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Review

A Review on Optical Beam Phase Correction Techniques for Ground to Space Free-Space Optical Communication

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Abstract: The Free Space Optical Communication (FSOC) links face significant challenges and issues resulting in an unattainable level of reliability and high performance due to phase distortions, scintillation, beam wandering, and atmospheric turbulence. In order to address these concerns, a comprehensive analysis of independent techniques to correct the optical beam steering and advanced compensation strategies is presented. For both terrestrial and ground to space FSOC applications, this assessment evaluates theoretical analyses, modelling studies, hardware implementations, and experimental demonstrations pertaining to the various optical beam phase correction methods. Adaptive optics, feedback-based beam steering, optical phase conjugation, non-mechanical phase correction methods and error correction techniques classify the various methods used for improving the optical beam performance. The comparative analyses in the reviewed studies indicate that traditional Adaptive Optics (AO) systems are very effective at weak and moderate turbulence levels but that neural network-based controllers perform better under rapidly changing or strong turbulence conditions. Furthermore, the use of hybrid schemes that employ various compensation mechanisms consistently resulted in increased link reliability and performance; however, the added level of complexity associated with hybrid schemes detracts from the overall efficiency of the system. This review provides a detailed analysis of the various state-of-the-art phase correction systems currently available, comparative performance data, and recent developments in the FSOC field.

Keywords: Free Space Optical Communication (FSOC), Adaptive Optics (AO), Optical Phase Conjugation (OPC)

1. Introduction

Free-Space Optical Communication (FSOC) is a highly promising technology capable of delivering very high-bandwidth, highly secure, and interference-free data transmission for both terrestrial and space-based links [1–3]. Unlike Radio-Frequency (RF) communication, FSOC uses the optical spectrum to support data rates exceeding 10 Gbps over distances ranging from a few meters to several kilometres [2]. Figure 1 shows the major components of a typical ground-to-satellite free-space optical communication system, including the optical transmitter, atmospheric propagation channel, and satellite receiver. However, the propagation of optical beams through the atmosphere faces several challenges primarily caused by atmospheric turbulence. These include wavefront distortions, which arise from random phase variations across

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the beam cross-section [4] like beam wandering, which results in positional fluctuations of the beam centroid; scintillation, characterized by intensity fluctuations due to variations in the beam path and beam spreading, where increased beam diameter reduces received power [5–9]. Together, these effects degrade the received signal quality, increase Bit-Error-Rate (BER), and compromise link availability for both terrestrial and ground-to-space FSOC systems [1, 10–12].

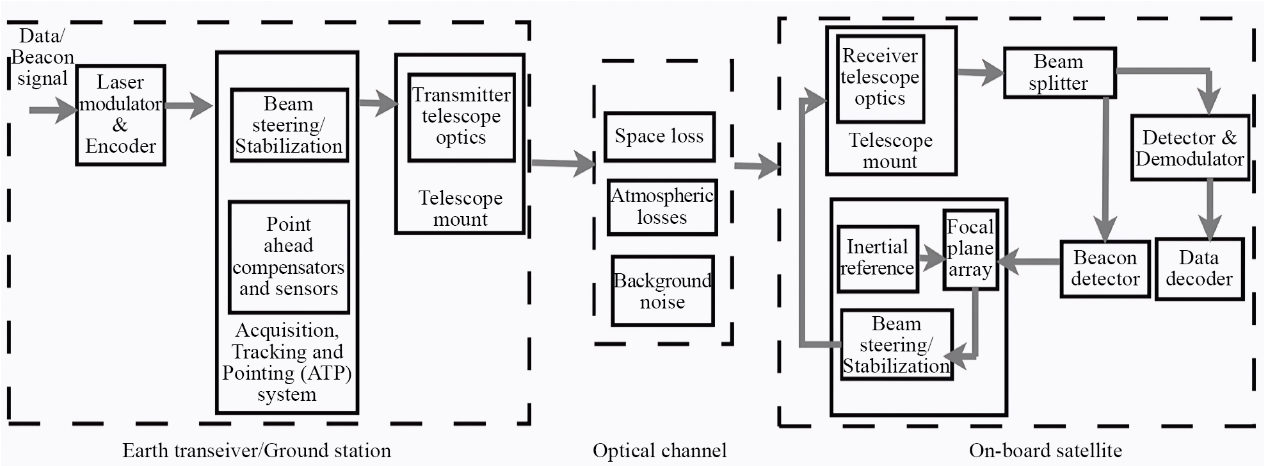

Figure 1. Various components for ground to satellite optical link communication

Phase correction of an optical beam encompasses techniques and methodologies designed to compensate for wavefront distortions and positional errors introduced by atmospheric effects [13, 14]. The primary objectives of phase correction are to preserve wavefront coherence for maintaining signal integrity [15], stabilize the beam position for effective receiver coupling [2, 16], reduce scintillation effects to mitigate power fading [17], and enhance link robustness to support reliable high-rate communication [18, 19]. These correction mechanisms may be implemented at the transmitter through pre-compensation [20, 21], at the receiver using post-compensation, or through a bidirectional adaptive system that combines both approaches.

This review comprehensively analyzes recent papers covering multiple aspects of FSOC performance enhancement. These include Adaptive Optics (AO) systems employing deformable mirrors and tip/tilt compensation [22–29], beam steering approaches utilizing piezoelectric Fast Steering Mirror (FSM) and Micro-Electromechanical Systems (MEMS) mirrors [30], control algorithms such as Proportional-Integral-Derivative (PID), fuzzy logic, neural networks, cognitive decision-making [6, 31, 32], optical phase conjugation technique based on nonlinear optics [33–36], non-mechanical beam shaping using Spatial Light Modulators (SLMs) [37], error correction and coding schemes designed for turbulent channels [38–41]; and a range of real-world implementations, testbeds, and experimental validations reported in recent literature.

The current surveys provide a general overview of the main challenges associated with FSOC [17, 42–45]. However, this review differs from these prior works in that it provides a comprehensive source for both classical and new phase correction approaches. It does so by providing a unified cross-sectional analysis of AO (traditional adaptive optics) [22–28], Optical Phase Conjugation (OPC) [33–36], and modern Artificial Intelligence (AI)-based control methods, including neural network and cognitive decision-making systems [6, 31, 32]. This paper also brings together theoretical and hardware implementation evidence in a single, comprehensive framework [7, 46] to establish a solid foundation for creating dependable ground-to-space optical links in changing atmospheric turbulence [20, 21, 29, 47].

2. Unified physical framework for ground-to-space phase correction

The phase correction of optical beams in ground-to-space FSOC systems cannot be considered as a collection of various technologies but rather as a multi-scale physical phenomenon in response to atmospheric turbulence [42–44].

Atmospheric turbulence causes distortions of the optical beam in the spatial, temporal, and angular domains simultaneously [15, 48]. A comprehensive interpretation of correction strategies must be made based on the physical constraints, rather than the hardware-based classification.

From a spatial analysis point of view, the atmospheric turbulence can be separated into low-order and high-order aberrations, which are modelled using Zernike modes in adaptive optics theory [22, 25]. The low-order aberrations, which are dominated by tip and tilt effects, are mainly observed as beam wander and centroid motion. These types of aberrations are usually corrected by Fast Steering Mirrors (FSMs) and MEMS mirrors in closed-loop control systems [30]. The high-order aberrations represent the complex wavefront phase distortions that affect the coupling efficiency and Strehl ratio [22]. The AO systems with deformable mirrors operate in the higher spatial domain, where wavefront errors are reconstructed and corrected in multiple actuator modes [22–28].

In addition to spatial order, temporal bandwidth is an important factor in correction performance. The dynamics of atmospheric turbulence are described by coherence times, which are related to the Greenwood frequency and the refractive index structure parameter (C_n^2) [49, 50]. The control bandwidth of correction systems must be sufficient to follow turbulence dynamics in real time. Deformable mirrors and fast steering control systems have millisecond response times that are adequate for dynamic correction [22], while SLMs and some iterative optimization algorithms are more appropriate for quasi-static or slow dynamic correction [37]. The temporal correspondence between turbulence dynamics and correction bandwidth is a fundamental limitation of practical implementation in ground-to-space FSOC systems.

Another characteristic dimension in ground-to-space communication is the direction and reciprocity of propagation. Downlink correction enables direct measurement of the atmospheric distortions at the receiver by wavefront sensing methods [20, 21, 29]. On the other hand, uplink pre-compensation requires partial reciprocity between the propagation and return paths [20, 21]. Nevertheless, satellite dynamics and point-ahead angles cause non-reciprocal effects that restrict the performance of optimal compensation [21, 29]. OPC and adaptive uplink correction schemes aim to compensate these distortions by nonlinear optical effects or tomographic reconstruction algorithms [20, 21, 29, 33–36]. The performance of these methods is highly dependent on the orbital environment.

Within this unified physical framework, the various methods described in the subsequent sections—beam steering [30], adaptive optics [22–28], optical phase conjugation [33–36], non-mechanical beam shaping by SLMs [37], and channel-level methods [12, 13, 48]—can be seen as complementary components that target different facets of the same problem of turbulence-induced degradation. Instead of being mutually exclusive options, these methods together constitute a hierarchical and multi-scale framework for turbulence mitigation in ground-to-space FSOC systems.

3. Classification of optical beam phase correction methods

The classification described in this section is meant to be used for analysis purposes and does not necessarily reflect the physical independence of the techniques. In real-world ground-space FSOC systems, adaptive optics, beam steering, and uplink pre-compensation are used as highly integrated subsystems within a single correction framework [29, 47]. Beam steering is often the low-order part of adaptive optics systems, while pre-compensation techniques use wavefront sensing and control loops similar to those used in receiver-side AO systems [29]. Thus, the categories described below are functional layers of a single correction framework rather than competing techniques.

It is necessary to make a clear distinction between physical phase correction methods, which work on the optical wavefront, and digital methods that work after the optical-to-electrical conversion [38–40]. Although adaptive optics, beam steering, and optical phase conjugation are direct methods of correcting phase errors in the optical signal, channel coding methods like Low-Density Parity-Check (LDPC) work on the digital signal processing level to counter residual errors due to turbulence-induced fading. Thus, digital error correction can be considered a link-layer mitigation method that is complementary to physical phase correction, rather than a phase correction method per se [38–40].

Adaptive optics is currently the most mature and widely used phase correction technology, originating in astronomical telescope applications and now widely implemented in FSOC systems [23–28, 42]. A deformable mirror consists of a reflective surface actuated by many piezoelectric or electromagnetic actuators arranged in a grid pattern, where each actuator moves independently to generate wavefront corrections that cancel atmospheric distortions [22, 28]. The key components involved in deformable mirror operation include a wavefront sensor, typically a Shack-Hartmann sensor that measures local wavefront slopes [23], control electronics that perform real-time processing to compute correction signals [22, 25, 51] and the deformable mirror itself, which responds to these signals within milliseconds [22, 52]. The overall structure and interaction between the wavefront sensor, control electronics, and deformable mirror in a typical adaptive optics system are shown in Figure 2. Prior studies also present a detailed analysis of mode-voltage constrained control for adaptive optics, demonstrating improved decoupling between deformable mirrors and tip/tilt mirrors, achieving residual wavefront errors as low as 0.02λ and high Strehl ratios [3, 22].

Traditional AO systems have been around for many years, and they are widespread and mature [23–28, 42], but they have limitations that affect their effectiveness at addressing highly dynamic (i.e., fast changing) atmospheric conditions. A key limitation of traditional AO systems is their latency—for example, the lapse time between wavefront sensing, the calculation of the compensation matrix, and the actual actuation of the mirror can result in outdated corrections for turbulence fluctuations [22, 52]. Additionally, under strong atmospheric turbulence, deformable mirrors reach the saturation point of their actuators, meaning that the amount of phase correction required exceeds the physical limits of the actuators to move and thus there will be residual error on the wavefront after correction [53]. Therefore, conventional AO systems are frequently much less effective under severe turbulence, which creates the need for composite and predictive machine-learning controllers [6] or hybrid multi-mirror strategies to mitigate significantly greater phase aberrations [37].

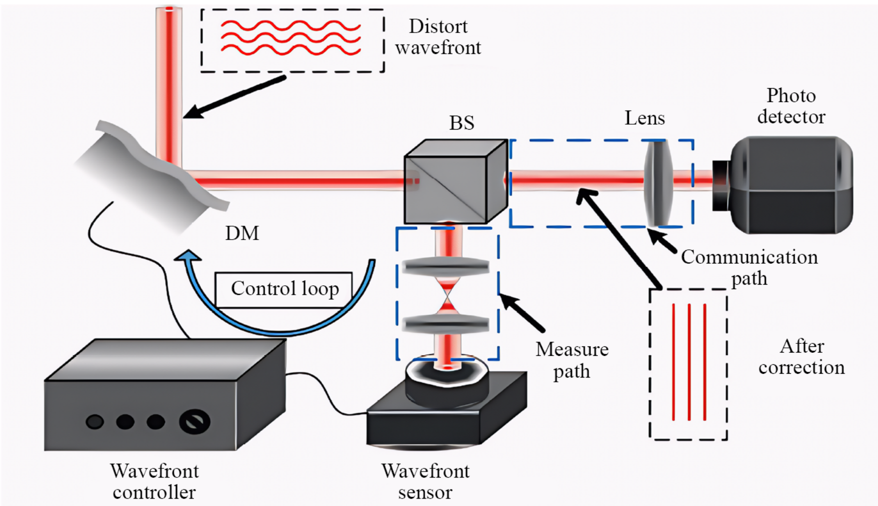

Figure 2. Adaptive optics system structure

Tip/tilt aberrations represent the lowest-order wavefront distortions and are especially problematic because they cause displacement of the entire beam [29, 54]. Fast tip/tilt mirrors correct these low-order distortions, while higher-order aberrations are simultaneously handled using deformable mirrors [55]. Traditional adaptive optics systems rely on wavefront sensors, whereas sensorless approaches rely on iterative optimization algorithms that eliminate the need for wavefront sensor hardware [5, 26, 31, 56]. The sensorless approach offers several advantages, including elimination of sensor hardware and calibration requirements, reduced overall system cost and complexity [56], and suitability for spectral regions where high-quality sensors are not available [5, 26, 31]. The emergence of machine-learning-driven methods has also introduced reinforcement learning–based adaptive optics, enabling autonomous development of optimal correction strategies without the need for conventional wavefront sensing [31, 32, 57].

Even advanced sensorless and machine-learning-based methods are not without their own operational difficulties. One of the key issues with iterative sensorless optimization algorithms is their slower convergence time relative to direct wavefront measurements [5, 26, 56]. As such, if atmospheric turbulence moves faster than the algorithm can calculate its optimal correction, then the algorithm will become incapable of adapting accordingly [31, 56]. Likewise, machine learning and neural network models require a large amount of diverse training data to be successful. Gathering sufficient quantities of high-quality training data that accurately represent the full range of possible C_n^2 profiles and weather conditions is time and labour-intensive and costly [4, 26, 31]. In addition, another important limitation of AI-based controllers is the degree of generalization they can achieve; if the system is faced with a scenario involving severe turbulence or scintillation patterns that were not represented in its training data, then it is likely that its prediction performance will degrade significantly, thereby reducing the robustness of the optical link [26].

Beam steering and feedback control are also critical subsystems in FSOC. Fast steering mirrors employing piezoelectric or electromagnetic actuators rapidly adjust the mirror orientation for active beam tracking and stabilization [30]. In such systems, position sensors such as Position Sensitive Detectors (PSDs) or quadrant detectors provide feedback on beam position [30, 55], while control electronics execute PID or more advanced algorithms [30, 58–60], and voice-coil actuators generate the required torque for mirror rotation [29]. MEMS mirrors offer compact, low-power alternatives to larger piezoelectric designs, making them suitable for satellite and airborne platforms [55]. Various control algorithms are used in beam-steering systems, including PID controllers that ensure robust and stable beam positioning [58, 59], fuzzy logic controllers that are effective for nonlinear environments and neural network–based controllers capable of predicting and compensating for complex atmospheric turbulence in real time [6]. It is important to view approaches based on neural networks not as methods for correcting aberrations per se, but rather as sophisticated control models that can be integrated into adaptive optics, beam steering, or hybrid systems. Additional adaptive algorithms such as the Stochastic Parallel Gradient Descent Algorithm (SPGDA) can perform real-time beam steering by estimating gradients of performance metrics [61]. The overall structure of a typical beam positioning system used in FSOC, including the fast steering mirror, position sensor, controller, and actuator is shown in Figure 3.

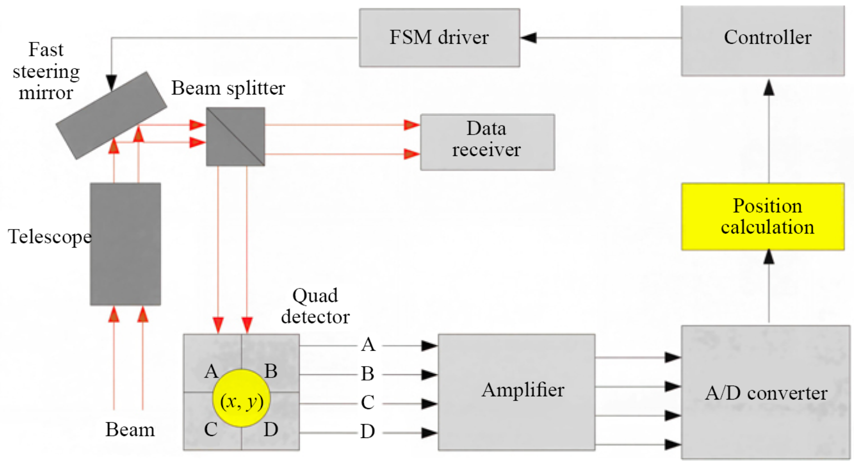

Figure 3. Beam positioning system

Designers of beam-steering systems used for FSOC links must make a clear decision when deploying the systems into the real world. There are two types of controllers available for use: deterministic and machine learning-based. Deterministic controllers like PID are simple with very low computational requirements and high reliability if there is little to moderate linear turbulence [58, 59]. Unfortunately, these controllers usually cannot sustain a stable lock when subjected to rapid fluctuations in wind and/or highly non-linear atmospheres [6]. Machine learning-based controllers such as neural networks work well for predicting and adapting to complex, non-linear wavefront distortions providing superior tracking under heavy turbulence [6]. The downside to using machine learning-based methods is that they have high computational latency, require more power-consuming processing hardware, and rely heavily on the quality of the training data used to develop the controller [26, 31]. Fuzzy logic provides a viable compromise between the two by functioning better than a PID for handling non-linear environments and not requiring the extensive amount of data and computation which deep neural networks actually need.

However, for iterative optimization algorithms like SPGDA and reinforcement learning-based controllers [57], the evaluation needs to be done in the context of the coherence time of the atmosphere [62]. The turbulence coherence time τ_0, which is inversely proportional to the Greenwood frequency, can be in the millisecond time scale for moderate to strong turbulence conditions in ground-to-space optical communication systems. Since iterative optimization algorithms require multiple iterations to converge to an optimal solution, it is important that the convergence time is smaller than the typical time scale of turbulence evolution. For rapidly changing turbulence conditions, if the convergence time is large, there could be errors in the correction process due to the residual phase errors [63].

During turbulence, the OPC can effectively undo the distortions, caused by the turbulence, experienced by the wave, by producing a time-reversed version of the original wave-front to retrace the path of propagation [33–36]. There are a variety of ways in which OPC may be implemented using nonlinear optical materials such as photorefractive materials or using two-photon processes and offer many advantages including the ability to eliminate the need for measurements of the incident wave-front and adapting naturally to dynamic turbulence [33–36]. On the other hand, there are significant practical limitations associated with the implementation of OPC in terrestrial FSOC systems. For instance, the manufacturing and integration of the nonlinear optical materials is inherently complex, which presents significant challenges to the deployment of OPC in FSOC systems in an operationally viable fashion [33, 34]. OPC setups are extremely sensitive to alignment and even tiny variations in alignment parameters will degrade the phase-conjugate reflectivity. In order for high efficiency phase conjugation to occur, the pump-laser intensities must be very high and therefore pose thermal management and power budget challenges to the optical terminal [35].

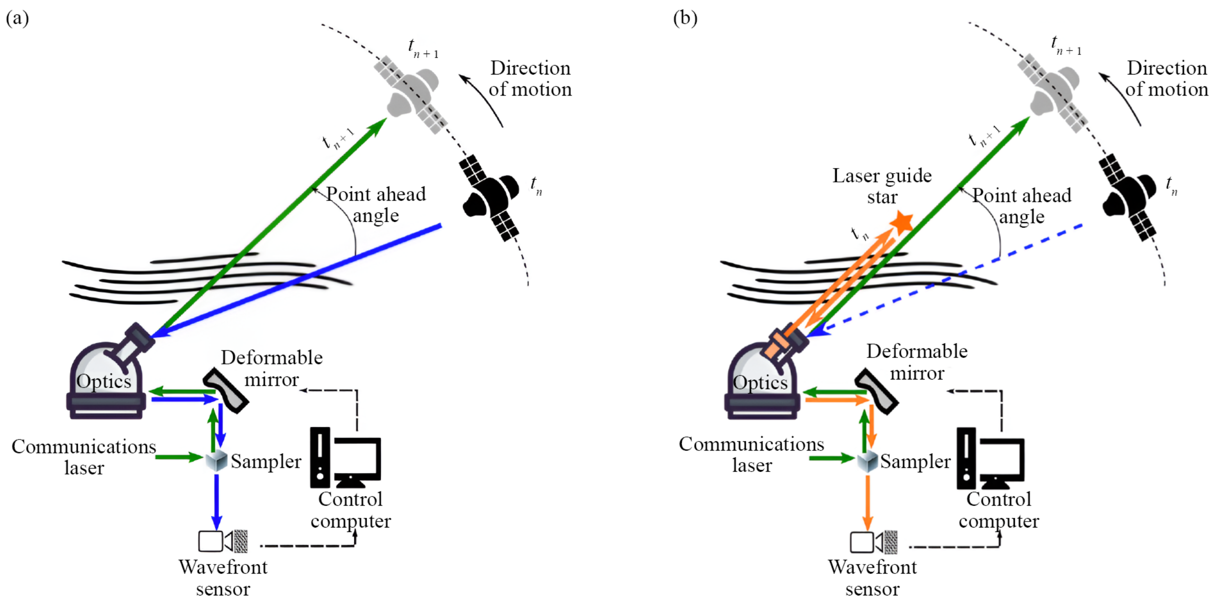

Figure 4. (a) The downlink/satellite beacon is used as a reference source for the wavefront sensor; (b) A laser guided star is propagated to the uplink expected locationand used as a refference source for the wavefront sensor

Transmitter-side pre-compensation is widely used in ground-to-space optical systems, where atmospheric turbulence can be predicted using downlink signals or beacons [20, 29]. In such approaches, the downlink or satellite beacon serves as a reference source for the wavefront sensor, or a laser guide star is propagated to the uplink location to serve as the sensing reference. Atmospheric pre-compensation involves applying ground-based turbulence measurements from the downlink path as pre-distortions to the uplink beam [20, 64]. For Geostationary Earth Orbit (GEO) feeder links, adaptive optics–based pre-compensation significantly improves uplink performance under turbulence [2, 29, 47]. Uplink pre-compensation using downlink tomography further enhances system performance by reconstructing the three-dimensional turbulence distribution from downlink measurements and applying the corresponding corrections to the uplink [21]. The two principal transmitter-side pre-compensation approaches are shown in Figure 4. In Figure 4a the downlink or satellite beacon is used as the reference source for wavefront sensing, and in Figure 4b a laser guide star is projected toward the expected uplink path to provide a reference for wavefront sensing.

Another constraint in ground-to-space optical communication comes from the Point-Ahead Angle (PAA) necessary for uplink transmission. Due to the motion of the satellite with respect to the ground station, the uplink beam needs to be pointed at the future location of the satellite instead of its current location [20, 21, 29, 47]. This results in the uplink and downlink optical signals passing through slightly different regions of the atmosphere, causing partial non-reciprocity of the turbulence-induced phase distortions [20, 21, 29]. This further makes assumption of reciprocity in uplink pre-compensation and OPC incomplete [20, 29, 33–36]. Therefore, although downlink wavefront sensing can be very helpful in understanding the nature of atmospheric turbulence, complete correction of the uplink phase distortions is not possible in dynamic satellite systems, especially in Low Earth Orbit (LEO) systems with higher relative angular velocities and larger point-ahead angles [21, 29, 47].

Non-mechanical beam steering and shaping techniques employ SLMs, which use liquid-crystal arrays or MEMS-based micro-mirrors to perform beam modulation without moving parts [37, 65]. Spatial light modulators can play two different functional roles in FSOC systems: (i) static or quasi-static wavefront shaping for pre-compensation and mode control, and (ii) non-mechanical beam steering by applying controlled phase gradients over the aperture [66]. This means that the classification of spatial light modulators is not strictly based on device type. In real-world applications, spatial light modulators can support adaptive optics or beam steering subsystems rather than being used as standalone correction systems [65, 66]. Advantages of such systems include the absence of mechanical wear and the flexibility of the beam pattern, which can be achieved by programmable phase control [37, 65]. However, liquid crystal SLMs have a refresh rate of 60-100 Hz, and the optimized versions have a refresh rate of only a few hundred hertz [37]. By contrast, the control bandwidths of deformable mirrors used in adaptive optics systems are typically in the kilohertz range [22, 52]. The refresh rate of liquid-crystal SLMs is thus often comparable to or even slower than the Greenwood frequency for moderate conditions of atmospheric turbulence [28]. This means that SLM-based wavefront correction is more suited to quasi-static wavefront correction, transmitter-side pre-compensation, or low-dynamic turbulence conditions than high-speed closed-loop compensation under strong or rapidly varying atmospheric conditions. SLM-driven beam shaping can also optimize laser guide star profiles to improve wavefront sensing performance in adaptive optics applications [37].

Since the control bandwidth must be higher than the dominant turbulence frequency components for effective real-time phase correction, this mismatch in timescales makes the SLM-based correction less applicable in moderate-to-strong turbulence conditions. As such, SLM-based approaches are more applicable in quasi-static wavefront correction, transmitter-side pre-compensation, laboratory demonstrations, or weak turbulence conditions where the dynamics of the atmosphere are relatively slow.

Consequently, the relevance of SLM-driven correction needs to be considered in the context of turbulence strength and system dynamics. In the case of turbulence regimes that are defined by low Greenwood frequencies, such as weak atmospheric turbulence, short-range terrestrial communication, or laboratory testbeds, SLM-driven phase control can be an effective solution, especially when combined in hybrid systems. Nevertheless, in the case of moderate to strong turbulence regimes, where high phase dynamics are prevalent, more dynamic correction systems such as deformable mirrors or fast steering mirrors are typically necessary.

Hybrid systems offer additional performance enhancements. Dual deformable mirror configurations, often described as woofer-tweeter systems, use a coarse, high-stroke mirror together with a fine, high-resolution mirror to achieve wide dynamic range correction. Multi-aperture reception, represented by Single-Input Multiple-Output (SIMO) architectures, improves FSOC resilience by mitigating beam wander through spatial diversity [7, 40]. On the communication side, LDPC coding has been shown to enhance error performance in turbulent FSOC channels, especially when integrated with spatial diversity methods [38–40]. More accurate statistical modelling of turbulence using Double-Generalized Gamma (DGG) fading model provides improved characterization of atmospheric fluctuations compared to traditional channel models [38, 67–69].

4. Performance comparison and thematic review

Some important metrics for evaluating the performance of phase correction techniques include residual wavefront Root Mean Square (RMS) error, which is measured as a fraction of wavelength (λ) [22]; the Strehl ratio, which represents the peak intensity of the point spread function relative to a diffraction-limited system [22]; beam wandering amplitude, which quantifies the maximum positional displacement of the beam centroid [2]; the BER, which determines the reliability of the communication link [12, 13, 48]; and the Signal-to-Noise Ratio (SNR), which describes the quality of the received signal [13, 48, 70]. In experimental implementations of adaptive optics, mode-voltage constrained control significantly improves performance, resulting in a residual wavefront RMS of 0.02λ compared to 0.05-0.07λ achieved by conventional algorithms, while also delivering Strehl ratio enhancements exceeding 0.8 [14, 22].

Although the main purpose of phase correction is the correction of the optical wavefront, digital coding techniques like LDPC are also used in link reliability and should be viewed as a complementary approach to physical phase correction [38–40].

Atmospheric turbulence is typically characterized using models such as Hufnagel-Valley and Kolmogorov, which describe refractive index fluctuations using the parameter C_n^2 [49, 50]. When applied to optical communication links, coordinated adaptive optics correction for bidirectional satellite–ground system yields superior performance compared to single-direction correction approaches [37]. Several studies also demonstrate hardware-in-the-loop testbed implementations to validate phase correction technologies. For instance, a 500 m terrestrial FSOC link utilizing a low-cost beam steering system with an Single-Mode Fiber (SMF) coupling setup demonstrates practical operation using a 49-element PSD array and Field-Programmable Gate Array (FPGA)-based control. Coherent beam combining experiments over a 10 km atmospheric link confirm the feasibility of coherent combining for long-distance free-space optical communication [11], while dual-mirror adaptive optics systems are validated through experimental wavefront correction studies performed on AO testbeds [46]. Simulation platforms such as large telescope adaptive optics simulators further support pre-deployment system design and performance optimization [71].

Real-world performance evaluations of FSOC under open atmospheric turbulence with beam-wandering compensation demonstrate a BER of 6.45×10^{-9} over a 500 m link [48], an effective scintillation index ranging from 0.0 to 0.15 [72], and beam wandering reduction to $\pm$ 0.16 mm [2].

It must be noted that the short-range terrestrial experiments (horizontal distances between 500 m and 10 km) are mainly intended as controlled validation testbeds for phase correction algorithms and may not necessarily capture the altitude-dependent turbulence structure as encountered in ground-space optical communication links [49, 50]. In vertical ground-space propagation, the turbulence contribution is generally confined to the lower atmospheric layers in the vicinity of the ground station, while the rest of the propagation distance is through successively thinner and relatively less turbulent atmospheric layers, as modelled by the standard turbulence models like the Hufnagel-Valley model [50]. Therefore, the performance parameters derived from horizontal terrestrial experiments should be scaled appropriately when applied to satellite feeder links or long-range space communication links [37].

5. Key algorithms and theoretical foundations

The fast steering mirror can be modeled as a second-order linear system analogous to a spring-mass-damper. Converting to angular motion:

$$J\ddot{\omega} + B\dot{\omega} + K\omega = \tau act \tag{1}$$

where J = moment of inertia, B = damping coefficient, K = torsional spring constant, and τact = actuator torque from voice coil.

Corresponding Transfer function:

$$G(s) = \frac{\tau(s)}{\theta(s)} = \frac{r}{Js^2 + Bs + K} \tag{2}$$

[58, 73].

PID control law in standard form:

$$u(t) = K_p e(t) + K_i \int e(\tau) d_\tau + K_d \frac{de(t)}{dt} \tag{3}$$

where $e(t)$ = position error between desired and actual beam position and K_p, K_i, K_d = proportional, integral, derivative gains [58, 59].

Fuzzy logic now maps crisp inputs to fuzzy sets using membership functions, followed by the application of rules for defuzzification by the centroid method.

SPGDA estimates performance metric gradients:

$$u(k+1) = u(k) - \gamma \frac{J(k+\Delta) - J(k-\Delta)}{2\Delta} \tag{4}$$

where J = performance metric (beam position error), γ = step size, and Δ = finite difference step.

Wavefront phase reconstructed by deformable mirror with N actuators:

$$\Phi(x,\ y) = \sum_{k=1}^{N} V_k F_k(x,\ y) \tag{5}$$

[22], where V_k = control voltage to k^{th} actuator and $F_k(x,\ y)$ = influence function (commonly Gaussian).

In the adaptive optics system, the deformable mirror is represented as a linear combination of actuator influence functions [22]. Here, N denotes the number of actuators, V_k is the control voltage applied to the k^{th} actuator, and $F_k(x,\ y)$ represents the corresponding spatial influence function over the aperture. The coordinates X_k and Y_k denote the spatial locations of each actuator on the mirror surface [22]. The piston constraint enforces zero mean displacement, while the tip and tilt constraints remove the global angular components from the reconstructed phase [22].

For modal reconstruction, R denotes the response matrix of the wavefront sensor, U_1 represents the transformation matrix from slope space to modal space, g is the measured wavefront slope vector, and D^+ is the Moore-Penrose pseudo-inverse matrix used for least-squares estimation of the modal coefficients [22].

Zernike Mode Decomposition and Constraints for mode-voltage constrained control, piston and tip/tilt constraints:

$$\sum_{k=1}^{N} V_k = 0 \quad \text{(piston constraint)} \tag{6}$$

$$\sum_{k=1}^{N} V_k X_k = 0 \quad (x\text{-tilt constraint}) \tag{7}$$

$$\sum_{k=1}^{N} V_k Y_k = 0 \quad (y\text{-tilt constraint}) \tag{8}$$

[22, 25].

Direct slope algorithm to obtain mode coefficients:

$$D = RU_1 \tag{9}$$

$$e = D^{+} g \tag{10}$$

where R = response matrix, U_1 = transition matrix, g = wavefront slopes, and D^{+} = pseudo-inverse.

The quad detector outputs proportional to beam position:

$$x = \frac{(B+C)-(A+D)}{A+B+C+D} \tag{11}$$

$$y = \frac{(A+B)-(A+D)}{A+B+C+D} \tag{12}$$

where A, B, C, and D are the outputs of the photodiodes.

Although the above equations represent classical linear control and modal reconstruction techniques, the neural network-based and reinforcement learning methods proposed in Section 2 can be considered as data-driven approximators of these inverse mappings [26, 31]. Rather than finding the pseudo-inverse or solving the modal constraints analytically, neural controllers learn a nonlinear mapping between sensor observations (e.g., wavefront slopes or beam position errors) and actuator commands [3, 26, 31]. In this regard, machine learning-based control can be considered as a generalized form of classical control theory, especially beneficial in the case of nonlinearities, model uncertainties, or time-varying turbulence statistics [26, 31].

6. Applications and system requirements

Ground-to-space optical communication systems rely heavily on a combination of uplink pre-compensation, downlink adaptive optics correction, and coordinated two-way correction mechanisms. In uplink pre-compensation, ground-based adaptive optics pre-distort the beam to counter atmospheric turbulence before transmission, ensuring improved energy delivery at the satellite receiver [20, 29]. For downlink communication, adaptive optics at the receiver enhance signal collection efficiency by correcting wavefront distortions induced during atmospheric propagation [20, 21, 37]. In systems requiring simultaneous bidirectional operation, two-way adaptive correction enables both uplink and downlink optimization, increasing overall link stability and performance [21, 37]. GEO communication links present additional challenges because propagation distances extend up to 36,000 km, resulting in significantly weaker downlink signals and stringent pointing accuracy requirements [29, 47].

In Low Earth Orbit (LEO) satellite communication, there are more system-level constraints imposed by the high relative angular velocities and the fast line-of-sight changes. Unlike in GEO satellite communication, in LEO satellite communication, the satellites have high angular slew rates, which demand fast acquisition, tracking, and pointing systems with sufficiently large control bandwidths. The time-varying nature of the link geometry imposes strict requirements on fast steering mirrors, acquisition sensors, and real-time control loops. In such cases, the correction bandwidth needs to cope with both the atmospheric turbulence dynamics and the satellite pointing dynamics. Thus, in LEO feeder links, multi-layer correction systems combining high-speed beam steering, adaptive optics, and predictive control systems are critical to ensure stable coupling efficiency and low BER in the rapidly varying alignment conditions [29, 36, 47, 55].

In terrestrial free-space links, short-range point-to-point communication over distances of 1-5 km has been effectively demonstrated using low-cost beam-steering systems for coupling into single-mode fibers. These implementations show that practical and affordable architectures can deliver robust performance even under moderate turbulence [5]. Extending the distance to 5-20 km, medium-range free-space links benefit from coherent beam-combining techniques, with demonstrations over 10 km validating the feasibility of multi-aperture reception architectures for long-distance optical communication. For these links, monitoring of laser beam wander using large apertures provides valuable characterization of turbulence-induced deviations, offering essential insights into link reliability and real-time performance assessment [7, 40].

High-Altitude Platform Station (HAPS) systems represent another significant domain for free-space optical communication. These platforms operate in the stratosphere and require turbulence-resilient optical links. Performance analysis and adaptive-optics-based improvements have shown that FSOC techniques can successfully extend communication capabilities to these high-altitude systems, ensuring stable links between ground stations and airborne platforms [3, 13].

Among emerging applications, non-mechanical pointing systems based on spatial light modulators and adaptive beam-shaping techniques demonstrate the feasibility of fully optical beam-steering approaches that eliminate moving parts. These systems offer advantages in terms of speed, compactness, and long-term reliability for next-generation FSOC terminals [37]. Another emerging direction is cognitive radio-inspired control for optical communication links. Cognitive decision-making controllers enable autonomous optical terminals to adapt beam steering based on real-time environmental feedback, leveraging machine-learning-based intelligence to optimize performance under turbulence and dynamic operating conditions [31].

To assist designers of optical systems, a decision-oriented framework can be applied to the optical telecommunications and photonics industries. The preferred optical system for optical telecommunications at short distances ($<$ 5 km) is typically a low-cost fast-steering mirror that utilizes PID control, as these systems tend to be less expensive than traditional optical systems and the optical signals are generally weaker than the ideal. As the distance between the optical telecommunications links increases (10 km to 1,000 km) the amount of atmospheric turbulence becomes significant enough that active optical tracking will be required [74]. Finally, for Ground to GEO optical telecommunications links, the distance to the GEO satellite is so great and the optical signal loss is so significant that high-performance, very high-order adaptive optics will be required to achieve a reliable telecommunications link [29, 47].

7. Comparative performance summary

In this Section, Table 1 physical and Digital mitigation technique comparison matrix shows a comparison of all major phase correction methods, including some detailed information on how each method works, its benefits and faults, and an example of when the technology may be used. Table 2 performance metrix summary presents all quantitative performance metrics found in literature to give an overview of the comparative effectiveness of each reviewed technique.

Table 1. Physical and digital mitigation technique comparison matrix

Technique	Spatial order addressed	Control bandwidth	Mitigation mechanism	Applicable turbulence regime	Key advantages	Key limitations
Fast Steering Mirror (FSM)	Low-order (Tip/Tilt)	100-1,000 Hz	Beam wander stabilization	Weak to moderate turbulence	High-speed centroid correction; compact implementation	Cannot correct high-order wavefront distortions
Adaptive optics (deformable mirror)	High-order aberrations	Up to kHz range	Wavefront phase reconstruction	Moderate to strong turbulence	High-precision correction; suitable for dynamic turbulence	High system complexity; cost; calibration sensitivity
Optical Phase Conjugation (OPC)	Full wavefront (theoretical all-order)	Depends on nonlinear medium response	Time-reversal-based correction	Reciprocity-dependent regimes	Theoretically complete wavefront correction	Sensitive to non-reciprocity; implementation complexity
Spatial light modulator (SLM-LC type)	Static/moderate-order shaping	60-200 Hz	Non-mechanical phase modulation	Weak turbulence/quasi-static conditions	No mechanical wear; flexible beam shaping	Limited refresh rate; unsuitable for fast dynamic correction
Hybrid AO + FSM (woofer-tweeter)	Low + High order	Multi-bandwidth (hundreds Hz to kHz)	Multi-scale correction	Moderate to Strong turbulence	Wide dynamic range; improved stability	Increased system integration complexity
Channel-level mitigation (e.g., LDPC + SIMO)	Intensity fading (not phase)	Not bandwidth-dependent	Post-detection correction	All regimes (complementary layer)	Improves BER performance; enhances link reliability	Does not correct phase distortion directly

Table 2. Performance metrics summary

System/technique	BER achievement	Residual Wavefronts (WF) RMS	Link distance
Neural network FSC	6.45×10^{-9}	0.1λ	500 m
AO mode-voltage	10^{-6}	0.02λ	Lab
Traditional AO	10^{-4}	$0.05\text{-}0.07\lambda$	Lab
Coherent combining	10^{-9}	0.15λ	10 km
LDPC coded SIMO	10^{-8}	0.2λ	Multi-hop

8. Emerging trends and future directions

Recent advances in free-space optical communication increasingly incorporate machine learning to enhance optical beam phase correction. Reinforcement learning approaches now allow adaptive optics systems to autonomously learn optimal wavefront correction strategies without relying on manually designed algorithms [26, 31, 57]. Neural networks have been shown to predict atmospheric turbulence conditions, enabling proactive compensation and improved link stability by anticipating distortions before they occur [6]. Deep learning models further contribute by providing sophisticated channel estimation, extracting complex turbulence characteristics directly from received signal statistics and thereby improving overall system robustness [75].

It is helpful to divide these advances into two categories in order to analyse their trajectory (short-term deployable solutions and long-term research frontiers). The short-term focus will be on strengthening enhanced optical links by using non-mechanical beam steering (e.g., SLMs) [37] and using deep learning for real-time channel estimation in order to predict fading prior to it occurring [75]. Long-term focus will include the integration of phase corrections into Quantum Key Distribution (QKD) networks where the quantum states must be preserved [76], as well as the development of fully autonomous, training-free, reinforcement learning systems that will dynamically adapt to unknown atmospheric conditions without prior modelling [26, 31, 57].

Looking ahead, future FSOC architectures are expected to evolve into multi-domain hybrid systems that integrate multiple complementary mitigation techniques. Transmitter-side adaptive optics will continue to play a critical role in ensuring high-quality initial beam shaping [20, 21, 29], while neural-network-based adaptive steering will offer responsive, real-time beam tracking under dynamic conditions. Optical phase conjugation will support dynamic phase correction by generating time-reversed wavefronts that compensate for turbulence-induced distortions along the propagation path [33–36]. Channel-optimized error correction, particularly through LDPC coding, will further strengthen link reliability in turbulent environments [38–40], and spatial diversity using multi-aperture reception strategies will mitigate the effects of beam wander and scintillation [7, 40].

The development of non-mechanical and all-optical beam-steering systems is also becoming increasingly significant, as eliminating moving components leads to improved reliability, higher modulation bandwidths, and reduced long-term maintenance. Spatial light modulators enable rapid, flexible wavefront control for steering and shaping beams without mechanical actuation [37]. Photonic integrated circuits provide compact and robust implementations suitable for deployment in spaceborne and portable optical terminals. Additionally, frequency-shifted Bragg gratings have emerged as promising devices for point-ahead correction in high-speed optical links, offering precise compensation for the relative motion between terminals [35].

Finally, the integration of phase correction techniques with quantum communication infrastructure is expected to be a key enabling technology for future secure optical networks. Quantum FSOC systems require ultra-low-noise receivers capable of operating with single-photon-level signals, and any phase correction applied must preserve delicate quantum states without introducing decoherence. To further enhance reliability, hybrid classical-quantum error correction schemes are being explored to support long-distance, high-integrity quantum communication over turbulent channels.

9. Conclusion

A wide diversity of approaches has been developed to address atmospheric turbulence in free-space optical communication [31, 37], combining adaptive optics, neural network–based control, optical phase conjugation, and error-correcting coding, each contributing unique strengths to turbulence mitigation from different perspectives [26]. These methods present important performance trade-offs; simpler techniques such as PID control offer low cost and long-proven robustness [30], whereas more advanced approaches—particularly neural networks and phase conjugation—achieve superior turbulence compensation at the expense of higher computational and implementation complexity [6, 58]. A substantial body of experimental validation supports these techniques [7, 46], with numerous hardware implementations demonstrating effective turbulence reduction under diverse atmospheric conditions and over multiple link distances [2, 24]. Current trends indicate that future high-performance FSOC systems will increasingly integrate multiple methods into unified hybrid architectures rather than relying on a single correction strategy [53]. This direction aligns with emerging opportunities such as machine-learning-based adaptive control, non-mechanical beam steering, and quantum-compatible optical correction systems that promise further enhancements in capability and reliability [31]. Practical implementations already range from cost-effective solutions using PSD arrays and fast steering mirrors suitable for near-term deployment, to advanced adaptive optics and optical phase conjugation systems designed for long-distance terrestrial and satellite links [4]. The field has now reached a mature stage with strong theoretical foundations, established experimental methodologies, and growing commercial and research relevance. Ongoing development is expected in the integration of AI and machine learning for adaptive control [31], the discovery of new nonlinear optical materials to support phase conjugation [35], the continued miniaturization of components enabling deployment on satellites and airborne platforms [37], and the increasing standardization required to facilitate interoperability across diverse optical communication systems [29, 47]. As FSOC evolves toward large-scale use in satellite networks and terrestrial infrastructures, effective optical beam phase correction will remain central to ensuring link stability [31, 33, 42], high performance, and consistent availability across operating environments.

Conflict of interest

The authors declare no competing financial interest.

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