CHAPTER I

INTRODUCTION

1.1. Background

Despite notable progress in global connectivity, where 5.5 billion people, or roughly 68% of the world's population, were online in 2024, approximately 2.6 billion individuals remain offline. Of these, around 1.8 billion reside in rural areas, highlighting that most of the unconnected population live in geographically isolated or economically disadvantaged regions. This enduring digital divide poses a serious obstacle to equitable access to education, healthcare, governance, and economic participation, making the expansion of reliable internet infrastructure in rural and remote areas an urgent global development imperative[1].

In developing countries such as Indonesia, expanding internet access to rural areas presents multifaceted challenges rooted in geographic, economic, and demographic constraints. The nation's archipelagic topography consisting of over 17,000 islands with mountainous and forested interiors renders the deployment of telecommunication infrastructure logistically difficult and financially demanding. These physical barriers are compounded by socio-economic conditions in rural areas, which often exhibit low population densities and limited household incomes. Such characteristics diminish the commercial appeal for private telecommunication operators to invest in high-capex infrastructures like fiber optic backbones or fixed broadband services [2].

Furthermore, national survey data underscores this disparity. According to the 2024 Internet Penetration Survey by APJII, internet penetration in urban areas reached 82.18%, while in rural areas it lagged at 74.00%, with urban regions contributing 69.49% of all internet users compared to only 30.51% from rural regions [3]. This digital gap illustrates not only infrastructural and economic disparity but also a continued marginalization of rural communities in Indonesia's digital landscape. Consequently, without targeted policy and hybrid infrastructure approaches, rural regions are likely to remain underserved and excluded from the broader benefits of digital inclusion.

The challenges of rural network expansion in Indonesia extend far beyond economic feasibility, delving into the realm of physical infrastructure limitations. High capital expenditure, lack of electricity reliability, and difficult terrain collectively obstruct the deployment of conventional broadband systems particularly fiber optic networks that depend on extensive ground infrastructure. Fiber installation necessitates physical access for cable trenching, pole construction, and long-term maintenance. In rural and mountainous areas, such undertakings are often impractical or prohibitively expensive due to uneven topography, landslide-prone slopes, and the absence of paved access routes [2].

Moreover, the APJII 2024 survey confirms that the lowest internet penetration rates are often found in areas with limited electrification and road connectivity, such as parts of Eastern Indonesia and the interior of Sulawesi and Nusa Tenggara. These regions frequently lack not only digital infrastructure, but also essential utilities like consistent electricity an indispensable requirement for powering routers, modems, and network equipment [3]. As noted by the OECD, these dual barriers geographic and infrastructural constitute a major deterrent for commercial operators to invest in rural broadband, reinforcing the need for terrain-resilient and energy-efficient alternatives [2].

Given these persistent bottlenecks, it becomes evident that wireline technologies alone such as fixed broadband and fiber optics are insufficient in meeting Indonesia’s universal connectivity goals. Instead, tailored hybrid approaches incorporating wireless technologies that require minimal civil works are increasingly vital to bridge the urban-rural digital divide.

Dalisodo Village is one of twelve administrative villages located within the Wagir District of Malang Regency, East Java Province. Situated on the western slopes of Mount Kawi, the village lies at an elevation ranging from 375 to 2,293 meters above sea level and is characterized by a hilly terrain dominated by moderate to steep slopes, as well as volcanic geological formations that are prone to weathering[4] . These geographical features place Dalisodo in a high landslide susceptibility zone, as evidenced by spatial mapping using Geographic Information Systems (GIS), which indicates that most of the village falls under medium to high risk categories [4]. This complex topography not only increases the risk of natural disasters but also presents significant barriers to the development of essential infrastructure, including telecommunications networks.

Figure 1. 1 Map of Dalisodo Village

Figure 1.1 illustrates the geographic location of Dalisodo Village, which serves as the study area for this project. Demographically, Dalisodo is home to more than five thousand residents, the majority of whom work as farmers, informal labourers, and micro-entrepreneurs. With a mid-sized population for a rural setting, the demand for internet access is considerable, driven by the growing need for digital communication, education, and economic activity. However, the village's challenging geography has contributed to persistent digital isolation. A notable example of this is the postponement of a fiber optic network deployment project by an internet service provider.

The initiative was delayed due to the high projected costs of construction and maintenance, which were deemed disproportionate to the potential return on investment given the village's low population density and limited physical accessibility. Considering the combination of difficult terrain, disaster vulnerability, infrastructure limitations, and the rising demand for connectivity, Dalisodo serves as a concrete example of the challenges faced in expanding internet access in Indonesia's rural areas. These factors make Dalisodo a relevant and representative case study for assessing the feasibility of alternative connectivity solutions that are more compatible with its geographic and socio-economic context.

Free Space Optics (FSO) represents a compelling technology for broadband transmission in regions where conventional infrastructure is difficult or economically unviable to deploy. By transmitting data through modulated light beams across free space, FSO systems emulate the performance of optical fiber networks without the need for buried cables. This feature is particularly advantageous in rugged or elevated terrains, as it reduces the need for invasive and capital-intensive civil works [5]. FSO offers high bandwidth capacity, low latency, and minimal power consumption, making it both an energy-efficient and cost-effective solution for moderate-distance applications [6]. However, FSO links are highly susceptible to atmospheric conditions particularly fog and dense particulate matter which can significantly degrade signal quality [7]. In rural highland regions such as Dalisodo, where infrastructure deployment is severely hindered by topographical and economic constraints, FSO offers an attractive "wireless fiber" alternative, although its performance remains closely tied to environmental clarity.

To address the inherent weather-dependence of FSO systems, hybrid architectures integrating Radio Frequency (RF) or Microwave links have emerged as a robust solution for maintaining connectivity during adverse environmental conditions. Unlike FSO, RF/Microwave systems are less affected by visibility impairments and can maintain stable performance under rain, dust, or fog [8]. These technologies operate over complementary physical principles while FSO offers high-speed transmission, RF provides reliability and broader coverage, particularly in non-line-of-sight scenarios [9]. By employing a dynamic switching mechanism between FSO and RF/Microwave channels, hybrid systems can ensure continuous network availability, automatically redirecting traffic through the more stable medium when atmospheric disruptions arise[10]. This approach is highly relevant for geographically isolated communities like Dalisodo, where weather fluctuations are frequent and infrastructural rigidity is not feasible, making link adaptability essential for reliable service delivery.

As the imperative to extend internet access into rural regions intensifies, alternative solutions beyond FSO have gained prominence, particularly satellite communications via LEO constellations, which offer broad coverage with minimal ground-segment requirements. However, the high cost of user terminals and subscription fees hampers deployment in low-income communities [11]. Moreover, geostationary satellites suffer from significant latency and are highly vulnerable to atmospheric disturbances, making them unsuitable for real-time applications such as e-learning and telemedicine [12]. Dependence on foreign operators for ground station infrastructure and spectrum licensing further introduces risks to national digital sovereignty [12].

While satellite constellations generally provide extensive coverage, insufficient local infrastructure such as reliable power supply and gateway equipment often creates technical bottlenecks in rural implementations [13]. Moreover, satellite services, despite their potential to bridge the digital divide, remain economically unviable for low-income rural communities without substantial government subsidies [14]. Even with ongoing improvements in capacity and coverage, satellite technology is still regarded as a last-resort solution due to its high costs, vulnerability to atmospheric disturbances, and limited practicality in remote, underserved areas [15]. Consequently, alternative solutions like Free Space Optics (FSO), which offer low latency, lower operational expenses, and the ability to deploy locally without dependence on foreign-controlled infrastructure, are becoming increasingly pertinent.

Free Space Optics (FSO) has gained traction as a promising solution for Internet deployment in rural regions of developing countries due to its low installation cost, high bandwidth capacity, and rapid deployment without the need for underground cabling advantages particularly relevant in mountainous or hard-to-reach areas such as Dalisodo [16]. FSO is recognized as one of the most cost-effective options for environments with limited fiscal resources and infrastructure constraints [16], and it can bypass right-of-way issues and accelerate implementation compared to FTTH-based fiber systems, which often face complex regulatory hurdles and high capital requirements [17] . In addition, FSO is energy-efficient and capable of delivering high data throughput, making it especially valuable in rural regions with unreliable power supplies and constrained operational budgets [6]. However, FSO remains highly susceptible to weather-induced impairments such as fog, heavy rain, and dust conditions common in rural highland environments prompting recommendations to hybridize FSO with complementary radio-based technologies to enhance system availability and ensure service continuity [7],[18].

Hybrid Free Space Optics (FSO) and Radio Frequency (RF) communication systems have emerged as promising solutions to address the shortcomings of standalone FSO technologies, particularly in rural regions prone to adverse weather and infrastructural limitations [6][7]. While FSO offers high bandwidth and rapid deployment, it suffers significant signal degradation under low-visibility conditions such as fog, dust, or heavy rain that frequently occur in tropical highland villages like Dalisodo. Hybrid models overcome these challenges by employing optical transmission during clear weather and seamlessly switching to RF during atmospheric disturbances [7], and by combining optical and RF channels such as through wavelength division multiplexing to maintain stable high-speed data transfer even when one link is compromised [6].

Beyond technical robustness, hybrid communication architecture offers greater resilience and feasibility in infrastructure-poor environments [18] . Wireless-based infrastructure planning has been shown to outperform fiber deployments in both cost-effectiveness and deployment speed for rural communities [16], while persistent legal and logistical bottlenecks continue to delay fiber rollouts in sparsely populated regions, making agile, modular hybrid wireless networks a more attractive alternative [17]. Taken together, these findings reinforce that hybrid FSO/RF constitutes not only a viable alternative but also a context-sensitive, scalable solution suitable for Indonesia's rural settings.

Despite these advancements, a critical gap remains in the current body of research: the absence of comprehensive studies integrating both technical performance modelling and economic feasibility assessment of hybrid FSO/RF systems within Indonesia's rural context. Existing work offers valuable insights into signal modulation, fog resilience, and switching logic [6], [7], while broader rural communication studies address deployment challenges and strategic planning [16], [18], and regulatory analyses highlight legal bottlenecks [17]. However, none incorporate cost modelling or sustainability evaluation, simulate operational behavior under environmental variations or terrain constraints, or include empirical weather data, terrain analysis, and infrastructure constraints specific to Indonesian rural environments where unstable electricity, steep topography, and low-income levels often dictate feasibility.

This fragmented approach limits the applicability of existing findings to real deployment in regions like Dalisodo, where a successful solution must balance environmental reliability, technical efficiency, and financial sustainability. Therefore, a localized, interdisciplinary study shows that model's hybrid FSO/RF system performance under region-specific weather patterns and simultaneously evaluates economic viability is urgently needed. Without such an integrative assessment, policy decisions and infrastructure investments risk being based on incomplete or non-replicable frameworks, leading to suboptimal outcomes in rural digital inclusion.

This research aims to design, simulate, and evaluate a hybrid Free Space Optics (FSO) and Microwave communication system as a viable connectivity solution for Dalisodo Village, located in a highland rural region of East Java. The study incorporates localized weather data, terrain characteristics, and technical link parameters to model system performance under real operating conditions. Furthermore, it includes a techno-economic feasibility analysis calculating the Total Cost of Ownership (TCO), Net Present Value (NPV), and operational costs over a multi-year lifecycle to assess long-term viability. By integrating both technical and financial dimensions into a single localized framework, this study addresses an urgent research gap and offers practical insights for decision-makers, ISPs, and rural planners. The outcomes are intended not only to improve digital access in Dalisodo but also to serve as a scalable, replicable reference for similar rural areas across Indonesia, contributing toward the broader national goal of achieving equitable and sustainable internet connectivity.

1.2. Statement of the Problem

Based on the background described above, the following research questions can be formulated:

1. How can Free Space Optics (FSO) be effectively deployed as an alternative to fiber optics in rural highland areas with challenging topography and weather, such as Dalisodo Village?
2. What hybrid architecture between FSO and microwave systems provides optimal network availability, especially under atmospheric disturbances like fog?
3. What are the appropriate configuration standards (e.g., link budget, transmission power) to ensure stable and scalable deployment of FSO-Microwave systems in such environments?
4. How economically feasible is the hybrid FSO-Microwave solution when deployed in rural Indonesian settings, considering local infrastructure?
5. To what extent can empirical weather data, local topographical mapping, and regulatory constraints be integrated into a techno-economic model to guide practical deployment strategies?

1.3. Objective

From the problem statements, the objectives and expected outcomes of this research can be outlined as follows:

1. To design and model a hybrid Free Space Optics (FSO) and Microwave network architecture suitable for deployment in rural highland regions with difficult installation terrain, such as Dalisodo Village in Malang.
2. To determine optimal network configuration parameters including link budget, transmission power, receiver sensitivity, and tower height to ensure stable performance under real-world topographic and atmospheric conditions.
3. To evaluate the technical feasibility of integrating FSO and microwave systems through performance metrics such as data rate, and resilience against atmospheric disturbances.
4. To assess the economic viability of deploying hybrid FSO-Microwave systems as an alternative to fiber optics by considering infrastructure cost, operational challenges, and return on investment in rural Indonesian settings.
5. To provide practical recommendations for policymakers and network operators regarding hybrid network deployment strategies that address the regulatory,

environmental, and financial barriers commonly faced in rural connectivity initiatives.

1.4. Scope of Work

This study is limited to the design, simulation, and techno-economic evaluation of a hybrid Free Space Optics (FSO) and Microwave communication system for rural internet connectivity in Dalisodo Village, Malang Regency, East Java. The scope of the research includes the following:

1. Geographical Focus: The analysis is specifically conducted for Dalisodo Village, considering its topographical features, altitude, and typical weather conditions, especially fog and rainfall patterns.
2. Technological Design: The system is limited to a point-to-point hybrid model integrating FSO as the primary transmission medium and Microwave as a backup link during adverse weather conditions.
3. Technical Evaluation: The technical assessment includes simulation of system performance under different atmospheric scenarios, focusing on link budget and potential disruptions.
4. Economic Analysis: The study estimates installation, operational, and maintenance costs, but does not include direct procurement or field deployment of equipment.
5. Exclusions: The research does not involve real-time testing or physical implementation of the system. It also excludes detailed regulatory or policy analysis and does not assess user behavioral responses or digital literacy aspects.

1.5. Hypothesis

This study hypothesizes that deploying a hybrid Free Space Optics (FSO) and Microwave backhaul system, equipped with a smart switching mechanism governed by a Bit Error Rate (BER) threshold, between Dalisodo Village and STO Klojen will meet the technical performance standards required for rural broadband service. At the same time, the solution is expected to be economically viable, as indicated by a positive Net Present Value (NPV) and an Internal Rate of Return

(IRR) that exceeds the project's discount rate; therefore, it is considered feasible and capable of bridging the digital connectivity gap in rural areas where fibre optic infrastructure remains limited.

1.6. Research Methodology

To systematically assess the techno-economic feasibility of hybrid Free Space Optics (FSO) and Microwave communication systems for rural internet connectivity, this research adopts a structured, multi-stage methodology. The approach integrates scenario-based simulations, environmental modelling, and cost-effectiveness analysis in a sequential and iterative framework. General research stages are illustrated in Figure 1.2.

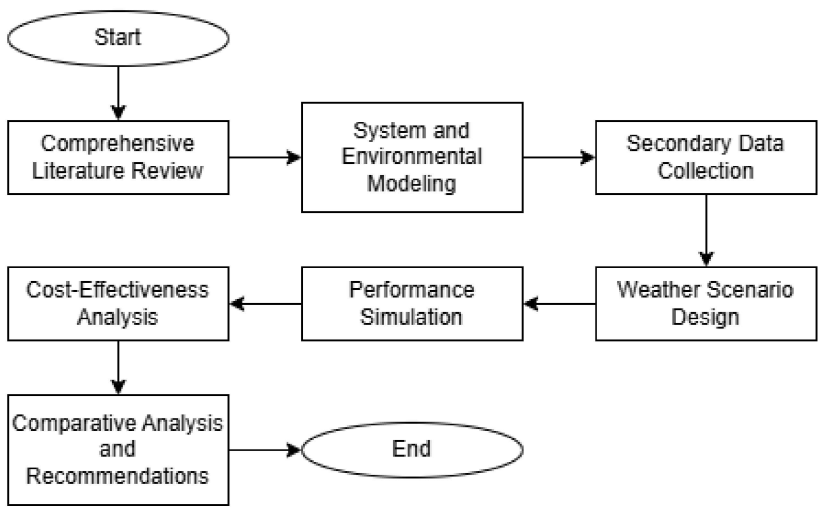

Figure 1. 2 Flowchart of the research methodology for evaluating hybrid FSO/Microwave network feasibility.

As illustrated in Figure 1.2, the research methodology is structured into a systematic flowchart to assess the feasibility of a hybrid FSO/Microwave communication network. The methodological framework comprises four interconnected phases. The first phase involves a comprehensive literature review, which serves to establish a theoretical foundation for both Free Space Optics (FSO) and microwave signal propagation under varying atmospheric conditions. This review synthesizes prior studies on bit-error rate (BER) performance, adaptive switching mechanisms, and techno-economic evaluations within telecommunication infrastructure projects, thereby informing the modelling and simulation stages that follow.

In the second phase, secondary data acquisition and scenario design provide the essential inputs for both technical and economic analyses. Historical meteorological records encompassing rainfall intensity, fog incidence, and temperature variation are obtained alongside equipment specifications supplied by commercial vendors. These data are then used to construct representative weather scenarios that faithfully reflect the climatic patterns observed in Dalisodo Village.

The third phase involves system modelling and performance simulation. Mathematical models of FSO and microwave links are developed to incorporate weather-induced attenuation and signal-propagation behaviour. A dynamic switching algorithm is also implemented to manage transitions between optical and RF channels based on predefined performance thresholds. These models are executed in MATLAB, generating quantitative metrics such as Bit Error Rate under each designed weather scenario.

Finally, the study conducts an economic evaluation and comparative analysis. All capital expenditures including equipment procurement, installation, and permitting are aggregated with operational costs such as maintenance, power consumption, and weather-induced switching overhead, as well as any downtime penalties. This yields a comprehensive cost metric for three network configurations: standalone FSO, standalone microwave, and the hybrid system. By integrating the simulation outcomes with cost-effectiveness results, the final phase identifies the most efficient and scalable architecture for rural highland deployment and offers actionable recommendations for network planners, policymakers, and future research.

1.7. Research Plan

To ensure the research is carried out in a systematic and structured manner, a research plan has been formulated outlining the main stages of activity. These stages include literature review, data collection, proposal writing, methodology development, simulation and modelling, economic feasibility analysis, and preparation for the final seminar. Each activity is arranged to follow logical progression, supporting the integration of technical and economic analysis throughout the research process.

Table 1. 1 Research plan table

No	Activity
1	Literature Review
2	Data Collection
3	Proposal Writing
4	Proposal Seminar
5	Methodology Development
6	Economic Feasibility Analysis
7	Results and Conclusion Analysis
8	Final seminar

This planned structure is intended to support the successful completion of the research, ensuring that each stage is well-integrated and contributes meaningfully to both technical accuracy and economic feasibility outcomes.

CHAPTER 2

LITERATURE REVIEW

2.1. Fundamentals of Wireless and Hybrid FSO/RF Communication

Wireless communication refers to the transmission of information between two or more points without the use of physical connectors or cabling. Instead, it utilizes electromagnetic waves that propagate through the air as the medium of signal transport. Depending on the application, various frequency bands are employed, ranging from low-frequency radio waves to extremely high-frequency optical bands. Wireless systems have become a cornerstone of modern telecommunications, supporting both fixed and mobile infrastructures, including cellular networks, microwave backhauls, satellite links, and emerging free-space optical systems [19].

Among the modern innovations in this domain is Free Space Optics (FSO), a point-to-point communication technology that transmits optical signals using a narrow laser beam through the atmosphere. FSO systems typically operate in the near-infrared spectrum, most commonly at 850 nm or 1550 nm wavelengths. Technology is particularly attractive due to its high bandwidth capacity (up to several Gbps), rapid deployment, license-free operation, and strong immunity to electromagnetic interference. These attributes make FSO an appealing solution for last-mile connectivity, particularly in urban or remote environments where trenching fiber is either economically or geographically prohibitive [20], [21].

However, the reliability of FSO is significantly influenced by atmospheric conditions. Factors such as fog, heavy rain, and dust particles introduce considerable attenuation, which may cause signal degradation or link outages. Optical signals, especially at higher wavelengths, are highly susceptible to Mie and Rayleigh scattering, leading to reduced link availability in adverse weather [20]. In tropical regions such as Indonesia where rainfall intensity and humidity levels are high, these environmental impairments are even more pronounced.

To overcome the weather dependency of FSO systems, researchers and network engineers have proposed the implementation of hybrid FSO/RF systems, which combine the high-speed performance of FSO with the robustness of radio frequency (RF) communication. In such systems, the FSO link functions as the primary communication path under clear or mildly degraded conditions. In contrast, the RF link, often operating in the microwave band (e.g., 18-23 GHz), is placed in standby mode and activated only when the quality of the FSO link falls below a certain threshold typically determined by Bit Error Rate (BER) or Signal-to-Noise Ratio (SNR) indicators [22].

This hybrid configuration effectively utilizes the complementary characteristics of both technologies. While FSO provides high data rates and security under favorable conditions, RF offers greater resilience during inclement weather, albeit at lower throughput and with licensed spectrum requirements. The switching mechanism, commonly referred to as cold standby, ensures seamless traffic migration between FSO and RF paths, thereby preserving service continuity and increasing overall system availability.

In practical deployments, the end-to-end architecture of a hybrid FSO/RF system comprises several key elements: an optical transmitter (laser diode), atmospheric transmission path, repeater or passive relay (if necessary), RF transceiver, and integrated switching controller. This controller dynamically evaluates link quality and executes the switchover process to maintain communication reliability. Such architecture not only enhances fault tolerance but also enables deployment in rural or geographically constrained areas where fiber optics or wired solutions are not feasible.

Ultimately, hybrid FSO/RF systems represent a promising solution for ensuring more availability wireless connectivity especially in environments. Their adaptability and complementary nature make them suitable for addressing last-mile broadband challenges in both urban expansions and remote underserved communities.

2.2. Free Space Optical (FSO) Communication Theory

Free Space Optical (FSO) communication systems utilize modulated optical beams transmitted through free space to enable high-speed, line-of-sight communication. Operating typically in the near-infrared spectrum, primarily at wavelengths of 850 nm and 1550 nm, these systems provide extremely high bandwidth capacities suitable for applications ranging from urban telecommunications infrastructure to remote area connectivity [20]

2.2.1. Transmission Principle

FSO communication transmits optical signals between two fixed points through air, employing laser diodes or LEDs as transmitters and photodetectors as receivers. The primary principle relies on intensity modulation/direct detection (IM/DD). Optical beams are highly directional, necessitating precise alignment between transmitter and receiver to maintain optimal signal quality [1].

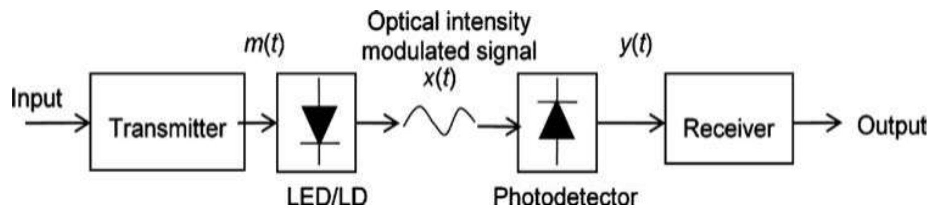

Figure 2. 1 Block diagram of an IM/DD optical wireless communication system [20].

Referring to Figure 2.1, the IM/DD system is comprised of essential modules such as the data encoder, optical transmitter, free-space channel, and photodetector, as commonly implemented in optical wireless communication [20]. On the transmitter side, the information-bearing electrical signal is used to modulate the intensity of the laser light. The optical beam is collimated and expanded using lenses to minimize divergence and then transmitted through the atmosphere. At the receiver end, the incoming beam is focused onto a photodetector (such as a PIN or avalanche photodiode), which converts it back into an electrical signal for further amplification and processing [20].

2.2.2. System Components and Parameters

The configuration of beam propagation and aperture alignment in FSO systems can be better understood by observing the geometrical layout shown in the illustration below.

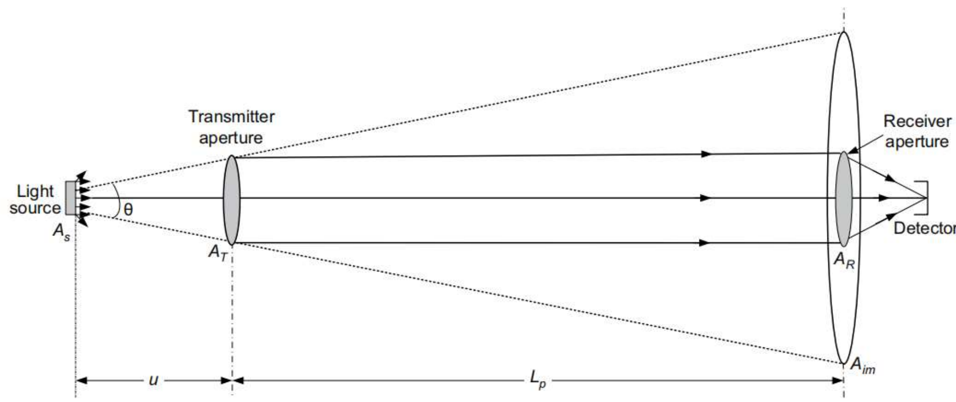

Figure 2. 2 T*ypical FSO link geometry showing divergence and aperture alignment [21]*

Referring to Figure 2.2, the diagram highlights how beam divergence and misalignment can significantly impact the performance of an FSO link, thereby requiring careful design of the optical path [21]. This figure visually depicts the core physical parameters of an FSO system, including divergence angle, optical path length, and aperture dimensions. It helps contextualize the interdependence between beam shaping, propagation, and receiver collection efficiency as described in the following discussion. Each parameter and component in an FSO system contributes to the overall performance, particularly in determining received power and system resilience to environmental impairments.

The transmitter output power, generally measured in decibel-milliwatts (dBm), determines the initial strength of the optical beam emitted. Increased power enhances link range and reliability but requires careful management to ensure eye safety and minimize interference [20]. Beam divergence quantifies the spread of the optical beam over distance, typically measured in milliradians (mrad). Smaller divergence angles focus energy more effectively but increase alignment requirements. The beam diameter at a given distance is expressed as

$$D_{beam} = D_0 + 2\theta d \quad (2.1)$$

Equation (2.1) describes optical beam expansion in a Free-Space Optics (FSO) link, D_{beam} is beam diameter at propagation distance d (m), D_0 is initial beam waist at the transmitter (m), θ is beam divergence angle (radians) and d propagation distance (m) [21]. The receiver aperture diameter significantly impacts the optical power captured. Larger apertures enhance received power but may heighten alignment sensitivity and costs. Receiver efficiency, encompassing photodetector responsivity, optical filters, and lens quality, crucially determines signal conversion effectiveness.

2.2.3. Link Losses and Atmospheric Effects

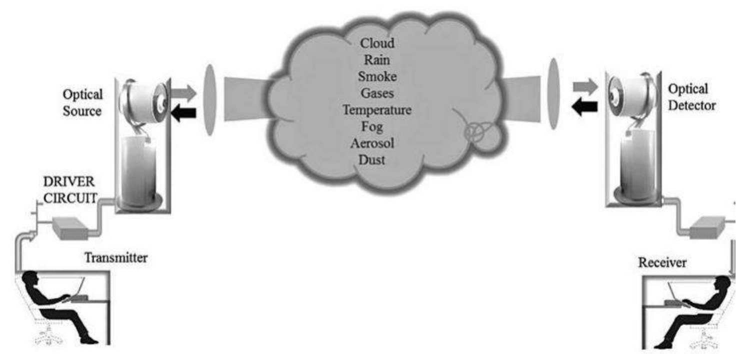

Figure 2. 3 System block diagram of an outdoor Optical Wireless Communication (OWC) link showing atmospheric interference sources [20]

As shown in Figure 2.3, the system block diagram of an outdoor Optical Wireless Communication (OWC) link highlights various sources of atmospheric interference that can affect signal quality and reliability [20]. Propagation of optical signals through the atmosphere is affected by a range of physical phenomena that introduce power attenuation. The total loss encountered during free-space transmission generally comprises atmospheric absorption, scattering by suspended particles, geometric beam divergence, and turbulence-induced fluctuations.

a. Atmospheric Attenuation Models

Atmospheric attenuation is influenced by various weather phenomena such as fog, haze, rain, and dust. The attenuation can be modelled through the Beer-Lambert law:

$$L_{atm}(dB) = \alpha_{atm} \cdot d \tag{2.2}$$

In equation (2.2), L_{atm} is the atmospheric attenuation in decibels, where α_{atm} is the specific attenuation coefficient (dB/km), and d is the link distance in kilometers. According to Ghassemlooy et al., this coefficient is highly sensitive to visibility and droplet size, with fog and dense rain causing the most severe degradations [20].

To estimate this attenuation, empirical models such as the Kim and Kruse models are used. These models relate visibility range to wavelength-dependent attenuation:

$$\gamma = \frac{3.912}{V}\left(\frac{\lambda}{550\ \text{nm}}\right)^{-q} \tag{2.3}$$

In equation (2.3), γ represents the specific atmospheric attenuation coefficient expressed in decibels per kilometer ($dBkm^{-1}$); ν is the visibility range in kilometres; λ denotes the optical wavelength in nanometers; and q is an empirical exponent whose value depends on the prevailing atmospheric condition, with larger q indicating heavier scattering environments such as fog or dense rain[20].

Table 2. 1 Kim Model Atmospheric Attenuation Exponent Table [20]

Visibility (V)	**Atmospheric Condition**	**Exponent q**
V > 50 km	Very clear atmosphere	q = 1.6
6 < V ≤ 50 km	Clean atmosphere	q = 1.3
1 < V ≤ 6 km	Moderate atmosphere	q = 0.16 V + 0.34
0.5 < V ≤ 1 km	Light fog	q = V - 0.5
V ≤ 0.5 km	Dense fog	q = 0

As shown in Table 2.1, the Kim model defines the atmospheric attenuation exponent (q) based on visibility (V) conditions, which is critical in modelling signal loss in Free Space Optics (FSO) systems. In very clear atmospheric conditions, where visibility exceeds 50 km, the exponent is fixed at q = 1.6. For clean atmospheres with visibility between 6 km and 50 km, q is set to 1.3. When visibility ranges from 1 km to 6 km, the exponent is calculated using the linear relation q = 0.16V + 0.34. In cases of light fog, with visibility between 0.5 km and 1 km, the attenuation exponent is defined as q = V - 0.5. For dense fog conditions where visibility drops below 0.5 km, the exponent is assumed to be zero. These parameters are instrumental in predicting atmospheric absorption and designing robust FSO links under varying weather conditions.

b. Divergence and Geometric Loss

Divergence loss resulting from beam spreading can be calculated using Equation (2.4).

$$L_{div}(dB) = 10\log_{10}\left(\frac{A_{beam}}{A_{rx}}\right) \tag{2.4}$$

Where A_{beam} is the beam area at the receiver plane and A_{rx} is the receiver aperture area. A mismatch leads to spatial losses, and careful optical design is necessary to minimize these [21]. In addition to beam spreading, geometric misalignments and mechanical instabilities can introduce further attenuation, commonly referred to as pointing error loss. This is quantified by Equation (2.5).

$$L_{geo}(dB) = 10\log_{10}\left[1 + \left(\frac{\theta_{pointing} \cdot d}{D_{rx}}\right)^2\right] \tag{2.5}$$

Where $\theta_{pointing}$ is the angular deviation and D_{rx} is the receiver diameter [2]. Accurate alignment and mechanical stability are essential in minimizing this form of loss, especially in long-range Free Space Optical (FSO) communication systems.

c. Scintillation and Turbulence Effects

Atmospheric turbulence, caused by temperature and pressure gradients, induces fluctuations in received signal power (scintillation). These are statistically modelled, with the Gamma-Gamma distribution often used for moderate-to-strong turbulence. The log-normal model applies for weak turbulence, assuming $C_n^2 \leq 10^{-14}\ \mathrm{m}^{-2/3}$ [20].

2.2.4. Total Link Budget

The total optical link loss in a Free Space Optics (FSO) system can be estimated using Equation (2.6).

$$L_{total}(dB) = L_{atm} + L_{div} + L_{geo} + L_{scin} \tag{2.6}$$

In equation (2.6), L_{total} is the overall optical link loss in decibels, obtained by summing the atmospheric attenuation L_{atm}, beam-divergence loss L_{div}, geometric spreading loss L_{geo}, and scintillation loss L_{scin}, each term being expressed in dB. Subsequently, the received optical power at the destination can be calculated using Equation (2.7)[20].

$$P_{rx}(dBm) = P_{tx}(dBm) - L_{total}(dB) \quad (2.7)$$

In equation (2.7), the received optical power P_{rx} equals the transmitted power P_{tx} minus the total link loss L_{total} yielding a practical estimate of signal strength at the receiver for any given environmental scenario. By subtracting the total link loss from the transmitted power, this equation enables practical estimation of the expected signal strength at the receiver under varying environmental conditions. It is especially useful for performance evaluation and link budgeting in real-world FSO deployment scenarios[20].

2.2.5. Noise and Bit Error Rate (BER)

In optical wireless communication systems, the total noise power is primarily contributed by thermal and shot noise. It can be approximated using Equation (2.8).

$$N_{dBm} = N_0 + 10\log_{10}(B) + NF \quad (2.8)$$

Where the N_0 thermal noise power spectral density, B is bandwidth (Hz) and NF is noise figure (dB). The signal-to-noise ratio (SNR), expressed in decibels, is then calculated as the difference between the received power and the total noise power, as shown in Equation (2.9).

$$SNR_{dB} = P_{rx}(dBm) - N_{dBm} \quad (2.9)$$

The signal-to-noise ratio SNR_{dB} is simply the difference between the received power P_{rx} and the calculated noise power N_{dBm}.

The Bit Error Rate (BER), which represents the probability that a transmitted bit will be received incorrectly, is closely related to the SNR. For On-Off Keying (OOK) modulation, the BER can be estimated using Equation (2.10).

$$BER = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{SNR_{linear}}{2}}\right) \quad (2.10)$$

Where SNR_{linear} is the linear (non-dB) receiver signal-to-noise ratio; and erfc(·) is the complementary error function that maps the SNR term to the corresponding probability of bit error[20].

2.2.6. Coherent receivers and the Role of DSP in FSO Systems

Free Space Optics (FSO) communication systems are increasingly relevant to support broadband connectivity, especially in rural areas that lack access to cable-based infrastructure. However, a major challenge lies in the system's vulnerability to atmospheric disturbances such as optical turbulence, scintillation, and signal attenuation due to particle absorption along the Line-of-Sight (LOS) path. To address these issues, coherent detection techniques, namely homodyne and heterodyne, combined with Digital Signal Processing (DSP), are widely adopted in modern FSO receiver architectures.

a. Coherent Detection: Homodyne and Heterodyne

Coherent detection allows FSO systems not only to read optical intensity but also to extract phase and frequency information. This is achieved by mixing the incoming optical signal with a signal from a local oscillator (LO) in the optical domain.

In homodyne detection, the LO has the same frequency as the carrier signal, resulting in a direct baseband output. Conversely, heterodyne detection uses an LO with a slightly shifted frequency, producing an intermediate frequency (IF) signal that must be digitally converted to baseband. Both techniques offer much higher sensitivity to channel variations compared to traditional direct detection.

According to Gelaw et al. (2025), a DP-16QAM based coherent detection scheme implemented in a MIMO-FSO setup demonstrated superior BER performance under moderate to strong atmospheric turbulence compared to non-coherent systems[23]

b. The Role of Digital Signal Processing (DSP)

After optical mixing, the detected signal is captured by a photodetector array, converted into the digital domain via an Analog-to-Digital Converter (ADC), and processed by a Digital Signal Processor (DSP). Key DSP functions in this architecture include:

- Frequency and phase offset correction due to LO imperfections,
- Channel equalization to mitigate optical signal distortion,
- Symbol recovery using algorithms such as the Constant Modulus

Algorithm (CMA) and Blind Phase Search (BPS),

- Post-demodulation processing of complex symbol vectors.

In a real-time experiment by Wang et al. (2023), a self-coherent homodyne hybrid FSO/wireless system with integrated DSP achieved data transmission rates of up to 10 Gbps, while significantly enhancing resilience to atmospheric distortion. The system also utilized delta-sigma modulation in its ADC design, offering more efficient signal digitization and improving signal estimation accuracy in the digital domain.

Wang et al. (2024) further emphasized that coherent detection integrated with adaptive DSP is particularly relevant for hybrid FSO/RF systems, where signal reliability and spectral efficiency are key [33].

2.3. Microwave Communication Theory

Microwave communication systems operate using electromagnetic waves typically in the frequency range from 1 GHz to 30 GHz. These systems exploit line-of-sight (LOS) propagation characteristics, making them suitable for point-to-point communication links. By using highly directional parabolic antennas, microwave communication systems concentrate transmitted energy into narrow beams, significantly reducing interference and enhancing spectrum efficiency. These systems are favoured for their rapid deployment, scalability, and ability to deliver high data rates across challenging terrains without extensive cabling, making them ideal for backhaul and remote area connectivity.

A detailed analysis of microwave communication systems unfolds through an interconnected series of evaluations, each contributing to a holistic understanding of link performance. The process begins with a comprehensive link budget calculation, which lays the foundation by quantifying the power gains and losses encountered as a signal travel from the transmitter to the receiver. This establishes a baseline for assessing whether the received signal power is sufficient under ideal conditions.

Following this, path loss assessment is conducted using models such as the Free Space Path Loss and the Log-Distance Path Loss, which reflect how signal strength diminishes with distance and environmental complexity. These models account for geometric spreading and environmental obstructions, respectively. Once geometric and environmental losses are understood, the analysis proceeds to consider atmospheric attenuation. Rain and gaseous absorption introduce additional losses that vary with weather conditions and operating frequency. This attenuation is not static but fluctuates based on climatic variability, hence it is a vital factor for long-term link reliability.

Next, the impact of elevation angle is evaluated, as signals traversing at low angles pass through denser atmospheric layers, amplifying attenuation effects. This influences link design, especially for links crossing hilly or mountainous terrain. Subsequently, receiver performance is examined, focusing on parameters such as sensitivity, thermal noise, and connector losses. These elements determine the weakest signal level that can be accurately detected and thus influence the link's resilience to degradation.

Finally, the overall system reliability is evaluated through bit error rate (BER) analysis. BER encapsulates all prior considerations transmitted power, losses, noise, and modulation scheme into a single metric that quantifies communication quality. A low BER signifies a well-optimized system, while a high BER points to potential weaknesses in the design or environment [19]. Each of these stages is intrinsically linked to the others, and a deficiency in one can cascade through the system, compromising performance. Therefore, a methodical and integrated approach is essential to ensure robust and efficient microwave communication design.

2.3.1. Link Budget Analysis and Effective Isotropic Radiated Power (EIRP)

The fundamental theoretical framework for analysing microwave link performance begins with the link budget, assessing gains and losses a signal encounters from the transmitter to receiver. Effective Isotropic Radiated Power (EIRP) represents the theoretical power level radiated by an ideal isotropic antenna to achieve the same power density as the actual antenna in the receiver direction. The EIRP is computed using Equation (2.11).

$$EIRP(dBm) = P_T(dBm) + G_T(dBi) - L_{T,cable}(dB) \quad (2.11)$$

where P_T is the transmitter output power, G_T is transmit antenna gain, and $L_{T,cable}$ represents cable and connector losses [19]. This equation provides a foundational reference for determining the strength of the signal that is effectively radiated into free space, and it serves as the starting point for further link performance evaluation.

2.3.2. Path Loss Models

Path loss quantifies the reduction of signal strength as electromagnetic waves propagate through the environment.

a. Free Space Path Loss (FSPL)

One of the most fundamental models is the Free Space Path Loss (FSPL), which describes the idealized attenuation experienced by signals traveling through a vacuum or unobstructed air. It is expressed mathematically in Equation (2.12).

$$L_{FSPL}(dB) = 32.45 + 20\log_{10}(f_{GHz}) + 20\log_{10}(d_{km}) \quad (2.12)$$

Where f_{GHz} is the frequency in gigahertz and d_{km} is the link distance in kilometers. This model assumes an ideal scenario, without obstacles or reflections, and is widely used as a baseline for evaluating other propagation effects [19].

b. Log-Distance Path Loss Model

For more realistic conditions, the Log-Distance Path Loss Model introduces an environment-dependent path-loss exponent to account for signal attenuation caused by obstructions, reflections, and terrain variations. It is given in Equation (2.13).

$$L_{PL}(dB) = L_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) \quad (2.13)$$

Where $L_{PL}(dB)$ is the path loss in decibels, L_0 is the reference-distance loss at d_0 (typically 1 km), d is the transmitter-to-receiver separation in kilometers, and n is the environment-dependent path-loss exponent that captures how quickly signal attenuation increases with distance [19].

2.3.3. Atmospheric Attenuation

Microwave signal propagation is significantly impacted by atmospheric factors such as rain and gas attenuation.

a. Rain Attenuation

Rain attenuation is a critical factor in high-frequency microwave and millimeter-wave communication systems, particularly in tropical and subtropical regions. The specific attenuation caused by rainfall can be estimated using the empirical model in Equation (2.14).

$$A_{rain}(dB/km) = k \cdot R^{\alpha} \tag{2.14}$$

where In equation (2.14), A_{rain} denotes the specific rain attenuation in decibels per kilometer k and α are frequency-dependent regression coefficients, and R is the rain rate expressed in millimeters per hour.

b. Gaseous Attenuation

Gaseous attenuation due to oxygen and water vapor also contributes significantly to total atmospheric attenuation, typically estimated from empirical data provided in standard references.

c. Total Atmospheric Attenuation

The total atmospheric attenuation, combining both rain and gaseous components, is expressed in Equation (2.15).

$$L_{atm} = \frac{(\alpha_{rain} + \alpha_{gas}) \cdot d}{\sin(\theta)} \tag{2.15}$$

In equation (2.15), L_{atm} denotes the total atmospheric attenuation in decibels; α_{rain} and α_{gas} are the specific attenuation coefficients for rain and gaseous absorption, d is the horizontal link distance in kilometres; and θ is the elevation angle of the path, with the term sin(θ) converting the horizontal distance to the corresponding slant length through the atmosphere [19].

2.3.4. Receiver Parameters

Receiver performance evaluation involves assessing parameters such as receiver sensitivity, cable losses, and noise characteristics.

- Receiver Sensitivity (S_{min})

Receiver sensitivity, the minimum detectable signal power required to achieve a specified BER, is influenced by thermal noise and required signal-to-noise ratio (SNR). The sensitivity is defined by Equation (2.16).

$$S_{min}(dBm) = N_{dBm} + SNR_{min} \quad (2.16)$$

In equation (2.16), $S_{min}$is the receiver sensitivity the minimum detectable signal power expressed in dBm; N_{dBm} is the thermal-noise power in dBm, and SNR_{min} is the minimum signal-to-noise ratio required to meet the target bit-error rate, expressed in decibels.

- Thermal Noise

The thermal noise power at the receiver is estimated using Equation (2.17).

$$N_{dBm} = -174 + 10\log_{10}(B) + NF \quad (2.17)$$

Where B is the bandwidth in Hz and NF is the receiver noise figure in dB[19].

2.3.5. Bit Error Rate (BER)

Bit error rate quantifies the performance reliability of communication systems. For binary modulation schemes such as Binary Phase Shift Keying (BPSK), the BER is given by Equation (2.18).

$$BER = \frac{1}{2}\operatorname{erfc}\left(\sqrt{SNR}\right) \quad (2.18)$$

In equation (2.18), BER is the bit-error rate, SNR is the linear (non-dB) signal-to-noise ratio at the receiver, and erfc(·) denotes the complementary error function that maps SNR to the probability of bit error for binary phase-shift keying. This detailed theoretical background provides a comprehensive basis for analysing and optimizing microwave communication systems, ensuring efficient and reliable operation even under challenging propagation conditions [19].

2.4. Damping and Loss Models in Wireless Systems

The various loss mechanisms in wireless communication systems particularly in hybrid FSO/RF networks can be grouped into three categories:

1. Geometric loss (FSPL): Affects both FSO and RF and increases with distance and frequency.
2. Atmospheric attenuation: FSO is primarily affected by fog and haze, while RF is more vulnerable to rainfall.
3. Component-level losses: Includes pointing loss (FSO), connector losses (RF), antenna gain, and noise figure.

A comparative analysis of dominant loss mechanisms in Free Space Optics (FSO) and Radio Frequency (RF) microwave systems is presented in Table 2.2. The table highlights the unique vulnerabilities and performance characteristics of each system, as well as the theoretical models used to quantify these effects.

Table 2. 2 Comparative Summary of Dominant Loss Mechanisms in FSO and RF (Microwave) Systems Along with Applicable Theoretical Models

Loss Mechanism	**FSO System**	**RF (Microwave) System**	**Relevant Model**
FSPL	High	High	FSPL Equation [1]
Fog/Haze Attenuation	Dominant	Negligible	Kim/Kruse Models [2]
Rain Attenuation	Moderate	Dominant	ITU-R P.838-3 [1]
Pointing Loss	Significant	Negligible	Beam Alignment Loss [2]
Antenna Gain	Not Applicable	Critical (> 40 dBi)	Parabolic Antenna Eq. [1]
Receiver Noise	Low (APD)	Moderate (LNB, NF > 6 dB)	Thermal Noise Eq. [1]

These loss models are critical for designing a hybrid switching mechanism that can ensure high system even under the challenging weather conditions found in tropical highlands like Dalisodo Village.

2.4.1. BER Thresholds for Switching Decisions

In hybrid FSO/RF systems, switching between links is often triggered when BER exceeds a predefined threshold. For systems aiming at carrier-grade reliability, typical thresholds are:

- FSO left: BER ≤ 10^{-6}
- Microwave RF left: BER 10^{-6} to 10^{-7}

These values are not arbitrary. A BER of is widely accepted as the upper limit for maintaining high Quality of Service (QoS), especially for real-time applications such as voice over IP (VoIP), video conferencing, or mission-critical telemetry [1], [2], [3].

Moreover, this level of BER remains within the correction capability of standard Forward Error Correction (FEC) techniques, thus minimizing the need for retransmissions and reducing latency. In practice, the system controller continuously monitors real-time SNR values, estimates BER accordingly, and executes switching logic when the BER crosses the defined threshold. This ensures optimal availability and service continuity in variable weather conditions, such as fog for FSO or rain for RF.

2.5. Regulations and Safety Standards

The development of communication systems based on Free Space Optics (FSO) and Radio Frequency (RF) technologies as connectivity solutions in rural areas must adhere to both national and international regulatory frameworks and safety standards. Optical safety, electromagnetic compatibility, and spectrum licensing constitute critical factors that significantly influence system design and determine the legal validity of its operation. This subsection outlines the principal regulatory references that serve as the foundation for ensuring that the proposed system complies with technical requirements and safety obligations.

2.5.1. Optical Safety Compliance in Free Space Optics (FSO) Systems

The deployment of Free Space Optics (FSO) systems for point-to-point communication requires particular attention to optical safety, especially regarding the laser radiation emitted during transmission. Consequently, FSO equipment must comply with internationally recognized safety standards, specifically IEC 60825-1:2014, which has been formally adopted at the national level through the Decree of the Minister of Communication and Digital Affairs of the Republic of Indonesia No. 43 of 2025 concerning the Technical Standards for Free Space Optics

Telecommunication Devices.

The IEC 60825-1 standard classifies laser systems based on their potential risk to human eyes and skin. This classification is determined by parameters such as output power, wavelength, exposure duration, and beam diameter. In the context of FSO systems, these classifications are directly related to the concept of Maximum Permissible Exposure (MPE) and the spatial extent of risk, referred to as the Nominal Hazard Zone (NHZ).

Class 1 and Class 1M laser systems are generally recommended for widespread use, as they are considered safe under direct exposure even over extended durations. However, Class 1M systems include restrictions when optical instruments (such as magnifying lenses) are used. Conversely, Class 3R and Class 3B lasers pose significantly higher risks and may only be deployed under specific conditions, depending on the classification of the installation environment. The use of such systems mandates administrative controls, technical safeguards, and certified safety training for personnel with access to the devices.

To facilitate a better understanding of the relationship between laser classifications and permitted installation environments, Table 2.3 presents an overview of FSO installation site categories along with the corresponding technical requirements in accordance with the applicable safety regulations. To facilitate a better understanding of the relationship between laser classifications and permitted installation environments, Table 2.3 presents a summary of Free Space Optics (FSO) installation site classifications along with the corresponding technical and regulatory requirements. This classification is adapted from IEC 60825-1:2014 and national guidelines as stipulated in Kepmenkominfo No. 43/2025.

Table 2. 3 FSO Installation Site Classification and Laser Safety Requirements Adapted from IEC 60825-1:2014 and National Regulation Kepmenkominfo No. 43/2025

Location Type	**Access Description**	**Permitted Laser Class**	**Additional Requirements**
Unrestricted Location	Open areas accessible to the public	Class 1 / 1M	No additional protection required
Restricted Location	Physically limited area with administrative	Up to Class 3R	Safety signage and mechanical enclosures must be in place

Location Type	Access Description	Permitted Laser Class	Additional Requirements
	controls		
Controlled Location	Accessible only to trained personnel	Up to Class 3B	Mandatory safety training, technical safeguards, and active Administrative Protective Rules (APR)
Inaccessible Space	Areas ≥2.5 m horizontal or ≥6 m vertical from human access	All classes	NHZ evaluation not required; public access must be physically impossible

The regulation stipulated in Ministerial Decree of Communication and Digital Affairs No. 43 of 2025 further mandates that FSO devices utilizing Class 2, 2M, 3R, or 3B lasers in Indonesia must be equipped with an Automatic Power Reduction (APR) feature. This mechanism enables the device to automatically reduce its transmitted optical power upon detecting the presence of an object or obstruction along the beam path. The primary objective of this requirement is to prevent sudden exposure hazards to individuals lacking protective equipment.

In the system design adopted for this study, the FSO device configuration has been deliberately maintained within the Class 1M classification, with a maximum output power not exceeding 10 mW at a wavelength of 1550 nm. This selection was made based on considerations of ocular safety for humans and the operational convenience of deploying the system in unrestricted locations, such as rooftop areas or other open environments, without requiring additional protective measures. Accordingly, the system analysed in this study is fully compliant with the optical safety requirements as prescribed by both international standards and the applicable national regulations.

2.6. Theoretical Basis for Economic Feasibility Analysis

This study conducts an economic feasibility analysis to assess the viability of hybrid Free Space Optics (FSO) and Radio Frequency (RF) technologies for rural internet connectivity. In areas like Dali Sodo Village, where fiber deployment is costly and impractical, a techno-economic approach is essential to evaluate alternative solutions. The analysis covers capital and operational costs, projected revenues, and uses standard investment metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP). Sensitivity analysis is also included to examine how external factors, such as weather and equipment costs, may impact system performance and profitability. The goal is to determine whether the hybrid FSO/RF system presents a sustainable and cost-effective investment for bridging the digital divide in rural settings.

2.6.1. Cost Benefit Analysis

Cost-benefit analysis (CBA) provides a standardized approach to evaluating whether a project's benefits outweigh its costs by expressing both in monetary terms. Wherever possible, both tangible costs and benefits are quantified using market prices, which reflect society's valuation of goods and services. Market prices serve as proxies for social value because they represent what individuals are typically willing to pay or accept at the margin. Similarly, input costs often reflect the opportunity cost of resources within the economy[24]. To ensure a comprehensive evaluation, CBA requires estimating the full stream of costs and benefits across the project's lifetime. This involves forecasting future values, a process that may use econometric or scenario-based techniques. However, practitioners must remain cautious of biases, such as overestimating benefits and underestimating costs that can arise in projections. When certain factors cannot be quantified such as environmental or social impacts, they should still be documented descriptively so that decision-makers can weigh them alongside measurable outcomes[24].

2.6.2. Revenue Modelling

A revenue model is an essential element of business planning, as it outlines how value generated from a service is converted into income. In the context of rural broadband deployment, revenue modelling helps project the financial viability of infrastructure investment by estimating income streams over time. This process involves analyzing variables such as service pricing, customer growth rate, expected market adoption, and recurring subscription fees[25].

In this study, revenue modelling is used to simulate potential income derived from providing internet access via hybrid FSO and RF technology. Given the unique challenges of rural markets, such as low population density and limited purchasing power, the model incorporates assumptions on achievable ARPU (Average Revenue Per User), service penetration rates, and growth trajectories. Revenue modelling thus serves not only as a forecasting tool but also as a strategic input for assessing the sustainability of broadband investments in underserved areas.

2.6.3. Capital and Operational Expenditures (CAPEX & OPEX)

In evaluating the economic feasibility of telecommunications infrastructure, it is critical to distinguish between capital expenditures (CAPEX) and operational expenditures (OPEX). CAPEX refers to one-time investments in acquiring or upgrading fixed assets, such as FSO transceivers, RF antennas, power supplies, poles, and civil works necessary for link deployment. These costs are typically incurred at the beginning of the project and represent the backbone of infrastructure setup [26].

On the other hand, OPEX comprises the recurring costs required to operate and maintain the network throughout its lifespan. These include electricity consumption, equipment maintenance, site rental, personnel salaries, and costs related to service downtime or weather-induced switching events. In rural deployments, OPEX tends to be a significant factor, especially where accessibility issues increase maintenance logistics. Understanding and accurately estimating both CAPEX and OPEX is vital for computing the total cost of ownership (TCO) and for determining investment efficiency in hybrid FSO/RF systems.

2.6.4. Net Present Value (NPV)

Net Present Value (NPV) is one of the most fundamental and widely applied methods for assessing the financial viability of investment projects. The concept is rooted in the principle that a given amount of money today is worth more than the same amount in the future. Therefore, in project evaluation, all future cash inflows and outflows must be converted into present value using a discount rate that reflects the time value of money [27].

NPV represents the difference between the present value of total expected benefits (cash inflows) and the present value of total costs (cash outflows). A project is considered financially feasible if the NPV is greater than zero, indicating that the projected benefits outweigh the costs. Conversely, a negative NPV suggests that the project would result in a net financial loss. The NPV is calculated using the following equation, shown in Equation (2.19).

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{C_t}{(1+D)^t} \tag{2.19}$$

In the net present value equation, NPV equals the sum of each period's net cash flow C_t discounted back to its present value by dividing by $(1+D)^t$. Here, Ct represents the cash inflows and outflows that occur during period t; t denotes the specific time index of the cash flow; D is the discount rate, reflecting the project's cost of capital or required rate of return; and n is the total length of the project's life cycle. This expression captures the principle that cash flows received earlier are more valuable than those received later because they can be reinvested sooner.

The main advantage of NPV is its ability to account for the time value of money and express investment returns in absolute monetary terms. However, this method is also sensitive to assumptions regarding future cash flows and the discount rate, which can introduce uncertainty into the analysis. Furthermore, NPV does not explicitly indicate how long it takes to recover the initial investment, making it less effective for comparing projects with different scales or time horizons[27].

2.6.5. Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is a critical metric used in investment analysis to determine the profitability of a project. It refers to the discount rate at which the Net Present Value (NPV) of a series of cash flows becomes zero. In other words, IRR is the breakeven rate of return where total expected benefits exactly match the total costs in present value terms [27].

In evaluating investment feasibility, a project is considered viable if the IRR exceeds the opportunity cost of capital i.e., the return that could be earned from an alternative investment with a similar risk profile. IRR effectively sets the upper bound for the cost of capital that an investor is willing to accept. A higher IRR implies a more attractive investment, indicating a greater return relative to the capital employed.

Internal Rate of Return (IRR) is another key financial indicator used in project evaluation, offering a percentage-based interpretation of a project's expected return. Conceptually, IRR is defined as the discount rate at which the Net Present Value (NPV) of all future cash flows equals zero. This relationship is expressed in Equation (2.20). Since this equation cannot be solved algebraically in most practical scenarios, IRR is typically approximated using linear interpolation between two discount rates: one that yields a positive NPV and another that yields a negative NPV. The interpolation equation is shown in Equation (2.21).

$$\text{NPV} = \sum_{t=0}^{n} \frac{C_t}{(1+\text{IRR})^t} = 0 \tag{2.20}$$

$$\text{IRR} = i_1 + \frac{\text{NPV}_1}{\text{NPV}_1 - \text{NPV}_2}(i_2 - i_1) \tag{2.21}$$

Notes:

C_t : cash inflows and outflows in one period t

t : time

n : project work period

NPV1 : NPV +

NPV2 : NPV -

i_1 : discount rate for NPV +

i_2 : discount rate for NPV -

While IRR is a popular decision-making tool due to its intuitive interpretation as a percentage return, it should be applied with caution particularly in projects with non-conventional cash flows, where multiple IRR values may exist or the method may yield misleading results [27].

2.6.6. Payback Period (PP)

The Payback Period (PP) is a financial metric used to determine the length of time required for an investment to recoup its initial capital outlay. It represents the number of years needed for cumulative net cash flows to equal the original investment amount. The method offers a straightforward way to assess investment risk by focusing on how quickly capital can be recovered [27]. The Payback Period is calculated using Equation (2.22).

$$PP = \frac{\text{Initial Investment}}{\text{Yearly Cash Inflow}} \quad (2.22)$$

Where:

- Initial Investment is the total upfront cost of the project
- Annual Net Cash Flow is the average yearly return, typically calculated as the sum of post-tax profits and non-cash expenses such as depreciation[28].

While the payback period provides a useful snapshot of liquidity risk and investment recovery, it has limitations. Notably, it ignores any cash flows that occur after the payback threshold is met and does not consider the time value of money. Consequently, the payback method is best used as a supplementary metric alongside other evaluative tools such as NPV and IRR, especially when comparing capital-intensive projects with varying financial structures.

Furthermore, when applying the payback rule in corporate settings, it is essential to establish an appropriate cutoff period. Projects that do not meet the defined payback horizon may be rejected, even if they generate significant long-term value highlighting the need for careful interpretation and complementary analysis[27], [28].

2.6.7. What-If Scenario Analysis

Investment feasibility studies in rural telecommunication projects are subject to a wide range of uncertainties arising from environmental variability, market conditions, and infrastructure costs. In order to evaluate the robustness and resilience of the proposed hybrid Free Space Optics (FSO) and Radio Frequency (RF) transmission system, this study employs *What-If Scenario Analysis* as an analytical tool to examine the potential impacts of changing multiple variables on key economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP) [29] .

Unlike sensitivity analysis which alters one parameter at a time, what-if scenario analysis allows the simultaneous variation of several input assumptions. This method facilitates the construction of plausible future conditions that reflect real-world uncertainties, such as prolonged fog seasons, unexpected price inflation in optical or RF hardware, or fluctuations in service adoption rates among rural users [30]. In this study, What-If Scenario Analysis serves to answer critical questions such as:

- What if the proportion of time with heavy fog increases by 50% annually?
- What if the unit cost of FSO transceivers increases by 25% due to supply chain volatility?
- What if the projected number of users subscribing to the internet service is 30% lower than expected due to low digital literacy in the rural area?

These scenarios are constructed using base-case parameters as the benchmark, and are complemented with best-case and worst-case variations, as outlined below [31]:

- Base-Case Scenario: Reflects the expected normal operational and financial conditions based on average historical weather data, standard equipment costs, and typical rural ARPU (Average Revenue Per User).
- Best-Case Scenario: Assumes optimal conditions such as extended clear-weather operation for FSO, discounted hardware procurement, and higher-than-expected user subscriptions.
- Worst-Case Scenario: Models adverse conditions including prolonged atmospheric attenuation, higher OPEX due to over-reliance on RF backup, and reduced user uptake.

Through these scenarios, the analysis captures how volatility in key factors influences the economic feasibility of the hybrid system. Scenario modelling not only aids in identifying risk thresholds but also supports the equation of mitigation strategies such as link switching thresholds, budget contingencies, and service pricing adjustments [32].

Ultimately, What-If Scenario Analysis provides a comprehensive view of potential future outcomes, thus enabling better-informed investment decisions in the development of sustainable internet connectivity for underserved rural areas.