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CONFERENCE PAPER

PERFORMANCE EVALUATION OF FREE-SPACE OPTICAL COMMUNICATION SYSTEMS UNDER ATMOSPHERIC IMPAIRMENTS FOR SUSTAINABLE HIGH-SPEED DATA TRANSMISSION

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Abstract

Free-Space Optical (FSO) communication has emerged as a promising alternative to conventional radio frequency (RF) systems for high-speed data transmission due to its large bandwidth, license-free spectrum, and immunity to electromagnetic interference. However, the performance of FSO systems is highly sensitive to atmospheric conditi ons such as fog, rain, and turbulence, which introduce attenuation and signal degradation.This paper presents a comprehensive performance evaluation of FSO communication systems under various environmenta l constraints using key metrics such as Bit Error Rate (BER), Signal-to-Noise Ratio (SNR), and received optical power. The analysis demonstr ates the impact of atmospheric impairments on system reliability and link performance.Furthermore, the study highlights the energy-efficient nature of FSO systems, making them suitable for sustainable communic ation infrastructures. The findings provide insights for designing robust and environmentally adaptive optical communication systems aligned with ICSEFT themes of sustainable and efficient technologies.

Introduction:-

The exponential growth in data traffic and the increasing demand for high-speed communication have necessitated the exploration of alternative transmission technologies beyond conventional RF systems. Free-Space Optical (FSO) communication has emerged as a viable solution due to its ability to provide high data rates, enhanced security, and efficient spectrum utilization.FSO communication employs optical signals transmitted through the atmosphere, eliminating the need for physical fiber infrastructure. This makes it particularly suitable for last-mile connectivity, disaster recovery, and remote area communication. Despite these advantages, FSO systems face significant challenges due to atmospheric impairments such as fog, rain, and turbulence, which degrade signal quality and limit transmission range.

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In the context of sustainable communication systems, FSO technology offers a promising approach by reducing power consumption and eliminating spectrum licensing requirements. This aligns with the major objectives of developing energy-efficient and environmentally sustainable communication technologies.

Literature Review:-

FSO communication has been extensively studied for its potential in high-speed wireless optical links. Andrews and Phillips (2005) analyzed atmospheric turbulence effects and their impact on optical signal propagation. Kim et al. (2001) developed empirical models for atmospheric attenuation, particularly under fog conditions, which remain one of the most critical limiting factors in FSO systems.Recent studies have focused on improving system reliability through adaptive modulation and hybrid RF-FSO systems. However, most existing research either concentrates on theoretical modeling or isolated environmental conditions. There is limited work that provides a comprehensive performance evaluation under multiple atmospheric impairments with a sustainability perspective. This paper addresses this gap by integrating performance analysis with environmental constraints and energy efficiency considerations.

Theoretical Modeling of Free-Space Optical Channel:-

Atmospheric Attenuation Characteristics:-

The propagation of optical signals through the atmosphere is primarily influenced by absorption and scattering caused by particles such as fog droplets, dust, and aerosols. As the optical beam travels through the medium, its intensity gradually decreases due to these effects. The extent of attenuation depends on factors such as visibility, particle size distribution, and wavelength. Fog introduces the most severe attenuation because the size of water droplets is comparable to the wavelength of the optical signal, resulting in strong scattering. Rain, on the other hand, has a relatively lower impact due to larger droplet sizes, while clear atmospheric conditions allow for efficient signal transmission with minimal losses.

Turbulence-Induced Signal Fluctuations:-

Atmospheric turbulence arises from variations in temperature and pressure, which create random changes in the refractive index of air. These variations cause fluctuations in the received signal intensity, a phenomenon commonly referred to as scintillation. Under weak turbulence conditions, the signal variations are relatively small and follow predictable statistical patterns. However, as turbulence increases, these fluctuations become more pronounced, leading to signal fading and reduced communication reliability. Statistical models are typically used to characterize these fluctuations and predict system performance under different turbulence regimes.

Noise and Signal Quality Considerations:-

The performance of an FSO system is also influenced by various noise sources, including background radiation, thermal noise from electronic components, and fluctuations in photon detection. These noise sources degrade the quality of the received signal and limit the achievable data rate. Signal quality is commonly evaluated using parameters such as Signal-to-Noise Ratio (SNR), which represents the strength of the received signal relative to noise. Higher SNR values indicate better signal quality and improved communication reliability.

Reliability and Error Performance:-

The reliability of an FSO communication system is typically assessed using the Bit Error Rate (BER), which measures the probability of incorrect data detection. As attenuation and turbulence increase, the received signal becomes weaker and more distorted, leading to higher error rates. In practical scenarios, BER is strongly influenced by both the strength of the received signal and the variability introduced by atmospheric conditions. Systems operating under favorable conditions maintain low error rates, while adverse weather conditions result in rapid performance degradation.

Link Stability and Design Considerations:-

For reliable communication, the received signal strength must remain above a minimum threshold required for proper detection. The difference between the available signal strength and this threshold determines the link stability. Environmental factors can significantly reduce this margin, particularly in foggy conditions where signal attenuation is severe. Therefore, system design must account for worst-case scenarios to ensure consistent performance.

Simulation Setup:-

The system is evaluated under practical operating conditions using representative parameters for optical communication systems.

j	Parameter	Value
1.	Wavelength	1550 nm
2.	Transmission Range	0.5-2km
3.	Weather Conditions	Clear,fog,rain
4.	Reciever' s type	PIN Photodiode
5.	Modulation	OOK

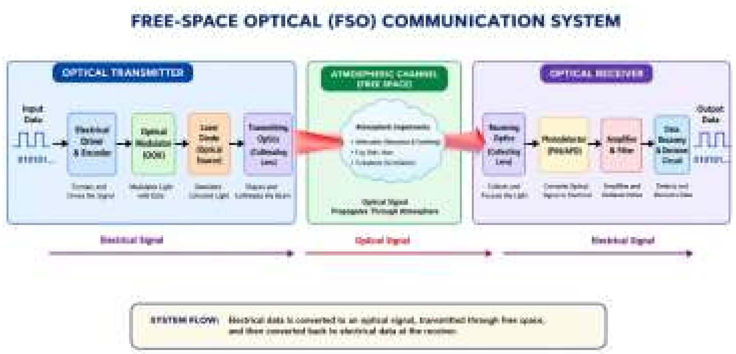

Figure 1: Representation of block diagram of of a Free-Space Optical (FSO) communication system showing signal transmission from optical transmitter through atmospheric channel to receiver for data recovery.

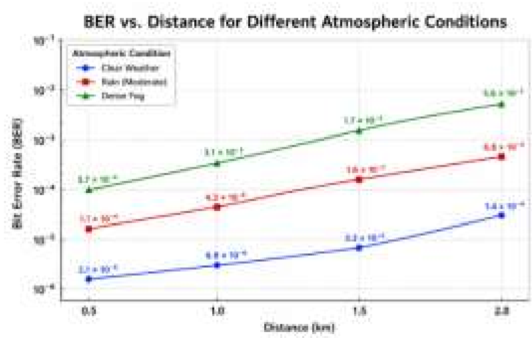

Figure 2:BER vs Distance plot showing degradation in communication performance under clear, rain, and fog atmospheric conditions in FSO systems.

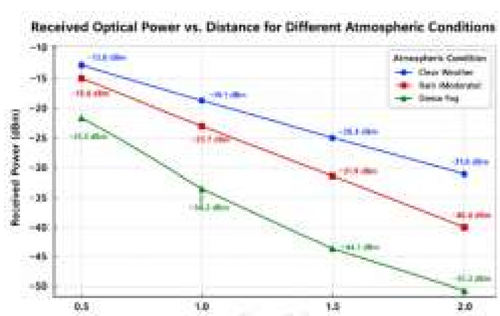

Figure 3:Received Power vs Distance graph illustrating signal attenuation under clear, rain, and fog conditions in FSO communication systems.

Results and Discussion:-

The performance evaluation of the FSO system under varying atmospheric conditions reveals a strong dependency of link reliability on environmental factors. The BER vs distance analysis shows a rapid exponential increase in error rate with increasing link range, particularly under dense fog conditions, where signal degradation becomes severe even at shorter distances. In contrast, clear weather conditions maintain significantly lower BER, indicating stable and reliable communication over longer ranges. The received power vs distance characteristics further validate this behavior, demonstrating a consistent attenuation of optical signal strength with distance, which becomes highly pronounced in fog due to scattering and absorption effects. Rain introduces moderate attenuation, positioning its impact between clear and fog conditions. The combined analysis of both graphs highlights a clear inverse relationship between received power and BER, confirming that signal weakening directly contributes to increased transmission errors. These findings emphasize that while FSO systems are highly efficient in ideal conditions, their performance is critically constrained by atmospheric impairments. Therefore, to ensure dependable operation in real-world scenarios—particularly in sustainable smart infrastructure and green communication systems—there is a strong need for adaptive techniques such as dynamic power control, diversity schemes, and hybrid communication models to mitigate environmental effects and enhance link robustness.

Conclusion:-

The presented study establishes that Free-Space Optical (FSO) communication exhibits highly promising performance characteristics in terms of high data rate capability, low latency, and spectral efficiency, making it a strong candidate for next-generation communication systems aligned with sustainable and green communication infrastructures. The analysis of BER and received power clearly demonstrates that atmospheric attenuation—particularly due to fog and turbulence—remains the primary limiting factor affecting link reliability and transmission range. While clear weather conditions support stable long-distance communication, adverse environments significantly degrade system performance, thereby necessitating intelligent mitigation strategies. The findings emphasize that future advancements should focus on adaptive link optimization, hybrid RF-FSO architectures, diversity techniques, and exploration of alternative optical bands such as mid-infrared to enhance robustness under harsh conditions. Furthermore, integration of FSO systems in smart cities, satellite communications, and energy-efficient backhaul networks aligns strongly with sustainable engineering goals, contributing to reduced electromagnetic pollution and improved energy efficiency. Thus, FSO communication stands as a critical enabling technology for future resilient, high-capacity, and environmentally sustainable communication ecosystems.

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