

Link Budget Planning and Modulation Performance Evaluation of a 1550 nm Terrestrial FSO Network for Intra-Office Scenarios

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Abstract- This study presents a link budget planning analysis and performance evaluation of a Free-Space Optical (FSO) communication system for short distances in an intra-office scenario. A geometry-based link budget analysis is applied to model key parameters, including beam divergence, receiver aperture, and link margin over distances ranging from 10 to 500 meters. The link budget analysis is conducted under clear-sky conditions to establish a baseline performance for the proposed intra-office FSO deployment. Furthermore, the bit error rate (BER) performance is evaluated across different signal-to-noise ratio (SNR) levels for OOK, BPSK, and QPSK modulation formats. The modulation schemes are compared based on the required SNR to achieve a target BER, the corresponding received optical power, and the maximum achievable transmission distance under identical system parameters. The results confirm the feasibility of achieving data rates up to 1 Gbps for intra-office FSO links and demonstrate that higher-order modulation schemes, particularly QPSK, provide longer transmission distances and improved power efficiency compared with OOK.

Keywords: Data rate, Free Space Optic, Link budget, Modulation, SNR.

Abstrak- Penelitian ini menyajikan analisis perencanaan link budget dan evaluasi kinerja sistem komunikasi Free-Space Optical (FSO) untuk komunikasi jarak pendek pada skenario intra-office. Analisis link budget berbasis geometri diterapkan untuk memodelkan parameter-parameter yang meliputi beam divergence, aperture penerima, dan link margin pada jarak yang berkisar antara 10 hingga 500 meter. Analisis link budget dilakukan dengan skenario clear-sky untuk membangun kinerja dasar bagi implementasi FSO intra-office yang diusulkan. Selanjutnya, performa bit error rate (BER) dievaluasi pada berbagai tingkat Signal-to-Noise Ratio (SNR) untuk skema modulasi OOK, BPSK, dan QPSK. Perbandingan antar skema modulasi dilakukan berdasarkan kebutuhan SNR untuk mencapai BER target, daya optik yang diterima, serta jarak transmisi maksimum yang dapat dicapai pada parameter sistem yang identik. Hasil penelitian menunjukkan bahwa sistem FSO yang diusulkan layak mengonfirmasi kelayakan pencapaian data rate hingga 1 Gbps pada komunikasi intra-office. Selain itu, hasil evaluasi menunjukkan bahwa skema modulasi orde yang lebih tinggi, khususnya QPSK, mampu memberikan jarak transmisi yang lebih jauh serta efisiensi daya yang lebih baik dibandingkan dengan OOK.

Kata Kunci: Data rate, Free Space Optic, Link budget, Modulasi, SNR

1. Introduction

Free Space Optic (FSO) technology has emerged as a compelling solution for modern connectivity needs due to its numerous advantages and offers a complement to traditional radio frequency (RF) and fiber optic systems. As a line-of-sight technology that transmits data through the atmosphere using modulated laser beams, FSO effectively bridges the gap where physical cabling is impractical. FSO serves a cost-effective alternative that eliminates the need for extensive groundwork and trenching, making it ideal for rapid-deployment scenarios and temporary setups. Furthermore, FSO is inherently

resilient to electromagnetic interference, ensuring stable, high-speed performance even in urban environments saturated with high RF noise.

A comprehensive review of next-generation FSO network was conducted by [1], where recent developments in both of single beam and multiple beams were discussed. Generally, FSO use cases are classified into terrestrial and outer space communications categories [2]. A study in [3] reviewed the link budget analysis in conditions of severe turbulence. The link budget and performance analysis of FSO communication



under various atmospheric effects at short distances (under 1 km) was reviewed by [4].

A wide range of applications for FSO systems was comprehensively discussed by [5]. Regarding performance, each modulation technique offers a unique set of advantages and disadvantages. Consequently, extensive studies comparing the resilience of various modulation schemes under both clear-air and turbulent atmospheric conditions were reviewed by [6] through [11].

The implementation of an Erbium-Doped Fiber Amplifier (EDFA) at the receiver stage of FSO systems offers substantial advantages, particularly in mitigating atmospheric attenuation and enhancing the SNR. A study by [12] demonstrates that by incorporating a single high-power EDFA, a single Broadband Light Source (BLS) can be effectively utilized for bidirectional transmission. This architectural approach delivers a more cost-effective and significantly less complex solution compared to traditional configurations that rely on multiple individual laser sources. In addition, placing an Avalanche Photodiode (APD) after the EDFA can further enhance receiver sensitivity; a study by [13] proves that the internal photoelectric gain of the APD provides an approximate 10 dB sensitivity advantage over conventional PIN detectors. In the Indonesian regulatory context, the technical requirements for FSO systems are governed by Keputusan Menteri Komunikasi dan Digital Nomor 43 Tahun 2025, which mandates specific safety and performance standards for all FSO equipment deployed nationally [14].

Although FSO technology has been widely studied for terrestrial communication systems, a systematic planning framework for its implementation at Politeknik Negeri Jakarta (PNJ) has not previously been reported. This study presents the first analytical planning of a terrestrial FSO network for the PNJ campus by evaluating the feasibility of inter-building FSO links through geometry-based link budget analysis and modulation performance evaluation. The proposed planning is intended to serve as the baseline planning framework for future FSO deployment at PNJ and serves as the initial stage of a long-term research roadmap involving the implementation stage and experimental validation. The proposed FSO link scenario in PNJ campus is designed to connect the Telecommunication Engineering Laboratory, the Electrical Engineering Department Classroom (D-Building), and the Electrical Laboratory over distances ranging from 10 to 500 meters. The selected distance range corresponds to the separation between the candidate buildings for the proposed FSO deployment at the PNJ campus.

2. Method

Figure 1 presents the research flow of the proposed FSO link budget analysis. The study starts by defining the system parameters, followed by geometry and link budget calculations to determine the received optical power and link margin. The obtained results are then used to

evaluate the BER performance as a function of SNR for OOK, BPSK, and QPSK modulation schemes. The selected modulation schemes represent the most commonly employed techniques in FSO communication systems. OOK (including NRZ-OOK and RZ-OOK) was selected as the benchmark direct detection scheme due to its implementation simplicity and widespread practical adoption [6]. BPSK [10] and QPSK were selected as representative coherent modulation schemes because they provide improved noise tolerance. This selection enables a meaningful comparison between low-complexity and higher-performance modulation techniques while maintaining the scope appropriate for an initial feasibility study. Finally, the performance of each modulation technique is analyzed to assess the feasibility of a 1550 nm terrestrial FSO link for intra-office applications.

The operating wavelength of 1550 nm was selected because it exhibits a very low specific molecular absorption (approximately 0.01 dB/km), resulting in lower molecular attenuation than shorter wavelengths such as 780 nm and 850 nm under clear-air conditions [15]. In addition, 1550 nm offers improved eye safety and compatibility with mature optical communication technologies, including EDFA-based amplification and commercially available fiber-optic components [16].

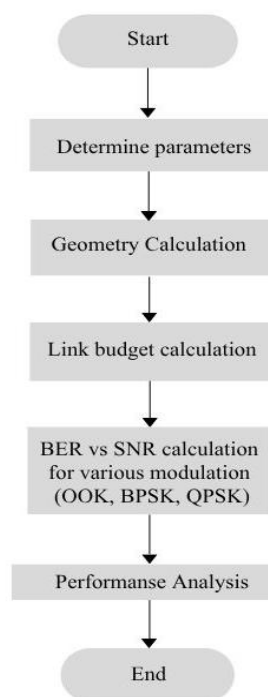


Figure 1. Research Methodology Flowchart

Figure 2 illustrates the proposed intra-office FSO network scenario used for the link budget analysis. The figure depicts an FSO network designed to interconnect the three buildings described earlier. Although this study focuses on a limited deployment scenario, the proposed architecture is scalable and can be extended to larger deployments. The link budget analysis is conducted under

clear-air atmospheric conditions. Therefore, the presented architecture under clear-air conditions serves as the baseline for future expansion of the FSO network at PNJ.



Figure 2. Illustration of Intra-Office FSO Link Scenario

Tabel 1. Parameter of FSO System

Parameters	Value	Unit
MFD	0.0073	mm
Focal length (f)	150	mm
Wavelength (λ)	1550	nm
Power transmits (P_t)	14	dBm
Divergence angle (θ)	48.7	μ rad
Transmitter efficiency (τ_t)	90	%
Receiver efficiency (τ_r)	90	%
Data rate (R_b)	1	Gbps
Temperature (T_{eff})	298	K
Responsivity of APD (R_{APD})	0.9	A/W
Sensitivity (S)	-45	dBm
Distance (l)	10-500	meters

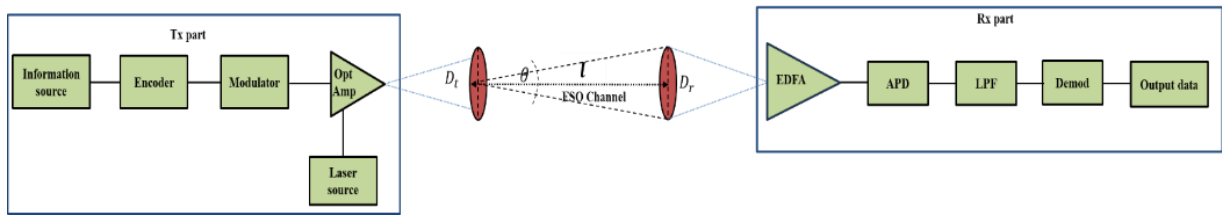


Figure 3. FSO Communications Block Diagram

The system parameters used in this study are summarized in Table 1. The parameters listed were selected based on design requirements for a short-range terrestrial FSO system and representative specifications reported in the literature [6], [17] and commercially available FSO devices. Furthermore, the proposed system configuration is consistent with the deployment characteristics specified in the Indonesian technical standard [14].

The complete block diagram of the proposed FSO transceiver architecture is illustrated in Figure 3. The system is structurally divided into three primary segments, the transmitter stage (Tx), which utilizes an encoder, a modulator, and an optical amplifier; the terrestrial FSO channel, which is subject to geometric, and the receiver stage (Rx), which utilizes a sequential EDFA pre-amplifier and Avalanche Photodiode (APD) configuration to maximize system sensitivity.

The modulation techniques employed include both OOK variants, namely NRZ-OOK and RZ-OOK. The effectiveness of an FSO receiver's signal is inherently influenced by atmospheric conditions, which are shaped by various natural factors within the FSO channel. To quantify this effect, the received optical power

(P_r [dBm]) of the FSO link [18] can be calculated as equation 1 follows:

$$P_r = P_t \cdot (D_r / \theta \cdot l)^2 \cdot 10^{-\gamma l / 10} \cdot \tau_t \cdot \tau_r$$

$$\theta = \left(\frac{MFD}{f} \right) \cdot \left(\frac{180}{\pi} \right)$$

Beam divergence plays a critical role in both transmitter-receiver alignment and the tracking accuracy of the receiver system. Meanwhile, the Mode Field Diameter (MFD) characterizes the spatial distribution of light within the fiber and is inherently linked to the physical core diameter. The receiver and transmitter apertures are of the same size ($D_r = D_t$). The mathematical formulation for calculating the transmitter aperture is presented in equation 2.

$$D_t = 4 \cdot \lambda \left(\frac{f}{\pi \cdot MFD} \right)$$

The link margin (L_M [dB]) quantifies the difference between the power received at the receiver and receiver's

sensitivity to maintain a specific Bit Error Rate (BER) for a given data rate, it can be calculated as equation 3:

$$L_M = \left(\frac{P_r}{S} \right)$$

To assess a direct detection receiver's performance, the output signal-to-noise ratio (SNR) is calculated as the ratio of detector's signal power to the total noise power. In most practical scenarios, a strong received signal power ensures that the signal photocurrent is much greater than both the dark current and background illumination noise. Consequently, shot noise N_s typically becomes the predominant noise source can be calculated as equation 4, N_{th} is the thermal noise presented in equation 5, and N_T in equation 6 represents the total noise power :

$$N_s = \sqrt{2 \cdot q \cdot I \cdot B}$$

$$N_{th} = \sqrt{\frac{4 \cdot k_b \cdot T_{eff} \cdot B}{R_L}}$$

$$N_T = \sqrt{(N_{th})^2 + (N_s)^2}$$

In these formulations, B is the signal bandwidth (for OOK and BPSK, $B = R_b$ and for QPSK, $B = R_b/2$), q is the unit of electron value $1.602 \times 10^{-19} C$, R_L is load resistor with typically value 50Ω , k_b is boltzman constant (1.38×10^{-23}), and T_{eff} is the temperature value within the APD.

The SNR of the photodetector is obtained using equation 7, where the average current (I) received at the APD is determined by equation 8 within the P_r is derived from equation 1.

$$SNR = \frac{I^2}{N_T^2}$$

$$I = R_{APD} \cdot P_R$$

The most relevant modulation with direct detection and extensively employed in FSO communication systems primarily due to its inherent simplicity and cost-effectiveness in implementation is OOK. Performance of NRZ-OOK and RZ-OOK modulation in different wavelengths has been reviewed by [7] and [9]. In this research, we compare the performance of OOK NRZ & RZ with BPSK and QPSK. BER of each modulation scheme can be calculated by equations 9 to 12 below:

$$BER_{NRZ-OOK} = \frac{1}{2} \operatorname{erf} \left(\frac{1}{\sqrt{2}} \sqrt{SNR} \right)$$

$$BER_{RZ-OOK} = \frac{1}{2} \operatorname{erf} \left(\frac{1}{\sqrt{2}} \sqrt{SNR} \right)$$

$$BER_{BPSK} = \frac{1}{2} \operatorname{erf}(\sqrt{SNR})$$

$$BER_{QPSK} = \operatorname{erf}(\sqrt{SNR})$$

3. Results and Discussion

The calculated link budget planning analysis results for the intra-office FSO network at Politeknik Negeri Jakarta under clear-air based conditions based on geometry are presented in Table 2. The results indicate that the system maintains a very high received power and large link margin at short distances because atmospheric attenuation is negligible ($\gamma=0$) for clear-air in short range based on ITU report ITU-R P.1814-1 [19] and the beam divergence angle is very small. This demonstrates that the proposed 1550 nm FSO system can operate very reliably in short-range intra-office scenarios under clear atmospheric conditions.

As the transmission distance increases, the received power gradually decreases due to geometric beam spreading, which consequently reduces the link margin. However, the obtained link margins remain sufficiently high even at distances up to 500 m, confirming the feasibility of the proposed FSO link for high-speed short-range communications. The obtained results are directly influenced by the transmitter power and receiver sensitivity because both parameters determine the available link margin. Increasing the transmitter power or improving the receiver sensitivity enhances the available margin, thereby extending the maximum achievable transmission distance. Conversely, reducing the transmitter power or using a receiver with lower sensitivity would decrease the link margin and shorten the maximum feasible communication distance. Despite these dependencies, the proposed analytical framework remains applicable because the link budget can be readily recalculated for different transmitter and receiver specifications.

Table 2 Link Budget Results

Distances (m)	Loss [dB]	P_r [dBm]	L_M [dB]
10	0.67	13.33	58.33
50	14.65	-0.65	44.35
100	20.67	-6.67	38.33
200	26.69	-12.69	32.31
300	30.21	-16.21	28.79
400	32.71	-18.71	26.29
500	34.65	-20.65	24.35

Table 3 Performance of RZ-OOK



BER	RZ-OOK		
	SNR [dB]	P_r [dBm]	l [m]
10^{-3}	6.79	-31.4	462
10^{-6}	10.53	-27.6	371
10^{-9}	12.55	-25.5	324
10^{-12}	13.93	-24.1	295

Table 4 Performance of NRZ-OOK

BER	NRZ-OOK		
	SNR [dB]	P_r [dBm]	l [m]
10^{-3}	12.81	-25.3	318
10^{-6}	16.55	-21.6	247
10^{-9}	18.57	-19.5	214
10^{-12}	19.95	-18.1	192

Table 5 Performance of BPSK

BER	BPSK		
	SNR [dB]	P_r [dBm]	l [m]
10^{-3}	3.39	-34.8	592
10^{-6}	7.13	-31.1	474
10^{-9}	9.15	-29	408
10^{-12}	10.53	-27.6	371

Table 6 Performance of QPSK

BER	QPSK		
	SNR [dB]	P_r [dBm]	l [m]
10^{-3}	0.38	-37.8	731
10^{-6}	4.12	-34.1	575
10^{-9}	6.14	-32	505
10^{-12}	7.52	-30.6	456

The results presented in Tables 3 to 6 show that QPSK provides the best transmission performance among all evaluated modulation schemes. QPSK requires the lowest SNR and received power to achieve a given BER target, resulting in the longest achievable transmission distance. Conversely, NRZ-OOK requires the highest SNR and exhibits the shortest transmission range because it requires the highest received optical power to satisfy the same BER requirement. The results indicate that QPSK provides approximately 30–40% longer transmission distance than both NRZ-OOK and RZ-OOK. This improvement can be explained theoretically by the BER characteristics of coherent modulation. For a given BER target, QPSK requires a lower SNR than OOK because its coherent detection process provides better noise immunity. Since the received SNR is proportional to the square of the

received optical power, a lower required SNR directly translates into a lower minimum received power. Consequently, the communication link can tolerate greater propagation loss before reaching the BER threshold, thereby extending the maximum achievable transmission distance. These results indicate that coherent modulation schemes such as BPSK and QPSK are more suitable for long-range high-speed FSO communication systems operating at 1550 nm.

4. Conclusion

This study investigates the performance of a high-speed FSO communication system designed for an intra-office link scenario. A geometry-based analytical approach was employed to evaluate the link budget over transmission distances from 10 to 500 m under clear-sky conditions. The performance evaluation demonstrated that coherent modulation schemes, particularly QPSK, provide longer transmission distances and higher power efficiency than OOK modulation formats. The main scientific contribution of this work is the development of the first analytical planning framework for a terrestrial FSO network at PNJ, integrating geometry-based link budget analysis with modulation performance evaluation to establish a baseline for a long-term FSO research roadmap and future large scale deployment. The current study is limited to analytical evaluation and has not yet been validated through hardware experiments or dedicated optical communication simulation tools. Future work will therefore focus on evaluating system performance under various atmospheric conditions, including simulation-based validation. In addition, other modulation scheme will be investigated to further optimize system performance before extending the proposed architecture to larger-scale FSO network deployments at PNJ.

5. References

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