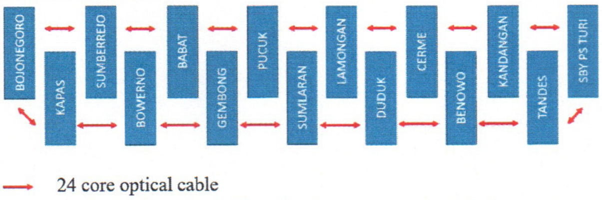

Fig. 1. Design of optical fiber deployment across Bojonegoro - Surabaya Pasar Turi

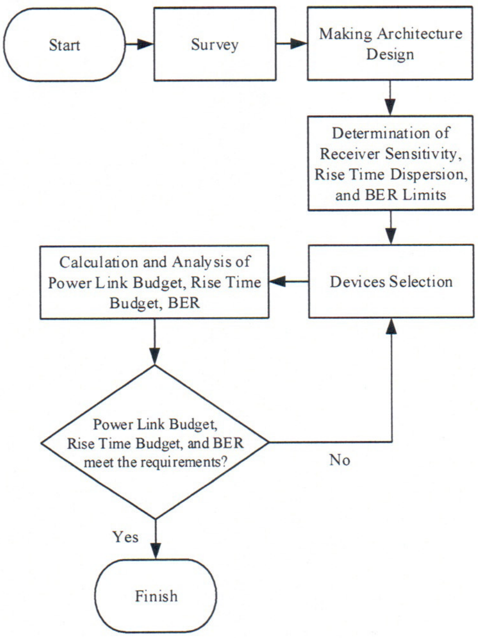

Fig. 2. Flow diagram of fiber optic network design

Table 1 shows the cable connection lines between optical links and their distances. The required cable length is calculated based on the distance between optical links added with a cable spare of 5% of the distance between optical links. This additional cable allocation has the purpose of facilitating the connection process when there are disconnected cables in operation, anticipating changes in the layout of the optical transceiver due to the development of the station, and the potential additional needs.

The total bandwidth for the 15 stations provided in this design is 1xSTM-1 (Synchronous Transfer Module level 1) with a capacity of 155.52 Mbps or equivalent to 63 E1 where 1xE1 is equal to 2,048 Mbps. The bandwidth used for communication between stations is 4xE1, and there is a reserved bandwidth of 3xE1. The bandwidth allocated for signaling equipment at each station is 2xE1. In contrast, the bandwidth for telecommunications is ER telephones, slender telephones, PAP phones, console telephones, and voice or data recorders, where the allocation of each station is 2xE1.

TABLE I. Optical Fiber Requirements

Route	Origin Station	Destination Station	Distance (Km)	Spare Cable 5% (Km)	Total Cable (Km)
1	Bojonegoro	Sumber Rejo	14.16	0.71	14.87
2	Kapas	Bojonegoro	6.20	0.31	6.51
3	Sumber Rejo	Babat	21.15	1.06	22.20
4	Bowerno	Kapas	20.15	1.01	21.16
5	Babat	Pucuk	11.32	0.57	11.88
6	Gembong	Bowerno	15.00	0.75	15.75
7	Pucuk	Lamongan	17.28	0.86	18.15
8	Sumlaran	Gembong	11.04	0.55	11.59
9	Lamongan	Cerme	21.59	1.08	22.67
10	Duduk	Sumlaran	23.33	1.17	24.49
11	Cerme	Kandangan	10.38	0.52	10.89
12	Benowo	Duduk	15.00	0.75	15.75
13	Kandangan	Surabaya Pasar Turi	8.63	0.43	9.06
14	Tandes	Benowo	8.52	0.43	8.95
15	Surabaya Pasar Turi	Tandes	5.25	0.26	5.51
				Total	219.46

TABLE II. Optical Communication System Parameters

Parameter	Value	Unit
Data Rate	155,52	Mbps
BER	10^{-12}	-
Encoding Signal	NRZ	-
Wavelength	1550	nm
Margin System	8	dB
Connector Attenuation	2	dB/connector
Joint attenuation	0,2	dB/splice
Transceiver NEC Spectral Wave MN 1200 [11]		
Transmit power	4	dBm
Receiver sensitivity	-24	dBm
Transceiver rise time	28	Ps
Spectral Width (σ_λ)	0,3	nm
Optic Fiber Cable (ITU-T G.654.B)		
Attenuation (α_f)	0,175	dB/km
Chromatic Dispersion (D)	3	Ps/nm.km

B. Devices Selection

After obtaining location and design data, the next step is determining the type and specifications of the equipment needed. The required optical cable uses the ITU-T G.654.B standard, which has a low loss characteristic and is capable of reaching distances of 100 km without using repeaters. The transceiver device used in the design of optical cable deployments has a high transmit power (4 dBm) and has a low sensitivity level (-24 dBm). Details of the optical cable and transceiver device parameters are in Table 2.

C. Calculation of Power Link Budget

This study considers the power link budget analysis to ensure that the receiver can receive the transmit power carrying information from the transmitter after passing through the optical fiber medium with a certain distance [12]. Equation (1) explains the calculation of total optical power losses or Total Optical Power Loss, and Equation (2) is a formula to calculate the received power. Equation (1) is to calculate the parameters. It includes α_f (the cable attenuation per Km (dB/Km)), L (cable length (Km)), m (the number of splicing), Ls (the loss per splicing (dB/splice)), n (the number of connectors), Lc (the loss per connector (dB/connector)), and M_S (the system margin).

$$P_T = \alpha_f . L + m. L_s + n. L_c + M_s \quad (1)$$

$$P_R = P_S + P_T \quad (2)$$

In Equation (2), the calculation parameters used are P_T, namely the total optical power loss (dB); P_S, i.e., Power Source or transmit power (dBm); and P_R, i.e., Received power (dBm).

D. Rise Time Budget Calculation

The rise time budget analysis is a parameter to determine the total time required by the optical system from the initial conditions to the steady-state [12]. Equation (3) is a formula to calculate the Rise Time Group Velocity Dispersion (t_{GVD}), where D is Chromatic Dispersion (ps/nm.km); L is the cable length (Km), and $\alpha\lambda$ is the Spectral Width (nm). Equation (4) is a formula to calculate the Total Rise Time ($tsys$), where the calculation component consists of the rise time transmitter (t_{tx}), rise time receiver (t_{rx}), Rise Time Group Velocity Dispersion (t_{GVD}). Equation (5) is a formula to calculate the maximum rise time dispersion (t_{Max_sys}).

$$t_{GVD} = D. L. \alpha\lambda \quad (3)$$

$$t_{sys} = \sqrt{t_{tx}^2 + t_{GVD}^2 + t_{rx}^2} \quad (4)$$

$$t_{Max\_sys} = \frac{70\% \ (NRZ)}{Data\ rate\ (bps)} \quad (5)$$

E. Bit Error Rate Calculation

BER analysis is a parameter to determine the number of bit errors that occur at the receiving end of each amount of bits of data sent in a specific time interval [13][14]. The smaller the BER value in a system, the better the system performance. We can obtain BER by using Q-factors derived from the Signal to Noise Ratio (SNR) calculated by Equation (6). Like BER, SNR is one of the parameters used to determine the performance of a receiver. SNR is used to determine the ratio of the received signal to noise in the system.

$$SNR = \frac{Signal\ Power}{Noise\ Power} \quad (6)$$

Signal power is the amount of signal power received at the receiver. Equation (7) is an equation to calculate the magnitude of the SNR. The SNR variables are PR (the receiving power (W)), η (the receiver efficiency (%)), q (the magnitude of the electron charge (1.6 x 10^{-19} C)), h (the Plank constant (6.626 x 10^{-34} Js)), v (the frequency (Hz)), and M (the gain of the APD (Avalanche Photodiode).

$$SNR = \frac{Signal\ Power}{Noise\ Power} \quad (7)$$

While noise power is the amount of noise in the system that is thermal noise (Thermal), dark current noise (N_{dc}), and shot noise (N_{shot}). Equation (8) is the Equation to calculate the amount of noise power in the system.

$$Noise\ power = N_{thermal} + N_{dc} + N_{short} \quad (8)$$

The following equations (9), (10), and (11) are used to calculate the amount of thermal noise, dark current noise, and shot noise in the system. T_{eff} is the effective noise temperature (K), k is Boltzman's constant (1.38 x 10^{-23} Joules/k), B is the optical fiber bandwidth, R is equivalent resistance (ohms), I_D is dark current (A), F (M) is a noise figure.

$$N_{thermal} = \frac{4kT_{eff}B}{R} \quad (9)$$

$$N_{dc} = 2qI_DB \quad (10)$$

$$N_{short} = 2q(2P_{opt}\frac{\eta q}{hv}BM^2F(M)) \quad (11)$$

Q-factor can be used to show the minimum SNR ratio needed to get a specific BER. Q-factor is a function of OSNR (Optical SNR). Equations (12) and (13) are representations of the relationship between SNR, Q-factor, and BER. Q is the magnitude of Q-factor, P_e is probability error.

$$SNR = 20 \log 2Q \quad (12)$$

$$BER = Pe(Q) = \frac{1}{\sqrt{2\pi}} \frac{e^{-\frac{Q^2}{2}}}{Q} \quad (13)$$

III. Results and Discussion

A. Link Power Budget Results

Power link budget analysis is the first considered parameter conducted by calculating the number of losses of total optical power using equations (1) and (2). Table 3 below shows the results of the calculation of total optical power losses on each route from Bojonegoro Station to Surabaya Pasar Turi Station.

Based on Table 3, it shows that the highest total optical power losses are 21.89 dB, which is on the 10^{th} route or the link from Duduk Station to Sumlaran Station. This condition happens because this route has the farthest distance compared to other paths, which is 24.49 km. The smallest total optical power losses occur on the link from Surabaya Pasar Turi Station to Tandes Station. With a cable length of 5.51 km, the total optical power losses generated are 17.56 dB.

TABLE III. CALCULATION OF TOTAL OPTICAL POWER LOSSES

Route	Cable loss (dB)	Connection loss (dB)	Connector loss (dB)	System Margin	Total of optical power losses
	Attenuation 0.175 dB/km	Attenuation @ 0.2 dB	Attenuation @ 2 dB	8 dB	P_T dB
1	2.60	1.00	8	8	19.60
2	1.14	0.60	8	8	17.74
3	3.89	1.40	8	8	21.29
4	3.70	1.40	8	8	21.10
5	2.08	0.80	8	8	18.88
6	2.76	1.00	8	8	19.76
7	3.18	1.20	8	8	20.38
8	2.03	0.80	8	8	18.83
9	3.97	1.40	8	8	21.37
10	4.29	1.60	8	8	21.89
11	1.91	0.80	8	8	18.71
12	2.76	1.00	8	8	19.76
13	1.59	0.80	8	8	18.39
14	1.57	0.80	8	8	18.37
15	0.96	0.60	8	8	17.56

TABLE IV. CALCULATION OF POWER LINK BUDGET, COMPARISON, AND ANALYSIS WITH SENSITIVITY VALUES

Route	Total of Optical Power *Loss*	Transmit Power	Received Power	Sensitivity (dBm)	Link Condition
	P_T (dB)	P_S (dBm)	P_R (dBm)		Feasible or not
1	19.60	4	-15.60	-24	OK
2	17.74	4	-13.74	-24	OK
3	21.29	4	-17.29	-24	OK
4	21.10	4	-17.10	-24	OK
5	18.88	4	-14.88	-24	OK
6	19.76	4	-15.76	-24	OK
7	20.38	4	-16.38	-24	OK
8	18.83	4	-14.83	-24	OK
9	21.37	4	-17.37	-24	OK
10	21.89	4	-17.89	-24	OK
11	18.71	4	-14.71	-24	OK
12	19.76	4	-15.76	-24	OK
13	18.39	4	-14.39	-24	OK
14	18.37	4	-14.37	-24	OK
15	17.56	4	-13.56	-24	OK

By using a four dBm transmit power, and the results of the calculation of the total optical power losses in Table 3, the received power is obtained on each route. The sensitivity value of the transceiver device is -24 dBm. The analysis is comparing the amount of receptivity (P_R) with receiver sensitivity. If the value of the P_R is higher than the receiver's sensitivity value of the device, then the link is appropriate to use. Based on Table 4, it shows that the amount of the received power from all-optical links is between -13.56 dBm (route 15) to -17.89 dBm (10^{th} route). Thus all optical links have a receiving power higher than the sensitivity value of the device, so it indicates that the optical link is suitable for optical communication lines.

B. Rise Time Budget Results

The next considered parameter is the rise time budget calculation observed using equations (3), (4), and (5). Table 5 shows the results of the calculation of total rise time on each route. Based on the estimate of the rise time budget in Table 5, it shows that the link from Duduk Station to Sumlaran Station has the highest total rise time of all paths that is 45.32 ps. In comparison, the link from Surabaya Pasar Turi Station to Tandes Station has the smallest Total Rise Time of 39.91 ps.

In the calculation results of the deployment of Bojonegoro-Surabaya Pasar Turi fiber optic cable crossing, if the value of the Total Rise Time (t_{sys}) is smaller than the maximum rise time dispersion (t_{Max_sys}) value, then the link is feasible to use. The maximum permissible rise time dispersion value is 4501.03 ps. Table 5 shows the results of the rise time budget analysis. It indicates that the amount the Total Rise Time of all-optical links has a value smaller than the maximum value of the rise time dispersion. Therefore, the optical link is suitable for optical communication lines.

TABLE V. CALCULATION OF TOTAL RISE TIME

Route	t_{gvd}	t_{tx}	t_{rx}	t_{sys}
	ps	28 ps	28 ps	ps
1	13.38	28	28	41.80
2	5.86	28	28	40.03
3	19.98	28	28	44.35
4	19.05	28	28	43.94
5	10.70	28	28	41.02
6	14.18	28	28	42.06
7	16.33	28	28	42.83
8	10.43	28	28	40.95
9	20.40	28	28	44.55
10	22.04	28	28	45.32
11	9.81	28	28	40.79
12	14.18	28	28	42.06
13	8.16	28	28	40.43
14	8.06	28	28	40.41
15	4.96	28	28	39.91

TABLE VI. CALCULATION OF THE RISE TIME BUDGET, COMPARISON, AND ANALYSIS WITH THE MAXIMUM VALUE OF THE RISE TIME DISPERSION

Route	t_{sys} (ps)	t_{max_sys} (ps)	Link Condition
		NRZ 155.52 Mbps	Feasible or not
1	41.80	4501.03	OK
2	40.03	4501.03	OK
3	44.35	4501.03	OK
4	43.94	4501.03	OK
5	41.02	4501.03	OK
6	42.06	4501.03	OK
7	42.83	4501.03	OK
8	40.95	4501.03	OK
9	44.55	4501.03	OK
10	45.32	4501.03	OK
11	40.79	4501.03	OK
12	42.06	4501.03	OK
13	40.43	4501.03	OK
14	40.41	4501.03	OK
15	39.91	4501.03	OK

C. Bit Error Rate Results

Based on the results of the power link budget analysis in Table 4, it shows that the received power in this design ranges from -13.56 ~ -17.89 dBm. This value range is the numbers for the calculation of SNR and BER. The considered calculated received power is -17.89 dBm, or the lowest acceptability of the design to find out the highest BER from the plan.

Table 7 shows the results of the BER calculation from deploying fiber optic cable across Bojonegoro-Surabaya Pasar Turi. In the BER calculation results in Table 7, it shows a BER of 2.31×10^{-13} obtained with an SNR of 3145.33 Watt or 34.97 dBW, and Q-factor 7.49. By following Table 7, the desired system BER is 10^{-12}. Thus the highest BER obtained is still smaller than the BER to be achieved so that the design of this system meets the requirements.

TABLE VII. BER CALCULATION RESULTS

Specification	Value	Unit
Received Power (P_R)	-17.89	dB
Signal Power	1.39×10^{-08}	Watt
N_darkcurrent	1.92×10^{-17}	A
N_thermal	3.25×10^{-12}	A
N_short	1.17×10^{-12}	A
N_power	4.43×10^{-12}	A
SNR System	3145.33	Watt
	34.98	dBW
Q	7.49	
BER System	2.32×10^{-13}	

IV. CONCLUSIONS

The design and analysis of the deployment of optical fiber networks have been carried out for Railway in Indonesia by taking a case study on the Bojonegoro Station line to Surabaya Pasar Turi Station. The proposed fiber-optic network design has a total bandwidth of 1 x STM-1 (63xE1), which is for signaling (2xE1) and telecommunications (2xE1) in the Railway system for each station, and it is 3xE1 for backup. The Bojonegoro cross-fiber optic network - Surabaya Pasar Turi was designed by jumping over one station in front of it to maintain system reliability. Calculation of power link budget, rise time budget, and BER for each station, shows that the link condition meets the parameters so that it is feasible for implementation. For the power link budget, the receiving power ranges from -13.5 ~ -17.89 dB, with a receiver sensitivity of -24 dB. For the rise time budget, t_{sys} at each station ranges from 39.91 ~ 44.55 ps with t_{max_sys} 4501.03 ps. As for BER, the results obtained were 2.31×10^{-13}. Based on the results and analysis of the design, the proposed network design can guarantee that the entire signaling and telecommunications equipment system will function properly.

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