

A Review on RIS-Assisted RoFSO Systems Over Málaga-M Turbulence for Smart City Applications

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Abstract: Radio-over-Free-Space Optics (RoFSO) systems have emerged as a promising solution to address the growing demand for high-capacity and flexible wireless communications in smart city environments. RIS-assisted RoFSO systems offer a compelling solution to the communication challenges inherent in smart city applications. By leveraging the reflective and reconfigurable capabilities of intelligent surfaces, these systems can overcome the traditional LOS limitations and significantly mitigate the adverse effects of atmospheric turbulence, as accurately modeled by the Málaga-M distribution. The demonstrated improvements in outage probability, channel capacity, and bit error rate highlight their potential to provide reliable, high-speed, and flexible wireless connectivity in dense urban environments. However, the performance of RoFSO links is significantly affected by atmospheric turbulence. The Málaga-M distribution has gained prominence as a comprehensive model to capture a wide range of turbulence conditions. Recent advancements in Reconfigurable Intelligent Surfaces (RISs) offer a new dimension to mitigating the limitations of FSO channels. This paper provides a comprehensive literature review on the integration of RIS with RoFSO systems over Málaga-M fading, focusing on their applicability in smart city deployments.

I. Introduction

Optical communication systems utilize either free space or optical fibers to transmit information-bearing signals. These systems have become indispensable in the telecommunications sector due to their capability to support high-speed data transmission over long distances [1]. The core components include optical transmitters—typically laser diodes or light-emitting diodes (LEDs)—which convert electrical signals into optical signals. This process is illustrated schematically in Fig. 1.

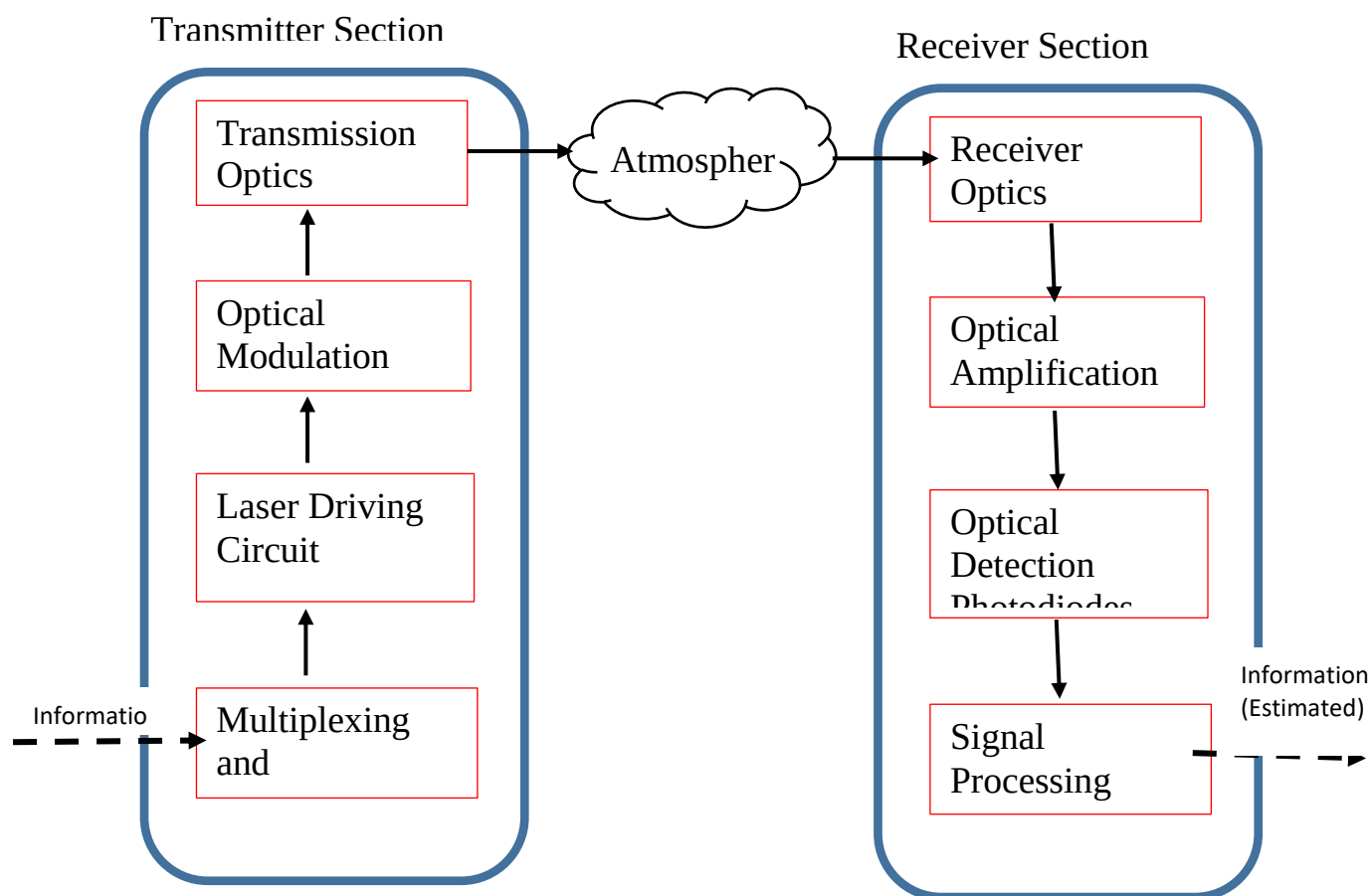


Fig. 1 Block diagram of the RoFSO system

Fig. 1 shows the RoFSO basic block diagram. In RoFSO, the message or information signal is modulated onto an optical carrier and sent to the receiver through the atmosphere. The received optical signal is transformed back into an electrical signal, and the information or message is estimated.

Information is transmitted via optical fibers using the principle of total internal reflection. These fibers, usually composed of glass or plastic, guide light over extended distances with minimal signal loss. However, signal degradation occurs due to absorption, scattering, and dispersion effects, necessitating the use of optical amplifiers to maintain signal integrity [2]. Fiber-to-the-home (FTTH), Gigabit Passive Optical Networks (GPON), and long-haul communication infrastructures extensively employ optical communication technologies [3, 4].

In addition to long-distance communication, Free-Space Optical (FSO) systems are widely used in data centers for high-speed interconnects between servers and storage units. Despite the advantages, FSO systems face challenges such as nonlinear effects and signal degradation due to dispersion. To mitigate these, techniques such as Coherent Optical Communication and Wavelength Division Multiplexing (WDM) are employed. Space Division Multiplexing (SDM) further enhances capacity through spatial mode utilization.

Wireless Optical Communication (WOC) is emerging as a frontier for high-speed broadband access due to several intrinsic advantages: exceptionally high bandwidth, ease of deployment, immunity from frequency regulation, low power consumption, reduced mass and size compared to RF systems, and enhanced security due to narrow beam divergence. Capable of data rates up to 10 Gbps, WOC supports high-quality voice and video transmission. WOC systems are broadly categorized into indoor and outdoor configurations. Indoor WOC includes directed and non-directed Line-of-Sight (LOS), diffused, and quasi-diffused systems, while outdoor WOC—often referred to as FSO—can be either terrestrial or space-based.

Applications of WOC span from terrestrial point-to-point links to satellite communications, including LEO-to-GEO, GEO-to-ground, and UAV-based links. WOC also finds usage in remote sensing, radio astronomy, defense communications, and even chip-to-chip interconnects, known as FSO Interconnects (FSOI).

Comparison of FSO and RF Communication Systems

The principal differences between FSO and RF systems stem from their operational wavelengths. Optical wavelengths (700–1600 nm) are orders of magnitude shorter than RF wavelengths (30 mm to 3 m), resulting in several distinctive features:

- (i) Optical systems offer bandwidths on the order of terahertz (THz), significantly exceeding the megahertz or gigahertz bandwidths typical in RF systems [5].
- (ii) Optical beams have much narrower divergence, increasing the received signal intensity and reducing interference.
- (iii) Due to higher gain from narrow beam divergence, FSO systems require smaller antennas and less power, making them suitable for compact and lightweight applications [6].
- (iv) FSO systems offer higher directivity and enhanced security which is as a result of the difficulty of intercepting narrow optical beams.
- (v) Unlike RF systems that require spectrum licensing, optical systems operate in unregulated spectrum bands, reducing setup deployment costs.

Atmospheric Turbulence in FSO

The major impairment in FSO communication system is atmospheric-induced scintillation which causes random variations in signal intensity. The main source of this impairment is the fluctuations in index of refraction produced by temperature variations, commonly referred to as optical turbulence. Atmospheric turbulence significantly impacts FSO performance by inducing random variations in the refractive index, resulting in amplitude and phase fluctuations in the received signal. These fluctuations arise from temperature and pressure variations along the optical path, modeled by Kolmogorov's turbulence theory[7]. The refractive index structure parameter C_n^2 quantifies the turbulence strength which varies with altitude, wind speed, humidity, and temperature. These fluctuations create inhomogeneities in the propagation path of an optical beam, causing scintillation, beam wandering, spreading, and fading—all of which degrade FSO system performance.

Refractive Index Structure Parameter (C_n^2)

C_n^2 is a statistical measure of the intensity of turbulence in the atmosphere. It quantifies the variance of refractive index fluctuations per unit volume. It is measured in $m^{-2/3}$. C_n^2 is typically highest near the ground and decreases with altitude. Higher during daytime due to solar heating; lower at night. Turbulent mixing increases with higher wind, raising C_n^2 . Strong vertical gradients lead to higher turbulence. Typical values range from weak turbulence: $10^{-17} - 10^{-15} m^{-2/3}$, moderate: $10^{-15} - 10^{-13} m^{-2/3}$ and strong: $>10^{-13} m^{-2/3}$.

Characterization of Atmospheric Turbulence

Turbulence is often modeled using statistical distributions:

Log-Normal for weak turbulence.

Gamma-Gamma for moderate to strong turbulence.

Málaga-M for generalized modeling including beam wander and scattering.

Rytov Variance (σ_R^2)

A key parameter to quantify turbulence strength. Derived from Rytov theory, it applies to plane and spherical waves.

For a plane waves $\delta_R^2 = 1.23 c_n^2 k^7 L^{11/6}$ and $\delta_R^2 = 0.492 c_n^2 k^7 L^{11/6}$ where $k = \frac{2\pi}{\lambda}$: optical wave number. L is link distance. λ is wavelength of the optical carrier.

Small- and Large-Scale Eddies – Parameters α and β

Atmospheric turbulence is formed from **eddies** of various sizes:

Large-scale eddies affect the direction and shape of the beam. Small-scale eddies affect the amplitude and phase of the wavefront.

Large-Scale Eddies (β):

These eddies have sizes comparable to or larger than the Fresnel zone. Cause slow intensity fluctuations and beam wander.

Small-Scale Eddies (α):

These eddies have sizes smaller than the Fresnel zone. Responsible for fast scintillation and wavefront distortion.

In statistical fading models: α and β control the shape and severity of irradiance distribution. Larger values of α and β imply weaker turbulence.

The parameters of the Malaga distribution α and β are calculated using the rytov variance,

$$\alpha = \left[\exp \left(\frac{0.49 \sigma_R^2}{\left(1 + 0.18 d^2 + 0.56 \sigma_R^{\frac{12}{5}} \right)^{\frac{7}{6}}} \right) - 1 \right]^{-1}$$

$$\text{And } \beta = \left[\exp \left(\frac{0.51 \sigma_R^2 \left(1 + 0.69 \sigma_R^{\frac{12}{5}} \right)^{\frac{-5}{6}}}{\left(1 + 0.9 d^2 + 0.62 d^2 \sigma_R^{\frac{12}{5}} \right)^{\frac{5}{6}}} \right) - 1 \right]^{-1} \quad [1]$$

Modulation Techniques

The limitations and characteristics of the devices used to carry out the modulation process of the optical carrier is different from that of RF carrier. There are two methods for implementing optical modulation: internal and external. Since the devices used to carry out the modulation process have different properties and restrictions, the modulation of optical carriers is different from that of RF carriers. There are two ways to do the optical modulation: internally or externally. In an internal modulator, the modulated optical signal is produced by directly varying the source's characteristics in accordance with the information signal. The bias current can be changed to provide intensity modulation. By altering the laser's cavity length, frequency or phase modulation may be achieved. Pulse modulation can be achieved by varying the driving current above and below the threshold. These modulations are limited to the linear range of power characteristics of the source.

In systems employing external modulators, a separate device is utilized to alter the properties of the optical carrier based on the input modulating signal. Such configurations enable the efficient utilization of the optical source's full output power. At optical frequencies, these modulators primarily influence the intensity of the carrier, which corresponds to the square of the electric field amplitude, rather than directly modulating the carrier's amplitude. Modulation techniques in this context are generally divided into two main types: baseband intensity modulation and subcarrier intensity modulation. The predominant method for optical signal detection is direct detection. When an intensity-modulated signal is received using a direct detection receiver, the technique is referred to as intensity modulation/direct detection (IM/DD), a standard approach in free-space optical (FSO) communication systems. Alternatively, coherent detection can be employed, which utilizes a local oscillator to convert the optical signal either directly to baseband (homodyne detection) or to a radio-frequency intermediate frequency (heterodyne detection). The resulting RF signal is then demodulated to baseband using conventional RF demodulation techniques.

Baseband Modulation

In baseband modulation, the information signal directly modulates the drive current of the LED or laser source, thereby influencing the optical carrier itself. This resulting signal, commonly referred to as the baseband-modulated signal, is transmitted through the atmospheric channel. At the receiver, the original information is retrieved using a direct detection method. Typical modulation techniques within this category include On-Off Keying (OOK) and Digital Pulse Position Modulation (PPM). Other emerging pulse-based modulation schemes, such as Digital Pulse Interval Modulation (DPIM), Pulse Amplitude and Position Modulation (PAPM), and Differential Amplitude Pulse Interval Modulation (DAPIM), have shown potential but have not yet gained widespread adoption in comparison to OOK and PPM. Among these, OOK remains the most extensively used modulation scheme in FSO systems, primarily due to its simplicity and ease of implementation. [8]

Subcarrier Modulation

In the subcarrier intensity modulation (SIM) scheme [9], the information-bearing signal is initially used to modulate a radio-frequency (RF) electrical subcarrier. This subcarrier may employ a variety of modulation formats, including binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), quadrature amplitude modulation (QAM), amplitude modulation (AM), or frequency modulation (FM). The resulting pre-modulated RF signal is then utilized to modulate the intensity of the optical carrier. At the receiver, signal recovery is performed using direct detection, similar to the intensity modulation/direct detection (IM/DD) approach. Unlike On-Off Keying (OOK), SIM does not require adaptive thresholding and offers better spectral efficiency than pulse position modulation (PPM). Furthermore, SIM benefits from the well-established techniques of RF communication systems, thereby simplifying its implementation.

A notable advantage of SIM is its ability to support the simultaneous transmission of multiple information streams over a single optical link. This is achieved through subcarrier multiplexing, where individually modulated RF subcarriers are combined using frequency-division multiplexing (FDM) before modulating the intensity of a continuous-wave laser source. However, this multiplexing approach introduces increased design complexity and requires stringent synchronization at the receiver. Both baseband and SIM signals can be demodulated using direct (non-coherent) detection methods, which are cost-effective, less complex, and widely adopted in free-space optical (FSO) systems.

QAM

Quadrature Amplitude Modulation (QAM) is a digital modulation scheme that conveys data by modulating both the amplitude and phase of a carrier signal. It combines two amplitude-modulated signals that are 90 degrees out of phase (hence, “quadrature”). QAM is widely used in wireless communications, optical systems (including FSO and RoFSO), DSL, and digital TV due to its high spectral efficiency.

Principle of QAM

QAM operates by modulating two orthogonal carriers (in-phase I and quadrature-phase Q): QAM in Optical and RoFSO Systems

QAM is useful in Radio over Free Space Optics (RoFSO) and optical wireless systems, where spectral efficiency is critical. Coherent detection systems can effectively demodulate QAM signals even under turbulence or fading. Higher-order QAM (e.g., 64-QAM, 256-QAM) may suffer from atmospheric turbulence—thus, adaptive modulation is often employed in practice.

Channel Modeling for Atmospheric Turbulence

Several statistical models have been proposed to describe atmospheric turbulence effects which include log normal, Gamma gamma and Malaga M.

Log-Normal Model

The log-normal distribution is suitable for weak turbulence conditions, where the scintillation index is less than 0.75 and propagation distances are under 100 meters [10]. The model is applicable for coherent optical systems and supports high-speed communication due to the frozen nature of weak turbulence. This model fails in moderate to strong turbulence conditions and cannot capture deep fades. The scope of the LN model is restricted in weak turbulence

regime. In [11], the outage probability for multi-hop FSO system with DF protocol has been analyzed based on the LN distribution. Compared with LN distribution, GG distribution can be used for all the turbulence regimes. The FSO signal transmission via K-distributed atmospheric turbulence channel, when selection combining (SC), equal gain combining (EGC) or maximum ratio combining (MRC) is employed, was analyzed in [13]. The analysis of the FSO system influenced by weak log-normal atmospheric turbulence conditions, employing SC and switch and-stay combining (SSC)/switch-and-examine (SEC) combining, was presented in [12] and [13], respectively.

Gamma-Gamma Model

The Gamma-Gamma distribution is widely adopted for moderate to strong turbulence. It models both small- and large-scale eddies using two independent Gamma distributions, offering better accuracy across a wide range of conditions [14]. Compared with LN distribution, GG distribution can be used for all the turbulence regimes. The outage probability and the average symbol error rate

(ASER) of the multi-hop DF FSO links over the GG turbulence channels considering the path loss and pointing errors have been studied systematically in [15]. Gamma-Gamma PDF was suggested by Andrews *et. al.* as a reasonable choice because of its much more tractable mathematical model [16]. The BER performance of a serial relayed Ro-FSO OFDM system over Gamma-Gamma distribution is studied in [17]. In a recent work [18, 19] the BER performance of Ro-FSO system based on OFDM scheme with QAM is analyzed. In [20], the authors proposed an analysis considering an FSO system over a Gamma-Gamma channel model with distance and jitter ratios, while in [20], the FSO channel is analyzed in light of the Huygens principle for a transmission over the Gamma-Gamma channel for single and multiple FSO links, respectively. In [20], the authors proposed a multi-branch RIS assisted FSO system with multiple optical RIS infrastructures, based on the Gamma function. Assuming Gamma-Gamma atmospheric turbulence conditions, implementation of the spatial diversity techniques was observed in [21], while the effect of the pointing errors was added in [22].

Málaga M Model

The Málaga or M-distribution is a generalized statistical model that encompasses various turbulence regimes from weak, moderate, and strong by adjusting its parameters. Derived from a mixture of exponential and Gamma distributions, the Málaga model accurately fits experimental data and includes log-normal and Gamma-Gamma as special cases [23]. It is characterized by parameters α and β , which represent the number of large- and small-scale scattering cells, respectively. These are related to the Rytov variance, a function of the angular wave number, propagation distance, and turbulence strength. A generalized and versatile statistical model, known as the **Málaga (M) distribution**, was introduced in [16] to characterize the irradiance fluctuations of unbounded optical wavefronts (either planar or spherical) propagating through atmospheric turbulence. Designed for homogeneous and isotropic turbulence scenarios, this model provides a unified framework that encompasses a wide range of existing turbulence-induced fading models, including the **Log-Normal (LN)** and **Gamma-Gamma (GG)** distributions, both of which are considered special cases of the Málaga-M model proposed by Jurado-Navas *et al.* [16]. Their study showed that M distribution unifies in an analytical expression most of the irradiance statistical models, such as LN, GG distributions etc. Several researchers have used this distribution to evaluate system performance under different configurations. For instance, Wang *et al.* [24] investigated the outage performance of FSO systems utilizing both serial and parallel relaying schemes over Málaga M fading channels. Building upon this, the same authors in [25]. For M distribution, a generalized model is proposed in [16]. The irradiance fluctuations of spherical or plain waves transmitted through a turbulent channel atmosphere were studied using this model. In [3], the authors further validated the Málaga-M distribution by demonstrating a close match between simulation results and experimental data. They concluded that this model is a generalized statistical framework, as several widely used models such as the Log-Normal and Gamma-Gamma distributions can be derived as special cases of the distribution [26]. In [3], the authors have derived closed-form expressions for the moments and the error rate of the M turbulent channel operating under the IM/DD technique in presence of pointing errors whereas in [27], the authors have derived the error rate in a series form for the coherent differential phase-shift keying in the absence of pointing errors. The average bit error rate (BER) expression for the Málaga-M distribution under the intensity modulation/direct detection (IM/DD) technique with on-off keying (OOK) signaling was derived in [28]. Additionally, Ansari *et al.* conducted a performance analysis of FSO systems over Málaga-M turbulent channels using heterodyne detection in the presence of pointing errors. This approach was favored due to the more mathematically tractable nature of the heterodyne detection model under such fading conditions [2].

In another recent study [29] novel analytical expressions for the average BER and outage probability of OFDM-based RoFSO links operating over Málaga-M turbulence channels were developed and evaluated. The study was further extended to incorporate the effects of pointing errors, providing a comprehensive performance assessment of RoFSO systems under realistic propagation impairments in [30]. In [31], Based on the Central Limit Theorem, the authors approximated the Gamma-Gamma (GG) fading channel using a Gaussian distribution, particularly in scenarios involving a large number of transmitting signals. In contrast with [32] and [31], a RIS-based nT-FSO communication system exploiting a single light-ray to transmit data over a G-G channel with pointing errors was investigated in [1]. The FSO system which is affected by atmospheric turbulence modeled by M-distribution using diversity techniques was analyzed in [33]. More specifically, the average bit error rate (BER) performance of a dual-branch FSO system employing **maximum ratio combining (MRC)** and **equal gain combining (EGC)** techniques was analyzed in [33], employing binary phase-shift keying (BPSK), considering Málaga-M distributed turbulence and the presence of pointing errors..

Receivers

There are two methods used for detection of the optical signal the direct detection and coherent detection. When the intensity-modulated signal is detected by a direct detection receiver, the scheme is known as intensity-modulated/direct detection (IM/DD) and it is commonly used in FSO systems. The coherent detection makes use of local oscillator to down convert the optical carrier to baseband (homodyne detection) or to RF intermediate frequency (heterodyne detection). This RF signal is subsequently demodulated to baseband via conventional RF demodulation process. Fig 2 below shows a diagram of direct detection receiver

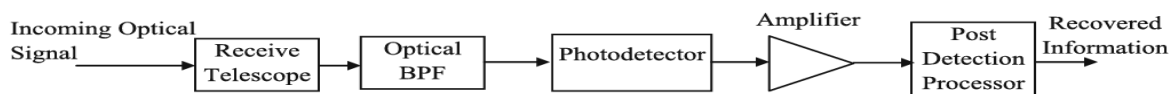


Fig 2. Block diagram of direct detection receiver

Coherent Detection

In a coherent detection receiver, the incoming optical signal is combined with a locally generated coherent carrier from a local oscillator (LO). This mixing occurs at the photodetector, where the weak received signal is amplified through interference with the strong LO signal, converting the optical signal into an electrical one. The high intensity of the LO boosts the signal level above the electronic noise floor, making the receiver's sensitivity primarily limited by the LO's shot noise. Moreover, due to the spatial mixing process, the receiver is only sensitive to signal and noise components that match the spatial and temporal mode of the LO. This selective detection enables coherent receivers to perform reliably even in the presence of strong background noise. A basic block diagram of a coherent receiver is illustrated in Fig 3.

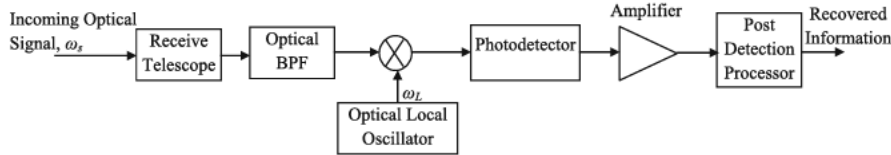


Fig 3. Block diagram of coherent optical communication system

There are two types of coherent detection which are heterodyne detection and homodyne detection that depends upon the frequency of the local oscillator ω_L and the frequency of the incoming signal ω_s . If ω_L is offset from ω_s by an intermediate frequency (IF) ω_{IF} , then it is called heterodyne detection i.e. $\omega_L = \omega_s + \omega_{IF}$. For homodyne detection the intermediate frequency is equal to zero $\omega_L = \omega_s$. In both heterodyne and homodyne receivers, the photodetector current I_p is proportional to the optical intensity and is given as

$$I_p \propto (e_R + e_L)^2 \quad [2]$$

where e_R and e_L are incoming received signal and local oscillator electric fields, respectively. Equation simplifies to

$$I_p \propto [\cos(\omega_s t + \phi_s) + E_L \cos(\omega_L t + \phi_L)]^2 \quad [3]$$

where E_R and E_L are the peak incoming received and LO signals, respectively, ϕ_s and ϕ_L are the phase of transmitted and LO signals, respectively. Solving Eq.(3) and removing higher frequency terms which are beyond the detector response can be written as

$$I_p \propto \frac{1}{2} E_R^2 + \frac{1}{2} E_L^2 + 2E_R E_L \cos(\omega_L t - \omega_s t + \phi) \quad [4]$$

where $\phi = \phi_s - \phi_L$. Since the signal power is proportional to the square of the electrical field, the above equation can be given as

$$I_p \propto P_R + P_L + 2\sqrt{P_R P_L} \cos(\omega_L t - \omega_s t + \phi) \quad [5]$$

In the above equation, P_R and P_L are the optical power levels of incoming signal and local oscillator signal, respectively. Photocurrent in relation to incident power P_R is governed by $I_p = \frac{\eta q P_R}{h\nu}$. Hence, the above equation can be written as

$$I_p = \frac{\eta q}{h\nu} [P_R + P_L + 2\sqrt{P_R P_L} \cos(\omega_L t - \omega_s t + \phi)] \quad [6]$$

where η is the quantum efficiency of photodetector, h the Planck's constant, and ν the optical frequency. Generally, the local oscillator signal power is much higher than the incoming signal power, and therefore, the first term in the above equation can be neglected. After that the signal component of the photodetector current is given as

$$I_p = \frac{\eta q}{h\nu} [2\sqrt{P_R P_L} \cos(\omega_L t - \omega_s t + \phi)] \quad [7]$$

For heterodyne detection, $\omega_s \neq \omega_L$ and therefore the above equation can be written as

$$I_p = \frac{\eta q}{h\nu} [2\sqrt{P_R P_L} \cos(\omega_{IF} t + \phi)] \quad [8]$$

It is clear from this equation that photodetector current is centered around an IF. This IF is stabilized by incorporating the local oscillator laser in a frequency control loop. In case of homodyne detection, $\omega_L = \omega_s$ and therefore Eq.(1.31) reduces to

$$I_p = \frac{2\eta q}{h\nu} \sqrt{P_R P_L} \cos\phi = 2R_0 \sqrt{P_R P_L} \cos\phi \quad [9]$$

In this case, output from the photodetector is in the baseband form, and local oscillator laser needs to be phase locked to the incoming optical signal. It is clear that the signal photocurrent in both homodyne and heterodyne receivers is effectively amplified by a factor $2\sqrt{P_R P_L}$. This amplification factor has the effect of increasing the incoming optical signal level without affecting the preamplifier noise or photodetector dark current noise. This makes coherent receiver to provide higher receiver sensitivity. Various noise contributors in coherent detection are signal shot noise, background shot noise, LO shot noise, signal-background beat noise, LO-

background beat noise, background-background beat noise, and thermal noise. When the local oscillator signal power is much greater than the incoming signal power, then the dominant source of noise is due to local oscillator shot noise, and its mean square noise power is given by

$$\bar{I}_L^2 = \begin{cases} 2qR_0P_LB & \text{for PIN} \\ 2qR_0P_LBM^2F & \text{for APD} \end{cases} \quad [10]$$

The SNR in this case (assuming no phase difference between source and local oscillator signal, i.e. $\phi = 0$) is given by

$$\text{SNR} = \frac{I_p^2}{2qR_0P_LBF} = \frac{2R_0P_L}{qBF} \quad [11]$$

The value of F is unity in case of PIN photodetector. It has been seen that coherent detection system provides larger link margin (approx 7–10dB) over direct detection system. Coherent system can employ any modulation scheme like OOK, FSK, PSK, PPM, etc. Due to complexity and high cost of coherent receiver design, it is rarely used in FSO systems. It becomes cost-effective at high data rates and may find applications in the future

Reconfigurable intelligent Surfaces

In RoFSO, as the optical signal passes through the atmosphere, it is affected by atmospheric turbulence, pointing errors, and attenuation. In addition to these effects, the blocking of signals due to the presence of a mountain, building, or big tree can prevent the transmitted signal from arriving at the destination, which is called a skip zone or dead zone problem. A reconfigurable intelligent surface (RIS) is one of the solutions proposed to avoid the skip zone problem [31, 32]. An earlier RIS was utilized to solve the dead zone problem in wireless communications and initiate smart communication [34–36]. Because of an obstruction (such as a tall structure or tree), there is no line of sight between the source and the destination. It is believed that the RIS element's reflection allows a single light beam to travel from its source to its destination. Positioned on the top floor of a building, the RIS acts as a reflector for the incoming optical signal, directing the transmitted signal in the direction of the receiver. RIS has emerged as a feasible option to reduce the skip or dead zone problem and enhance the signal-to-noise ratio (SNR) in wireless communication systems [37, 38]. In addition to fixing the skip zone problem, it provides channel reconfigurability to wireless systems [38, 39]. Fig. 2 shows the RIS-assisted RoFSO system.

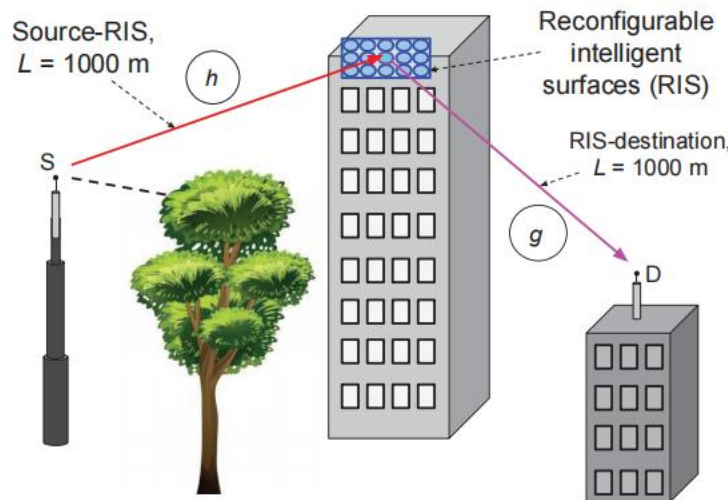


Fig. 2 Fig. 4: A block diagram of RIS-aided RoFSO system.

By precisely adjusting these properties (e.g., electromagnetic properties), RIS can dynamically reconfigure the wireless propagation environment, enabling enhanced signal strength, reduced interference, and improved spectrum and energy efficiency.

Unlike traditional technologies that rely on active relaying or complex antenna arrays, RIS is passive, low-power, and cost-effective, making it highly suitable for integration into the infrastructure of smart cities, indoor networks, and Internet of Things (IoT) ecosystems. The ability to control the wireless environment in real-time opens new opportunities for channel hardening, beamforming, and environment-aware network design.

RIS-enabled systems can transform objects like walls, building facades, or indoor panels into smart surfaces that reflect or refract signals toward intended receivers. This capability allows line-of-sight (LoS) restoration in blocked environments and supports robust communication links in scenarios affected by severe fading, mobility, or non-stationarity of users.

In the context of Free Space Optical (FSO) and Radio over FSO (RoFSO) communications, RIS can serve as a powerful tool to overcome challenges posed by atmospheric turbulence, pointing errors, and scattering, especially in urban environments characterized by dynamic and unpredictable channel conditions. The integration of RIS with FSO links, particularly over Málaga-M fading channels, is gaining significant research interest as a viable enabler for B5G/6G smart city applications.

The Reconfigurable Intelligent Surface (RIS) is composed of man made electromagnetic material often referred to as metasurfaces that can intelligently manipulate the propagation characteristics of incident electromagnetic waves. These characteristics include key parameters such as amplitude, phase, and polarization. By adjusting these parameters in a programmable manner, RIS can effectively reshape the wireless environment to enhance signal quality, directivity, and coverage [40-43]. Metamaterials are artificially engineered structures designed to manipulate the fundamental properties of electromagnetic waves such as polarization, phase, and amplitude during both reflection and transmission. Their unique subwavelength structure enables precise control over wave propagation, making them a key enabler for reconfigurable intelligent surface (RIS) technologies [40, 44]. Intelligent Reflecting Surfaces (IRSs) are planar structures composed of metamaterials with sub-wavelength thickness and are made up of a large number of sub-wavelength elements, commonly known as unit cells. Each unit cell is capable of independently manipulating the incident electromagnetic wave, typically by adjusting its phase, and in more advanced configurations, also its amplitude and polarization. This allows the IRS to dynamically control the wireless propagation environment in a highly programmable and energy-efficient manner [44]. To achieve a desired wavefront manipulation, the Reconfigurable Intelligent Surface (RIS) introduces **controlled phase shifts** to the incident electromagnetic waves via its individual **unit cells**. By precisely adjusting the accumulated phase of the reflected wave across the surface, the RIS is able to steer, focus, or shape the reflected beam. The behavior and functionality of the RIS are fundamentally determined by the phase shift profile applied across these unit cells. In most studies reported in the literature, a linear phase shift gradient is assumed across the surface, enabling the RIS to produce anomalous reflection, where the reflected beam is directed toward a desired non-specular angle. This programmable control of reflection facilitates beam steering, coverage enhancement, and interference mitigation in wireless communication systems [40, 45, 46]. In radio frequency (RF) wireless communication systems, Reconfigurable Intelligent Surfaces (RIS) have been extensively explored as a means to enhance various aspects of network performance. Specifically, RIS technology has been leveraged to extend coverage, improve physical layer security, control and exploit interference, and enhance the quality of non-line-of-sight (NLOS) links. By intelligently reconfiguring the wireless propagation environment, RIS enables more reliable and efficient communication, even in scenarios traditionally constrained by multipath fading or blockage[41]. For free space optical (FSO) systems, require a clear line-of-sight (LOS) connection, the authors of [47] employed an optical IRS to connect a transmitter with an obstructed receiver. Unlike **radio frequency (RF) waves**, which typically exhibit a planar wavefront and a uniform power distribution across the surface of the RIS, the Gaussian beams commonly used in free-space optical (FSO) communication systems possess a curved wavefront and exhibit a non-uniform power distribution. This difference introduces additional design considerations when integrating RIS into FSO systems, particularly in terms of beam. In [47] authors exploited geometric optics using a far-field approximation to determine the impact of RISs on the performance of FSO systems. Furthermore, the authors of[48] applied an optical RIS to enhance an indoor communication link. In [49], the impact of RISs on visible light communications (VLC) was investigated. However, VLC employs non-directional beams which exhibit a different behavior compared to the Gaussian laser beams used in FSO systems.

Recently, Reconfigurable Intelligent Surfaces (RIS) have garnered significant attention due to their numerous advantages and seamless integration with modern **wireless communication** systems. One prominent example is RIS-assisted unmanned aerial vehicle (UAV) communication, which has been investigated in various studies to enhance **coverage**, connectivity, and energy efficiency in dynamic and complex environments. In such systems, the RIS can be strategically deployed to reflect and redirect signals toward UAVs, thereby overcoming line-of-sight (LoS) blockages and improving link reliability in urban or remote settings as studied in [50], the highly closed-form accurate approximations of the channel distribution of the RIS-assisted system were derived in [51], the RIS-aided system security was investigated in [52], and the RIS-assisted system coverage analysis was analyzed in [53]. In addition, similar to the deployment of the RIS in microwave band operations, the optical RIS has also attracted considerable attention since it can customize the reflecting incident beam, control the beam intensity, phase, frequency, and polarity, as well as adjust the orientation of the output beam due to user's movement [32]. In [54], a new

pointing error model caused by beam jitter and intelligent channel reconfigurable node (ICRN) jitter was presented, in which a geometric and misalignment losses (GML) model

was established to study the influence of size, position, and direction of the optical RIS on the FSO channel. The FSO communication with an optical RIS in the presence of both atmospheric turbulence and pointing errors was investigated in[31] The symbolic Meijer G models for the RIS-assisted FSO communication systems was developed in [55]. In RoFSO, as the optical signal passes through the atmosphere, it is affected by atmospheric turbulence, pointing errors, and attenuation. .RIS has emerged as a feasible option to reduce the skip or dead zone problem and enhance the signal-to-noise ratio (SNR) in wireless communication systems[37, 38] . In addition to fixing

the skip zone problem, it provides channel reconfigurability to wireless systems [[38, 39]. In [[56, 57], the RIS was used to amplify the incoming optical signal. In [58], two types of indoor visible light communication (VLC) RIS structures were investigated. In [59], the authors analyzed the RIS-assisted FSO system by considering a gamma–gamma channel model with various distance and jitter ratios. In [54] , [60]the RIS-assisted FSO channel was considered using the Huygens principle for transmission over the

gamma-gamma channel for single and multiple FSO links, respectively. In[25], a multibranch RIS-assisted FSO system was proposed, where multiple optical RIS infrastructures were used based on the gamma function.

Strength of Reconfigurable Intelligent Surfaces

- **Improved Reliability:** RIS-assisted systems show considerably lower outage probabilities and bit error rates compared to direct RoFSO links, particularly in the presence of strong turbulence and blockages.
- **Increased Capacity:** The ability of RIS to enhance signal strength and coherence leads to higher ergodic channel capacities, supporting the high-bandwidth demands of smart city applications.

Weakness of Reconfigurable Intelligent Surfaces

Channel Estimation: Accurate and real-time channel state information (CSI) is essential for effective RIS operation, but estimating channels involving RIS can be complex due to their passive or semi-passive nature.

- **Integration with Other Technologies:** Seamless integration of RIS-assisted RoFSO with existing and emerging smart city technologies like IoT, AI, edge computing, and other wireless communication standards (e.g., millimeter-wave, sub-6 GHz) is crucial for a cohesive network.
- **Energy Efficiency:** While RIS generally improves energy efficiency by reducing the need for high-power transmitters, the overall energy consumption of the RIS control plane and potential active elements needs careful consideration for sustainable smart city deployments.

II. Conclusion

The integration of Reconfigurable Intelligent Surfaces (RIS) with Radio-over-Free-Space Optical (RoFSO) communication systems represents a transformative advancement in addressing the pressing challenges of reliability, scalability, and coverage in next-generation smart city networks. By passively manipulating the propagation environment, RIS offers a cost-effective and energy-efficient means to dynamically steer and enhance optical signals without requiring active RF or optical elements.

In this context, the Málaga-M fading model plays a pivotal role by providing a comprehensive statistical framework for accurately characterizing atmospheric turbulence and scattering conditions commonly encountered in urban FSO deployments. This model allows for precise performance analysis and system design under realistic environmental conditions.

As smart cities continue to evolve with an increasing demand for adaptive, high-throughput, and low-latency communication infrastructure, RIS-assisted RoFSO systems emerge as a highly promising solution. These systems not only address the inherent line-of-sight (LOS) limitations of conventional FSO links but also significantly mitigate turbulence-induced degradations by leveraging the reconfigurable and programmable nature of RIS elements.

The observed improvements in key performance metrics such as outage probability, ergodic capacity, and average bit error rate (ABER) underscore the substantial gains in link robustness, reliability, and efficiency. Collectively, these attributes position RIS-assisted RoFSO links over Málaga-M channels as a strong candidate for the future of smart urban communication infrastructure, offering scalable, high-speed, and resilient connectivity tailored to the demands of modern metropolitan environments.

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