A Survey on Acquisition, Tracking, and Pointing Mechanisms for Mobile Free-Space Optical Communications

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***Abstract*—This paper presents a comprehensive survey on acquisition, tracking, and pointing (ATP) mechanisms used in free-space optical (FSO) communications systems. ATP mechanisms are a critical component for a wide variety of use cases of mobile FSO communications. ATP mechanisms are used to align FSO transmitter and receiver to attain line-of-sight, which is required for effective operation of FSO communications. Motion is not only associated to mobile stations but also to temporary displacements experienced by stationary FSO terminals, such as in building-to-building FSO communications. The surveyed ATP mechanisms are categorized according to their working principles, use cases, and implementation technology. The advantages and disadvantages of surveyed ATP mechanisms are listed and discussed. We also discuss current challenges and future research directions.**

***Index Terms*—free-space optical communications, free-space optics, optical wireless, acquisition, tracking, and pointing, mobile stations, line-of-sight.**

I. Introduction

Free-space optical (FSO) communications is a line-of-sight (LOS) technology that propagates modulated light to transmit data between stations in stationary or mobile conditions [1]. FSO communications are also known as optical wireless communications. Recently, FSO communications technology has attracted considerable attention because it has the potential to provide transmissions at very-high data rates between two terminals separated over a distance that varies from a few meters to thousands of kilometers. FSO finds its applicability to many use cases, such as in high-speed trains, UAVs, building-to-building, satellites, indoor and outdoor local- and wide-area networks, and deep-space communications [2]. Figure 1 shows some FSO applications with their communication ranges. Mobile communications is the most challenging one for FSO communications from these cases. FSO is a technology that may be used as a stand-alone communications system or in combination with radio-frequency (RF) systems. As compared to existing RF-based wireless systems, FSO possesses multiple advantages, such as high bandwidth, license-free band use, long operational range, spatial reusability, security, and immunity to electromagnetic interference [3]. Frequencies used in FSO communications are much higher than those used in RF communications. Therefore, FSO communications can provide proportionally much higher data rates than RF communications while using antennas that occupy smaller real estate [4]. Moreover, the coherence of laser light in FSO links may reduce geometrical loss and enable the transmission of high data rates at long distances [5]–[8].

In particular to the mobile communications market, there is a plethora of RF communications technologies competing with FSO communications. Vehicle-to-everything (V2X) communication is a mobile communications system used to exchange information between a vehicle and any other entity, such as another vehicle, pedestrian, ground station, or fixed infrastructure to form an intelligent transportation system [9]. Some existing communications technologies, such as IEEE 802.11p [10] and LTE [11], [12], have been proposed for V2X communications. IEEE 802.11p provides dedicated short-range communications in the band of 5.85 - 5.925 GHz [13]. IEEE 802.11p has been designed to exchange/broadcast safety and traffic efficiency messages that do not demand high bandwidth [14], [15]. Moreover, the theoretical maximum data rate of IEEE 802.11p is 27 Mbps, which may not be suitable for high-speed data exchange/Internet access in an intelligent transportation system [14]. LTE, as an alternative communications technology for V2X, provides a peak throughput of 31 Mbps to a mobile LTE receiver traveling at 200 km/h, which may not meet the demand for high-speed Internet access in high mobility scenarios [16]. 5G using millimeter wave may be also employed for V2X communications. It is expected that 5G will provide a peak data rate of 10 Gbps in low mobility, such as local wireless access, and peak data rate of 1 Gbps in high mobility scenarios in the near feature [17]. However, 5G is not yet deployed. Similar to FSO, 5G using millimeter wave requires LOS between communicating stations. Moreover, 5G will require spectrum licensing. In contrast, FSO is a mature technology which can provide higher data rates than 5G and it is license free. Therefore, FSO communication is one strong candidate for V2X communications with further advantages for high mobility scenarios.

An example of a high-mobility station is a high-speed train, which travels at a speed of about 400 km/h. Providing high-speed Internet access (i.e., on the order of Gbps) to the passengers on a high-speed train by using existing RF-based communications systems, such as long term evolution (LTE), is challenging because of the high speed of the train [18].

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LTE and other RF-based communication technologies, while not requiring LOS, may fall short to provide high data rates due to the impact of the Doppler effect, frequent handovers, and the operational frequencies and bandwidths [19], [20]. For example, an experiment carried out by Ericsson showed that the maximum achievable data rate of LTE is 19 Mpbs on a jet plane flying at 700 km/h [19]. This data rate is remarkably less than what an FSO communication system may provide [19].

The narrow and directional characteristics of a laser beam employed in FSO enable spatial reuse and make it hard to eavesdrop, thus raising the level of security. The use of light as carrier of FSO communications provides immunity to electromagnetic interference [3]. Despite its many advantages, FSO communications are susceptible to some weather conditions, such as fog, rain, sleet, and snow [21], and to misalignment of transmitter-receiver terminals [22]. Atmospheric conditions may impair the propagation of an optical signal because the propagation of light may undergo absorption and scattering. Pointing error caused by misalignment of the transceivers is another major challenge in FSO communications [23]. This error is defined as the Euclidean distance between the centers of the photo detector and the beam footprint at the receiver [24]. Pointing error may result in degradation or even total loss of the received signal. This error may arise because of transceiver sway, platform vibration, the motion of mobile stations, error or uncertainties in the tracking system [25], or any kind of stress in electronic or mechanical devices used in FSO communications system. Another type of pointing error is beam wandering caused by the inhomogeneity of large-scale eddies in the atmosphere (i.e., atmospheric turbulence), where the transmitted beam may deviate from its intended path [3].

Acquisition, tracking, and pointing (ATP) mechanisms in FSO communications systems may avoid or reduce pointing errors by continuously measuring system-wide performance metrics, such as the received signal power and Strehl ratio, which is the ratio of the intensity on the optical axis of an aberrated or corrected point spread function (PSF) to the on-axis intensity of the diffraction-limited PSF [7], and adjusting correction elements, such as gimbals, mirrors, or adaptive optics.

The tasks of an ATP mechanism include pointing the transmitter in the direction of the receiver, acquiring the incoming light signal, and maintaining the FSO link by tracking the position of a remote FSO terminal [26]. Pointing is the process of aligning the transmitter in the field-of-view (FOV) of the receiver. Signal acquisition is the alignment process of the receiver in the arrival direction of the beam. Tracking is the maintenance of both pointing and signal acquisition throughout the optical communication between communicating terminals.

In addition to ATP mechanisms, an appropriate selection of the beam divergence may allow to mitigate pointing errors. Particularly, the pointing error decreases as the size of the beam footprint at the receiver increases. The geometric path loss of an optical wireless link increases as the divergence angle increases. Geometric path loss is defined as the spread of the transmitted power through the communication distance. This loss depends on the divergence angle of the transmitted beam, the distance between communicating stations, and the area of the receiver aperture [1]. Some optimization models have been presented to provide optimum beam width for minimum bit error rate (BER) and outage probability of an optical wireless link affected by pointing error and signal-to-noise ratio [22], [24], [27]–[32]. A discussion of this particular subject is beyond the scope of this survey.

Because of the increased geometric path loss with the increase in beam divergence, FSO communications generally employ a narrow beam, where the divergence angle of the transmitted beam is smaller than or equal to a milliradian (mrad). Employing a narrow beam increases the received power density and improves link margin under diverse weather conditions, but it requires a precise alignment between a pair of communicating transceivers because of the small footprint of the beam at the receiver [33]–[37]. Satisfying this requirement becomes more difficult when at least one of the communicating parties is mobile.

In this survey, we discuss existing ATP mechanisms used in FSO communications. Maintaining LOS between stations is particularly challenging for mobile FSO stations. ATP mechanisms are crucial components of FSO communications systems for fulfilling LOS requirements of mobile FSO communications. We categorize ATP mechanisms according to their working principles, use cases, and used mechanics. We also discuss the working principle of each ATP mechanism presented in this survey, including advantages and disadvantages. We also discuss current challenges and future research directions.

The remainder of the paper is organized as follows. Section II presents commonly used ATP mechanisms for FSO communications systems. Section III classifies FSO communications systems according to their use cases and describes the ATP mechanisms proposed for these systems. Section IV provides some challenges and future research directions. Section V presents our conclusions.

II. ATP Schemes

ATP mechanisms are generally adopted in stationary and mobile FSO communications systems when a narrow beam is employed. The high data rate of concentrated light intensity and the long reach of a narrow beam are some of the motivations to use such beams. However, the use of a wide beam may relax the performance requirements of the used ATP mechanism or it may be even help to eliminate this mechanism altogether. Some FSO applications have been proposed to benefit from using a wide beam to relax the requirements of ATP mechanisms [38]–[41]. This paper focus on systems that employ a narrow beam as they heavily depend on ATP mechanisms.

ATP mechanisms in FSO communications systems may be classified according to their working principles, used mechanism, and use cases. Figure 2 shows a classification of ATP mechanisms according to their working principles and mechanics. A second classification of ATP mechanisms according to use cases is presented in Section III. The categories listed

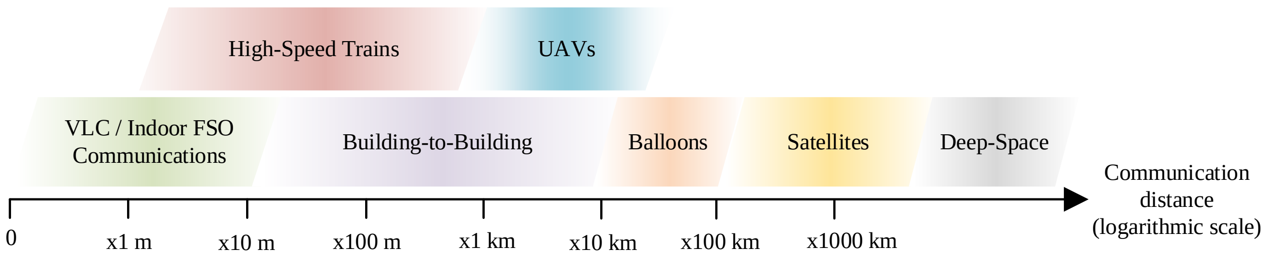


Fig. 1. Comparative representation of FSO communications by distance between transceivers.

in Figure 2, i.e., gimbal-based, mirror-based, gimbal-mirror hybrid, adaptive optics, liquid crystal, RF-FSO hybrid, and other ATP mechanisms are detailed in the following sections.

A. *Gimbal-based ATP Mechanisms*

Gimbal-based ATP mechanisms use a mechanical rotary gimbal controlled by motors. The motorized platforms provide two or three-axis moving capability to the gimbal. Figure 3 shows a two-axis gimbal and a mirror mounted on it. Such a gimbal is able to perform pan and tilt movements. Gimbal-based ATP mechanisms are preferred specially fit for transceivers that require a wide angular range of motion [7], [42]–[46]. For instance, ground-to-satellite and satellite-to-satellite FSO communications systems may require a wide pointing range to direct the light beam to the receiving terminal or acquire the incoming optical signal from the transmitting terminal. However, gimbals have coarser pointing resolution (i.e., large step size) than mirror-based ATP mechanisms. This limitation is especially distinctive in cases where fine-grained pointing and tracking are sought. For instance, the angular pointing resolution of gimbals currently available in the market is in the range of μrad, whereas that of mirror-based ATP mechanisms is in the range of sub-μrad [47]–[49]. A gimbal may be used together with a fast steering mirror (FSM). This mirror is mounted on a flexure of a support system that can move independently from the natural frequency of a spring/mass system to point a laser beam or other light towards a receiver [50]. The FSM provides fine tracking that complements the coarse tracking of a gimbal [51]. Mirror-based ATP mechanisms are discussed in Section II-B. The large mass of a gimbal is another limitation [52]. Because of the bulky servo motors rotating the gimbal, gimbal-based ATP mechanisms may not be suitable for vehicles or moving stations requiring a weight limit. For instance, small UAVs must conform to a flying weight limit, which entails a low-mass FSO terminal and hence, a lightweight ATP mechanism [45]. On the other hand, gimbal-based ATP mechanisms are used for mobile vehicles where the weight of the ATP mechanism is not an issue, such as cars, large UAVs, satellites, and recently, on trains [48], [53]–[55].

An example of a gimbal-based ATP mechanism is proposed for ground-to-unmanned aerial vehicle (UAV) FSO communications [42]. This work experimentally demonstrates the repeatability and accuracy of gimbal-based ATP mechanisms for ground-to-UAV FSO communications. In this work, a 633-nm laser, mounted on a gimbal and acting as the transmitter, is directed to a stationary duo-lateral position sensing photodiode (PSD) acting as a receiver. The PSD is connected to a data acquisition module that acquires the position information of the laser. A personal computer (PC) controls the movement of the gimbal. This movement control is based on the acquired positioning data to point the laser beam at the center of the PSD. The reported distance between the gimbal and the PSD in the experiment is 1.77 meters. Through simulations, this work also showed how the resolution and repeatability of the gimbal-based ATP persist under different weather conditions [42]. In these simulations, an UAV follows a circular path with a radius and altitude of 4 km each. A 1550 nm-laser with an output power of 20 mW is used to transmit the laser beam through a propagation path of 5,656.85 m. A photodiode with a sensitivity threshold of -30 dBm and a focusing lens with an aperture size of 30 cm and focal length of 20 cm are used to analyze the fading probability of the FSO link. According to the simulation results, a Gaussian beam profile with a spot size of 10.56 m is observed at the receiver's plane, and the geometric path loss associated with the FSO link is estimated as -15.5 dB. Moreover, the divergence angle used in these simulations, 0.05°, provides enough offset for compensation of errors introduced in the alignment and tracking algorithm.

A gimbal-based auto tracking mechanism is demonstrated to exhibit the tracking capability of a mechanical gimbal for mobile FSO communications systems without employing any lenses [43]. In this work, a 633 nm-laser, able to move in x, y, and z, directions is used as the transmitter using an output power of 1.35 mW. The proposed auto-tracking system consists of a PSD mounted on a two-axis gimbal and a PC that analyzes the output of the PSD and generates control signals to steer the gimbal and point the laser to the center of the PSD.

B. *Mirror-based ATP Mechanisms*

Mirror-based ATP mechanisms use FSMs to perform beam stabilization, pointing, and tracking. FSMs deflect the incident beam onto the receiving sensor. Unlike gimbal-based ATP mechanisms, FSMs are light of weight because the mirror they move have a small mass. As a result, FSMs have high steering speed and fine pointing resolution (e.g., sub-μrad) [56], [57]. Therefore, FSMs are mostly preferred for fine-grained and high-speed ATP operations in FSO communications. Typically,

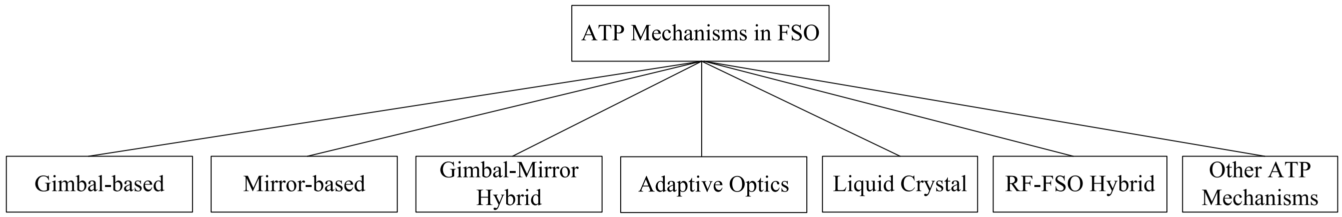


Fig. 2. Classification of acquisition, tracking, and pointing mechanisms in FSO communications according to their working principle.

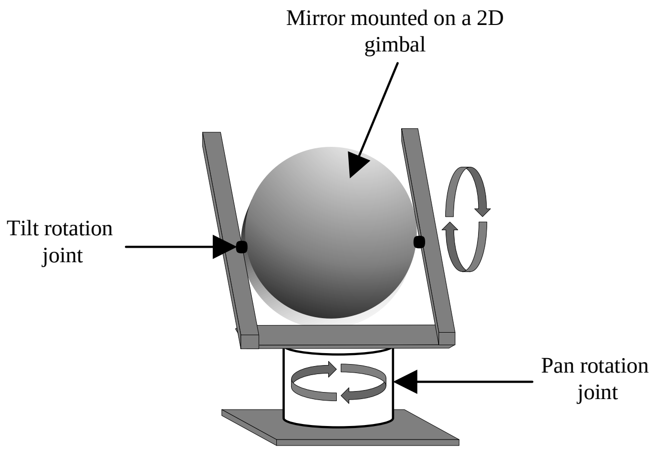
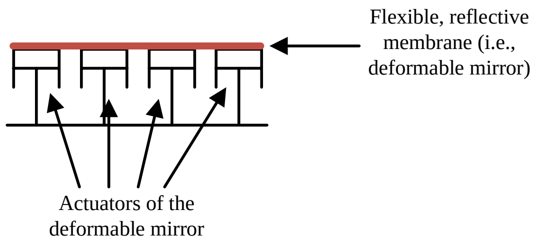


Fig. 3. A gimbal capable of performing pan and tilt rotations with a mirror mounted on the gimbal.

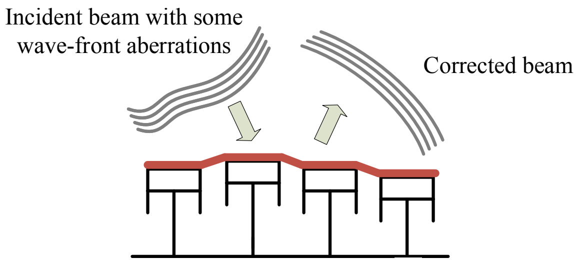
a feedback control system is employed to sense errors in the trajectory or phase of the reflected beam and to fine-tune the position of the mirror. One drawback of FSMs is their limited angular range of motion that may restrict their field-of-view for data acquisition/tracking as compared to gimbals [56].

FSMs may be roughly classified under three categories according to their actuator types: mechanical, piezoelectric (PZT), and micro-electromechanical systems (MEMS) [46]. Conventional mechanical FSMs typically use voice coils, similar to speaker coils but with a moving magnet instead of a moving coil. Modulating the amplitude, frequency, and direction of the current flowing through the coil provides a precise push or pull effect to move the mirror. The advantages of voice coil actuators are a large angular range of motion, potential for smaller increments of motion, and a moderate frequency response. Moreover, the size of FSMs can be larger than PZT and MEMS mirrors [46]. In a typical PZT actuator, laminated stacks of piezoelectric material are packed in a steel cylinder and triggered by a modulated high voltage. PZT-actuated mirrors offer high response speeds and are capable of moving fairly large optics. Moreover, PZTs may perform small displacements, showing a higher resolution than voice-coil actuators. However, PZTs suffer from a very limited angular range of motion, typically on the order of a milliradian [50], [58]. Furthermore, the actuation technology of PZT mirrors may generate non-linearity on the motion range and that may require the use of a complex closed-loop controller. MEMS deformable mirrors (DMs) are tiny integrated mirrors that are capable of reflecting an incident beam by deforming a reflective surface [59]. These DMs are manufactured by combining silicon-based microelectronics, micro-machining technology, and micro-optics. As a combination of MEMS and micro-optics, MEMS DMs are referred to as micro-opto-electromechanical system (MOEMS) mirrors. MEMS DMs can be implemented by using multiple micro mirrors that are positioned adjacently and capable of moving in parallel and independently of each other [60], [61]. These micro-mirror arrays may be classified under a category called spatial light modulators, where the amplitude or phase of a light beam is manipulated by the optical components (i.e., tiny mirrors) [61], [62]. Another way of implementing MEMS DMs is by using a a thin layer of reflecting material, called membrane, and an actuator array beneath the surface, which is used to reshape the membrane [59]. Figure 4 shows a MEMS DM that has multiple actuators controlling the flexure of its reflective surface. Although MEMS DMs are typically used in wavefront shaping for adaptive optics, they are also capable of performing tip/tilt (and sometimes piston) moves [63], [64]. Gimbal-less designs of MEMS DMs are engineered to perform tip/tilt motions at high speed for both axes while requiring low power [65]. Section II-D presents an additional discussion on MEMS DMs.

A compact antenna design for FSO communications using a miniature fine positioning mirror (i.e., a fast steering mirror with a tracking control bandwidth of 1 kHz) to couple the received power to a single mode fiber was proposed [66]. This design mitigates the power fluctuations caused by atmospheric turbulence. The ATP mechanism used in this FSO communications system employs four beacon lights to determine the orientation of the remote optical terminal, a charge couple device (CCD) camera for coarse tracking and initial alignment, and a quadrant photo detector (QPD) for fine tracking. These coarse and fine tracking mechanisms are combined to achieve effective beam tracking and maximization of the received power. A digital signal processing unit controls the actual position of the optical antenna by analyzing the output of the CCD, or beam position. The QPD tracks the beacon lights by comparing the output signals gathered from its quadrants. If the beam spot is at the center of the QPD, output voltage levels from all the quadrants are almost equal, implying that the laser beam is well aligned. Although this FSO communications system is tested and validated for stationary FSO terminals transmitting at a data rate of 2.5 Gbps, the working principle of the ATP mechanism has also been employed in mobile FSO



(a) The surface of the deformable mirror is flat when no voltage is applied to its actuators.



(b) Adjusted curvature of the deformable mirror when voltage is applied to its actuators according to the incident beam's wave-front aberrations.

Fig. 4. A MEMS deformable mirror with multiple actuators beneath its reflective surface.

stations, including high-speed trains [67]–[71].

Mirror-based ATP mechanisms are found applied in FSO communications systems for high-speed trains [67]–[69], [71]. These ATP mechanisms are responsible for maintaining an optical link between the ground stations and the train. One of the challenges in this application is train-induced vibrations. These vibrations may jeopardize the connectivity between a ground station and a transceiver on the train. The effects of these vibrations must be overcome by the ATP mechanism [41], [71]. An ATP mechanism for these trains is also critical for performing handovers when the train moves from the range of a station to another. One objective of an efficient handover is to reduce or eliminate disconnection time when handover is performed. Therefore, the use of FSO communications for high-speed vehicles, such as high-speed trains, may mitigate the negative impacts of frequent handovers of RF technologies by increasing the communication range [72], [73].

A high data-rate ground-to-train FSO communications system for high-speed trains using a mirror-based ATP was proposed [69]. The application of this system is to perform tracking, pointing, and handover for high-speed trains [67]–[70]. Each FSO transceiver in this proposal employs light emitting diodes (LEDs) with wide beam characteristics as beacon lights. The ATP system uses two QPDs, one with a wide-angle lens and the other with a telescopic (i.e., narrow) lens. These two QPDs are used to control an FSM that corrects a possible misalignment of the incident beam. The QPD with the wide-angle lens has a wider field-of-view as compared to the one with the telescopic lens and performs acquisition and coarse tracking. When the beacon light is captured and aligned at the center of the wide-angle QPD (i.e., the optical link becomes stable), the ATP mechanism switches to fine tracking mode to perform high precision alignment of the received beacon light using the telescopic lens. Incident light differences on the quadrants of QPDs generate voltage differences to control the actuator of the FSM that aims to direct the received beam to the center of the QPDs. As the train moves along the track, an FSO link is maintained between the train and ground stations for continuous communications. Therefore, a handover must be performed by the train with every two neighboring base stations (BSs), which are referred to as the source and target BSs. An overlapping region illuminated by the source and target BSs allows the transceiver on the train to capture two beacon lights and to switch from the source BS to the target BS during the handover. Performing handovers depends on the voltage differences generated by the inequality of the incident light on the quadrants of the wide-angle QPD. When the train's FSO terminal enters the coverage area of a target BS, the wide-angle lens of the train's FSO transceiver captures the beacon light emitted from the target BS in addition to the beacon light that is currently being received from the source BS. This voltage difference triggers a handover if the difference is greater than a predefined threshold. Handover execution is then performed by steering the FSM of the receiver FSO terminal until the new beacon light is centered. The handover procedure also includes MAC and IP address exchange between the source and target BS and the transceiver on the train [74]. Seamless handover may not be possible unless two or more transceivers connected to different BSs are employed [75].

In another version of a mirror-based ATP mechanism for FSO communications of high-speed trains, the wide-angle lens is replaced by a high-speed image sensor [71]. Figure 5 shows a simplified block diagram of this ATP mechanism. In this figure, the image sensor with a size of 512x480 pixels allows high-speed detection and acquisition of the beacon light emitted from the target BS and decreases the total handover time by providing a more precise position of the target BS than a QPD. Moreover, this image sensor captures 20 frames per second and uses image processing to detect two different beacon lights, one from the source and the other from the target ground stations, at the same time. The train's station starts a handover after detecting two beacon lights from different ground stations. Coarse tracking is performed by the high-speed image sensor, and fine tracking is performed by the QPD. Both the outputs of the image sensor and QPD are used to control the movement of the FSM in two dimensions. In addition, the ATP mechanism uses a proximity sensor that detects the distance between the mirror and the base plate of the mirror. The experimental results in this work demonstrate that the proposed ATP mechanism can perform a physical-layer handover in 31 ms for an automobile traveling at 90 km/h.

C. Gimbal-Mirror Hybrid ATP Mechanisms

Hybrid ATP mechanisms employ a gimbal and an FSM in tandem to perform both coarse and fine tracking. Mounting an FSM on a gimbal provides a wide field-of-regard, which is the area that can be covered by a movable sensor, to the hybrid ATP mechanism as an addition to the fine tracking capability of the FSM.

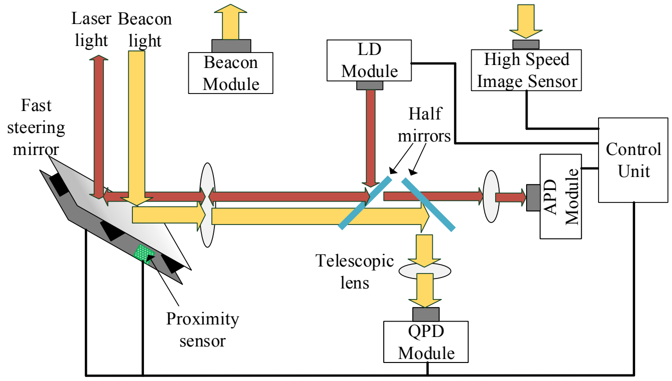


Fig. 5. Simplified block diagram of an ATP mechanism designed for FSO communications of high-speed trains [71].

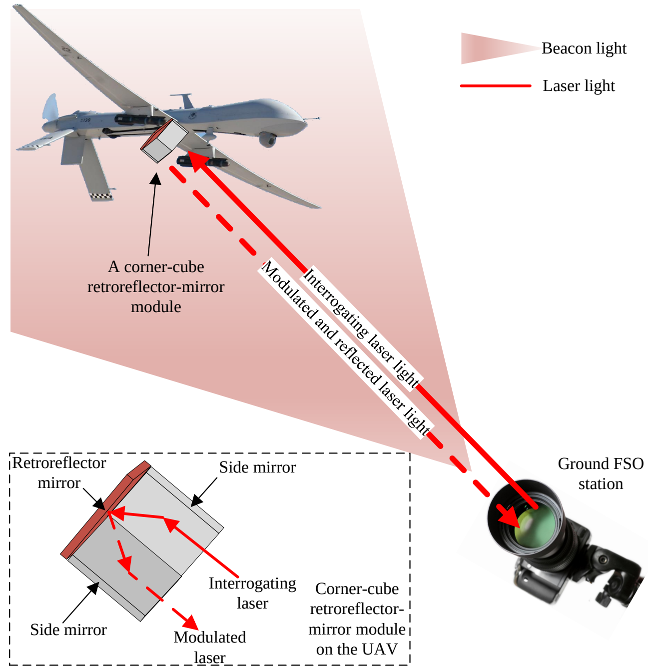


Fig. 6. Conceptual illustration of the hybrid ATP mechanism on the ground and a retroreflector mirror mounted onto the UAV to modulate and reflect back an interrogating laser.

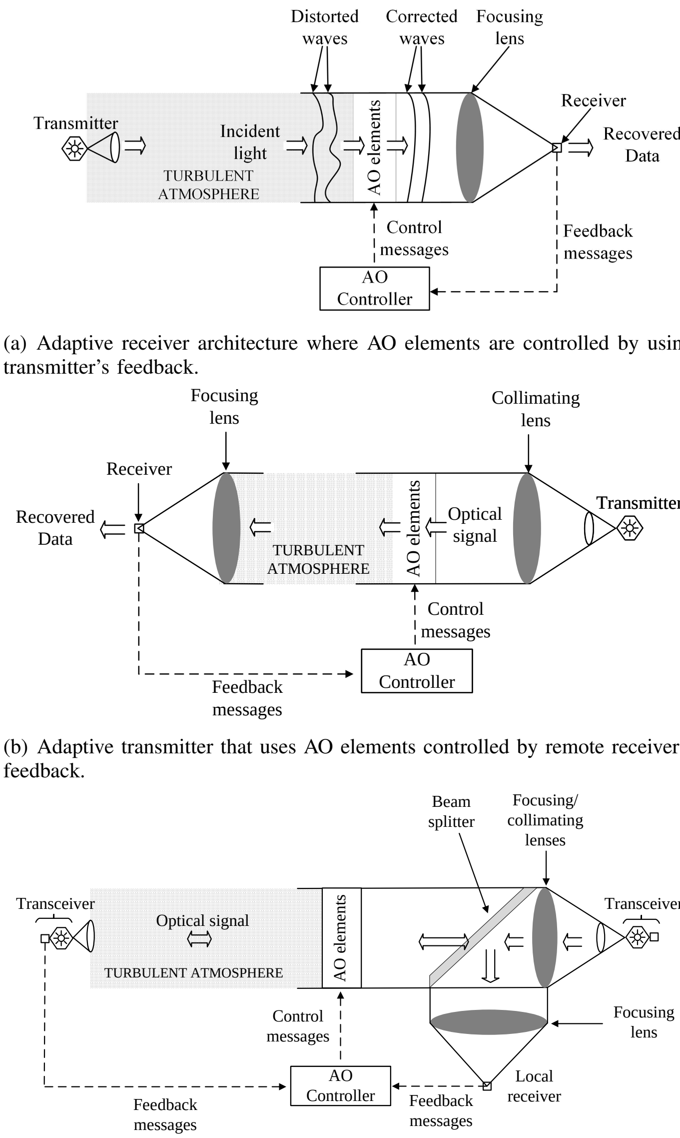
An air-to-ground FSO communications system equipped with a MEMS retroreflector mirror as the main component of the ATP mechanism on an UAV was proposed [45]. The ground station of this FSO communications system consists of a gimbal and an FSM. The hybrid ATP mechanism on the ground, using a gimbal and FSM, provides coarse and fine pointing. Figure 6 shows a conceptual illustration of the proposed UAV-to-ground FSO communications system. The retroreflector mirror in the UAV modulates a continuous interrogating laser emitted from the ground FSO station and reflects it back to the ground with encoded information. The retroreflector mirror in Figure 6 can be identified with the shape of a corner cube with two side mirrors. The coarse pointing and tracking of this ATP mechanism is performed by using a global positioning system (GPS) to provide the position of the UAV to the ground station. The provided GPS position of the UAV is used by the gimbal in the ground station to continuously track the trajectory of the UAV and transmit (IR) an infrared beacon light to illuminate the UAV. The beacon laser forms a spot size of around 5 meters to always illuminate the UAV and compensate for possible GPS errors. A motorized lens guarantees that the spot size remains constant regardless of the distance between the UAV and the ground FSO terminal. The reflected beacon from the UAV's retroreflector mirror is captured by an IR camera on the ground, and a combination of control signals provided by the GPS and the IR camera is used to control the movement of a gimbal, which is capable of positioning the beam with a resolution of 0.0064° and an angular speed of up to 100°/s, to track the UAV. The fine pointing stage of this ATP mechanism involves the use of the FSM to correct the fine misalignments of the interrogating communication laser. Note that current GPS technology provides an accuracy of 4.9 m under open sky, and that is used to perform accurate localization and tracking if the beam width of a beacon light illuminates an area with a size of 4.9 meters or larger at a distance where the FSO receiver is located [76], [77]. Beam width is the size of a beam's footprint at a given distance from the transmitter of the beam. Moreover, super-accurate GPS chips will be released to provide an accuracy of 30 cm [78]. These new GPS chips may allow to decrease the beam width of a beacon light down to 30 cm.

A hybrid ATP mechanism that employs an array of MOEMS mirrors and a motorized positioning system, or gimbal, was proposed for a ground-to-satellite FSO communications system [79]. This approach considers communications through air turbulence. MOEMS mirror array performs fine tracking operation with an angular motion range of $\pm 5°$ in x and y axes. This mirror array is mounted on a motorized platform having an angular motion range of $\pm 15°$ for acquisition and coarse tracking. The ground station consists of electronic-control circuitry based on field-programmable gate arrays, a positioning system and illuminating optics in addition to MOEMS mirrors, and a motorized positioning system. The ground station emits a collimated laser beam, which is reflected by MOEMS mirrors towards the satellite. A QPD on the ground station is used to calculate the displacement of the emitted laser beam from its center and generates a feedback signal to adjust the mirrors. An optical turbulence generator chamber is placed between the MOEMS mirror array and QPD to regenerate temperature-induced atmospheric turbulence conditions for experimental testing.

D. Adaptive Optics

Adaptive optics (AO) is a technology inherited from astronomical telescopes. AO corrects wave-front distortions of optical waves through atmospheric turbulence by using DMs and wave-front sensors [80]. AO finds use cases in FSO communications because atmospheric turbulence is a deteriorating factor for the transmitted beams in FSO communications. Turbulence may limit the maximum achievable data rate of FSO communications as it causes beam spreading, beam wander, and scintillation, especially for long distance (e.g., greater than 1 km) [80]–[82]. An AO may help in these cases as it is used to perform low-order beam-aberration correction and nano-scale beam steering. Moreover, AO can be combined with a tip/tilt mirror to correct high-order beam aberrations, which corresponds to beam steering in a wider range than AO alone can perform. Specifically, AO has been proposed for improving the received power and bit error rate (BER) of an FSO link by mitigating the atmospheric-turbulence-induced effects. AO mechanisms usually rely on DMs to correct deformations of incoming wave fronts. DMs based on MEMS are the most widely used technology for compensating or mitigating the wave-front phase distortions [59]. DMs provide one of the highest position resolutions among all ATP categories; they can be adjusted with a nrad resolution [59]. In conventional AO mechanisms, a wave-front sensor is generally used to measure wave-front distortions. These measurements are then interpreted to perform wave-front control by using a DM or a combination of a tip/tilt mirror and a DM. High-order aberrations are corrected by DMs [7]. However, strong intensity scintillations make wave-front measurements difficult to perform and hard to correct with conventional AO mechanisms [7], [80]. Therefore, non-conventional AO mechanisms may be used to avoid wave-front measurements in strong scintillation scenarios. These non-conventional AO mechanisms typically use model-free optimization methods to maximize a system performance metric, such as the Strehl ratio or the received power without employing a wave-front sensor [7], [80].

A non-conventional AO can be implemented through different architectures: adaptive receiver, adaptive transmitter, or adaptive transceiver, where all architectures adapt themselves to varying atmospheric-turbulence conditions and correct the transmitted distorted waves [80]. Figure 7 shows the diagrams of non-conventional AO mechanisms. In the first mechanism of this figure, the adaptive receiver accommodates AO elements (i.e., mirrors, control mechanism, and all other equipment related to AO) at the receiver. The received signal with possible turbulence-induced distortions are corrected at the receiver by using a local feedback mechanism. The receiver sensor generates feedback signals based on a system performance metric, such as received signal strength, which is then used to control the AO elements, as Figure 7(a) shows. The adaptive receiver may only correct the light waves that have already entered the receiver aperture. Therefore, an adaptive transmitter may be used to increase the irradiance at the receiver by pre-compensating the wave-front distortions, as Figure 7(b) shows [80]. In the adaptive transmitter architecture, the transmitted beam is corrected before is sent through the air. Feedback messages are generated by the remote receiver and sent through a separate wireless link using RF. Note that the reaction time of wave-front correction may increase as the propagation distance between the FSO terminals increases. Another way to notify the transmitter about the wave-front distortions is by emitting an auxiliary beacon light from the remote receiver. This operation assumes that the beacon light experiences almost the same conditions the laser beam does. Therefore, the transmitter optimizes the received power by adjusting the AO elements to pre-compensate for the wave-



(a) Adaptive receiver architecture where AO elements are controlled by using transmitter's feedback.

(b) Adaptive transmitter that uses AO elements controlled by remote receiver's feedback.

(c) Adaptive transceiver architecture combines feedbacks from local and remote receivers to control AO elements.

Fig. 7. Non-conventional adaptive optics architectures [80].

front distortions of the laser beam. In an adaptive transceiver architecture, the received and transmitted beams propagate through the same adaptive optical system. Feedback messages in this architecture may be originated by the remote receiver, or by a local receiver that receives a portion of the beam through a beam splitter, or by a combination of these two approaches, as Figure 7(c) shows.

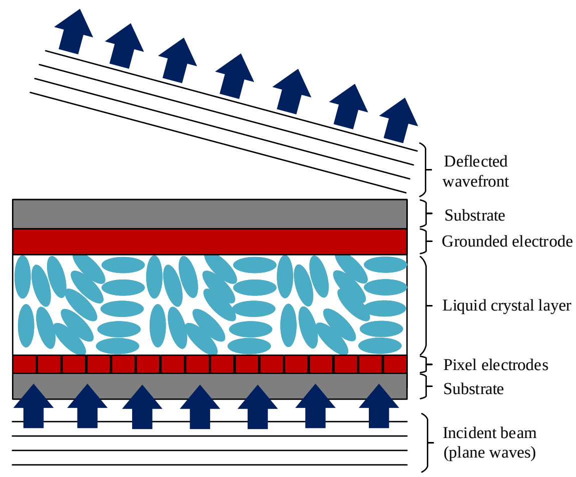
An AO mechanism has been proposed for high-resolution wave-front correction under strong scintillation conditions [80]. It employs a MEMS DM as wave-front corrector, a slow tracking mirror to correct large-scale pointing errors caused by thermal expansion of the buildings where FSO terminals are attached, and an FSM to compensate for tip/tilt errors [80]. The MEMS DM is managed by a controller that runs the stochastic parallel gradient descent (SPGD) algorithm [83]. This algorithm aims to maximize the received optical power by iteratively minimizing the distortion of the captured images of the received light using an imaging sensor. The stochastic version of the algorithm converges faster than the batch gradient descent [84] and yields a reasonably good approximation to the actual minimum of the cost function that maximizes the received power in practice [85]. Moreover, the application of the SPGD algorithm and its implementation on very-large-scale integration technology make the high-speed and real-time compensation of phase aberrations of a laser beam feasible when the number of control parameters, which are typically voltages applied to wavefront-corrector electrodes, is large [85], [86].

E. Liquid-crystal-based ATP mechanisms

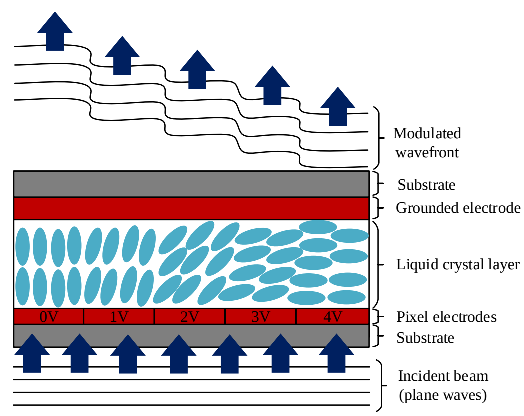
Liquid crystal (LC) based ATP mechanisms use non-mechanical, fine beam-steering devices that consist of one-dimensional array of tens of thousands of long thin electrodes to manipulate the amplitude or phase pattern of a light beam [87], [88]. The refractive index of the LCs on top of a pixel electrode layer can be controlled to produce a modulated wavefront or a diffractive grating that deflects the beam towards the intended direction with a desired angle (within the angular range of the device). The refractive index variation of the LCs is achieved by applying a voltage to each electrically addressable pixel of the device. The LC devices can be transmissive or reflective [62]. The transmissive LC devices steer or modulate the light when it passes through the device, whereas the reflective LC devices steer or modulate the light by means of their reflective surfaces. Figures 8(a) and 8(b) show transmissive LC devices that steer and modulate an incident plane wave by using the orientation of their liquid crystals, respectively. Different voltage levels applied to the pixels underneath the LC layer generate the orientation variation of the liquid crystals. Liquid crystals or liquid-crystal-based spatial light modulators are non-mechanical fine beam-steering devices. These devices can be used in an ATP mechanism that requires low cost, low power consumption, light-weight and sub-mrad steering accuracy. Acquisition, tracking, and pointing operations can be performed in a similar way as that performed by a fast-steering mirror. Note that the idea of using liquid crystals as a beam steering device in an ATP mechanism is to enable sub-mrad steering ability, which is the outstanding feature over other beam steering devices, such as mirrors.

The LC devices offer several other advantages, such as low cost, low power consumption, light-weight, and the ability of agile redirection of the steering elements, over the mechanical light modulators and conventional DMs [87], [89], [90]. Moreover, LC-based ATP mechanisms can be quickly reconfigured to provide random access beam steering [88]. A disadvantage of LC-based ATP mechanisms is the limited angular motion range (e.g., ± 4 mrad [90]).

A study that combines multiple layers of fine LC beam steering modules provides wide-angle (i.e., $\pm 40^\circ$) coarse beam steering [90], [91]. This transmissive multi-layer beam steering approach stacks multiple fine beam-steering modules, each of which covers an effective angular range of $\pm 1.25^\circ$, to yield a total angular range of $\pm 40^\circ$ in two dimensions with a resolution of $\pm 1.25^\circ$ [91]. Each individual steering module in this mechanism is a thin, transmissive, and birefringent film. The technique used in this mechanism is called liquid crystal polarization grating [92]–[95], where the incident light can be selectively steered to a specific direction depending on the handedness of the polarization of the input light. To provide a total of 2^{N+1} distinct steering angles for the final wide-angle coarse steerer, N single-stage fine steering modules are required. For instance, if five single-stage steering modules (i.e., $N = 5$) with a resolution of $\pm 1.25^\circ$ are cascaded, a total angular coverage of $\pm 32^\circ$, or 64° (i.e., $2^{(5+1)} = 64^\circ$), is provided.



(a) A transmissive liquid-crystal-based spatial light modulator that steers incident light.



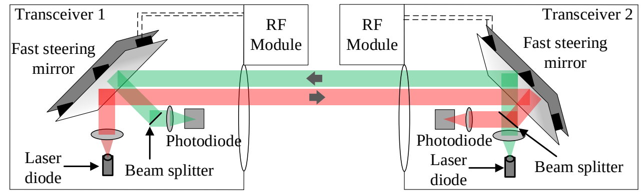
(b) A transmissive liquid-crystal-based spatial light modulator that modulates incident light.

Fig. 8. A transmissive liquid-crystal-based spatial light modulator that steers and modulates incident light by applying different voltage levels to pixels under the liquid crystal layer.

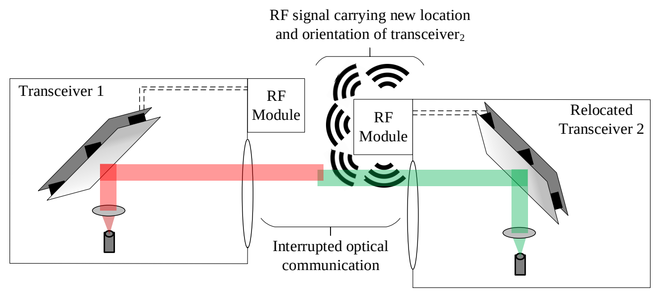
F. RF-FSO Hybrid ATP Mechanisms

Ground-to-mobile, mobile-to-ground, or mobile-to-mobile FSO communications require fast re-acquisition of the light signal to minimize link outage time when LOS between two communicating FSO terminals is temporarily blocked by an obstacle, such as a bird or a tree [96]. Moreover, dense fog or clouds can be considered as other obstacles similar to opaque objects, which may cause the optical link between the communicating transceivers to be interrupted temporarily. In this case, RF-based signaling can be used as an auxiliary link where the positioning messages are transmitted when the FSO link is down. This means that beacon lights used in an ATP mechanism can be substituted by an RF module to help the remote terminal to point the laser beam to its counterpart. The position-conveying role of the RF link of an RF-FSO hybrid ATP mechanism becomes more important when terminals are mobile. Figure 9 shows a fast re-acquisition scenario for an RF-FSO hybrid ATP mechanism where the optical link between two transceivers, Transceivers 1 and 2 in the figure, is restored by using the RF link carrying the location and orientation information of Transceiver 2 after this transceiver relocates and the optical link is interrupted. In addition to conveying positioning messages, an RF link in an FSO terminal may be used as an auxiliary link to maintain the communication between the optical terminals when the FSO link is unavailable because of LOS blocking or severe weather conditions. The omni-directional nature of its propagation model and the ability to penetrate through opaque objects make RF a suitable candidate as an auxiliary link in FSO communications systems. However, RF provides low data rates with a limited communication range as compared to an FSO link. Moreover, the cost and complexity of an FSO communications system increase if an RF-FSO hybrid ATP mechanism is employed because of the additional RF module.

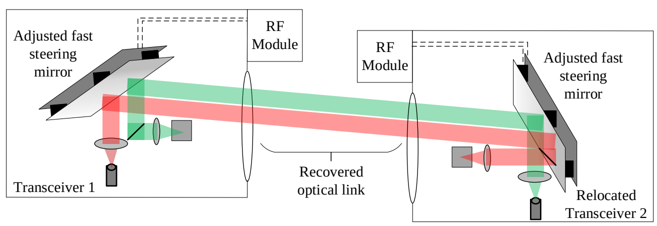
An ATP mechanism that employs an auxiliary RF link to transmit the position of a moving vehicle is demonstrated as a part of a vehicle-to-ground FSO communications system comprising of a stationary optical ground station and a vehicle traveling at a speed of 30 km/h [96]. The distance between the ground station and the vehicle varies from 1,300 to 1,900 meters. An intensity-modulated laser light with a wavelength of 1550 nm and a transmission power of 180 mW is used as the light source, which transmits video at 1.5 Gbps from the mobile terminal to the ground station. The mobile FSO terminal is equipped with a transmitter laser telescope, a tracking camera capable of performing azimuth/elevation moves to capture the incoming beacon from the ground station, and a GPS system to provide location information. The mobile terminal's location information is sent through a low-rate RF link operating at 868 MHz to the ground station. The ground station is equipped with a 500-mW beacon light to indicate its location to the vehicle. Moreover, an InGaAs tracking camera for fine pointing and a 200-mm receiving telescope, positioned on an azimuth/elevation mount to face towards the direction of the mobile terminal, are used by the ground station. This hybrid FSO communications system was demonstrated using obstacles to temporarily block LOS between the two parties. In the case of temporary blocking, the light signal is re-acquired by using the RF link that conveys the positioning information of the remote mobile terminal. The optical communication immediately resumes when the LOS is cleared by means of this ATP mechanism.



(a) Two communicating RF-FSO hybrid transceivers.



(b) The optical link between Transceivers 1 and 2 is interrupted when Transceivers 2 is relocated. Transceiver 2 uses its RF link to convey its new position and orientation to transceiver 1.



(c) A fast re-acquisition is performed by Transceiver 1, and the optical link between Transceivers 1 and 2 is re-established.

Fig. 9. A fast re-acquisition and pointing scenario for an RF-FSO hybrid ATP mechanism where the optical link between Transceivers 1 and 2 is restored by using an RF link carrying the location and orientation information of Transceiver 2 after this transceiver relocates.

G. *Other ATP Mechanisms*

Here, we list other state-of-the-art ATP mechanisms that do not fall in the aforementioned categories.

a) Rotating Head: A rotating head mechanism is proposed for FSO communications between two autonomous mobile nodes [52]. A movable head carries an FSO transceiver, capable of mechanically rotating 360°, to maintain LOS between the mobile nodes. The feasibility of a simple FSO auto-alignment system between mobile nodes by only employing a compass and a steerable FSO transceiver is provided in this rotating head mechanism. The mobile nodes are initially unaware of each other's moving directions and they move in random directions by following straight lines. The first phase to establish the FSO link between the nodes is the discovery phase. During the discovery phase, both nodes continuously rotate their steerable heads in the same direction (both clockwise or counter-clockwise) and periodically send synchronization (SYN) frames to establish LOS. When one of the nodes receives a SYN frame, it sends a synchronization acknowledgement (SYNACK) frame back as a reply and waits for an acknowledgement (ACK) frame from the remote party to complete a three-way handshake. Receiving an ACK frame finishes the discovery phase as it guarantees that the transceivers of both nodes are facing each other by having LOS between them. While establishing the link, nodes also exchange the information about their velocities, the direction in which they are moving and the orientation of their rotating heads. A node's compass is used to provide the information about its movement direction and the orientation of its head. In the second phase, the maintenance phase, recently acquired LOS in the discovery phase is maintained by rotating the heads of the nodes as they move. Each node calculates an angular velocity and the rotation direction of its head to keep the LOS with the remote party. The nodes exchange their velocity and their movement information for recalculation of their head's angular velocity and the rotation direction. All the calculations on angular velocity and the rotation direction of the steerable heads are based on the orientations of the nodes and local geometric computations. The nodes periodically perform the three-way handshake to check whether the link remains. If not, they go back to the discovery phase and restart the procedure. The rotating head used in this ATP mechanism resembles a gimbal with a limited movement capability where the motion is restricted to the horizontal plane.

Another rotating head mechanism is proposed to maintain an FSO link between two autonomously flying UAVs as a 3D system [97]. These rotating heads carrying FSO transceivers are mounted onto the UAVs and have a hemispherical structure capable of rotating 360° in the horizontal plane and 180° in the vertical plane. The steering capability of the rotating heads is used to maintain the LOS for FSO communications between two UAVs. It is assumed that UAVs are initially unaware of the locations of other UAVs within their communication ranges, and UAVs can only move along straight lines but in any direction. UAVs are equipped with inertial measurement units, which provide them with a sense of velocity and orientation. A proposed solution to establish and maintain LOS between the nodes consists of two phases: discovery and maintenance. In the discovery phase, UAVs exchange information about their velocities, the direction in which they move, their positions, and the orientation of their heads with the aid of GPS and RF communications to initially establish an FSO link. This information is then used to calculate and set the velocity and direction of rotation (clockwise/counterclockwise and up/down) of the heads on both UAVs. In-band information exchange using the FSO link takes place regularly in the maintenance phase to keep the nodes up to date about their moving directions. Each node recalculates the rotation velocity and the directions of its heads if the received beam deviates from its optical axis more than a pre-determined value, or the received signal-to-noise ratio (SNR) is smaller than a minimum threshold. The rotating head used in this mechanism may be considered as a two-axis gimbal, and it is referred to as a rotating head [97].

It is worth noting that the working principle of a rotating-head is the same as a gimbal-based ATP mechanism as both mechanisms use a mechanical head that can rotate in axes orthogonal to each other. However, gimbals are usually bulky devices that are rotated by servo motors [52]. Therefore, gimbals may not be appropriate for vehicles or moving stations

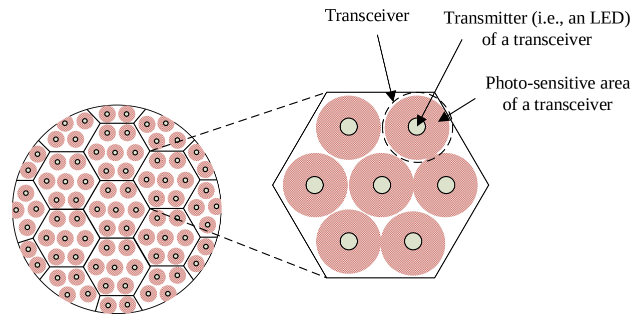


Fig. 10. A spherical node design with honeycombed array of transceivers covering the surface of an FSO node.

requiring a weight limit. For instance, UAVs must conform to a flying weight limit, which entails a low-mass FSO terminal, and hence a lightweight ATP mechanism [45]. On the other hand, rotating-head ATP mechanisms [52], [97] were proposed to be used in autonomously moving nodes and autonomously flying UAVs.

b) Spherical Node Design: A spherical FSO node design where the whole surface of the FSO node is covered by transmitter and receiver modules was proposed [6], [98]. The node is aimed at enabling FSO communications in mobile ad-hoc networks. The proposed design aims to provide angular diversity and a coverage with almost omni-directional LOS capabilities for all directions. The implementation of this node is realized by using a honeycombed array of transceivers covering the whole surface of the spherical FSO node, where each transceiver consists of a LED acting as a transmitter and a donut-shaped photosensitive area around the LED acting as a receiver. Figure 10 shows the conceptual design of the proposed spherical FSO node, covered by transceiver modules. The hexagon boards forming the surface of the spherical FSO node are equipped with multiple transceivers to provide a fully-covered angular range around the FSO node. This node design eliminates the use of a mechanical ATP mechanism. It instead incorporates an electronic auto-alignment mechanism to establish and maintain a continuous FSO communication link between two spherical FSO nodes by monitoring the incoming light beams from different transceivers and dynamically switching to the appropriate transceiver within LOS range.

Table I summarizes the capabilities, major features, and the application scope(s) of the surveyed ATP mechanisms. The beam pointing resolution of the ATP mechanism shows the pointing precision of the ATP mechanism in radians. The second feature, the field of regard, shows the total area that can be covered by the ATP mechanism. The wider the field of regard is, the larger the covered area becomes. The column of angular speed in the table shows the steering-speed capability of the ATP mechanism. If the steering speed is high, the ATP mechanism may be capable of tracking a fast-moving object. The mechanics of an ATP mechanism shows whether the working principle of the ATP mechanism is based on whether the parts are mechanical or electronic. The dimensionality column describes whether the ATP mechanism is applicable to a 2D or 3D space. The last column of the table provides the reported application scope of the ATP mechanism. Note that the ATP mechanisms in the table may not be limited to the reported application scope(s).

Table II lists the ATP mechanism(s) employed by a specific application of an FSO communications system. Note that a specific application in this table may not be limited to the provided ATP mechanism(s).

III. Classification of the ATP Mechanisms According to Their Use Cases

We list the use cases of FSO communications systems using a single or a combination of multiple ATP methods. In parallel to their use cases, we mention the requirements of the employed ATP mechanism that may be application-specific. Therefore, we first categorize the use cases of FSO communications systems under two major categories: outer space and terrestrial FSO communications. We then provide the mechanics and working principles used by the ATP mechanism to overcome challenges specific to the application. The outer-space FSO communications category includes satellite/ground-to-satellite/ground and deep-space FSO links [99]–[101], and the terrestrial FSO communications includes indoor and outdoor FSO links with building-to-building and ground/vehicle-to-vehicle/ground categories. Figure 11 shows this classification.

The ATP systems used in the outer-space FSO communications may be more sophisticated than those used in the terrestrial FSO communications systems because of the much greater distances between the communicating platforms. For instance, the lunar-laser communication demonstration (LLCD) [102], conducted by National Aeronautics and Space Administration (NASA), aims to provide laser communications between Earth and the moon, which are separated by a distance of 384,400 km. The long distance required for this outer-space FSO link introduces a major challenge, called pointing loss, for the ATP mechanisms. The pointing loss is the pointing error that is caused by the overall displacement of the received laser beam center from the center of the receiver aperture [103]. In such a distance, even a small vibration of a spacecraft may result in having the incident beam miss the receiver aperture, which may lead to communication interruptions. Therefore, an ATP mechanism for outer-space FSO links should be able to compensate for such pointing errors [104], [105]. The vertical atmospheric turbulence is another challenge to ground/satellite-to-satellite/ground and deep-space FSO communications links, where the transmitted beam goes through Earth's atmosphere and experiences different refractive indices at different altitudes [106], [107].

As compared to outer-space FSO communications, the light beam used in terrestrial FSO communications systems is transmitted over shorter distances (e.g., tens of kilometers) [108], [109]. One major challenge in terrestrial FSO communications is the atmospheric attenuation, where a major contributor is fog [34]. In addition to the atmospheric attenuation, terrestrial FSO links experience similar problems to those experienced in outer-space FSO links, such as atmospheric turbulence and pointing loss. The type of atmospheric turbulence for deep-space FSO communications systems; however, it is vertical, which is different from horizontal atmospheric turbulence that may be observed in terrestrial FSO communications systems [8]. Specifically, the transmitted beam in either ground-to-deep-space or deep-space-to-ground FSO communications may experience a more complex turbulence than that of experienced in terrestrial FSO communications as the beam travels through multiple atmospheric layers with different diffraction indices.

1) Outer-Space FSO Communications Systems: The first category of the outer-space FSO communications systems is the ground/satellite-to-satellite/ground FSO communications. Low Earth orbit (LEO) and geostationary Earth orbit (GEO) satellites may benefit from FSO technology because the mass and the power requirements of an optical terminal are smaller than those of an RF communications terminal [8]. As a ground/satellite-to-satellite/ground FSO application, the LLCD achieved a downlink data rate of 622 Mbps with a code word error rate of 10^{-5} and an error-free uplink with a data rate of 20 Mbps [102], [110]. The ATP mechanism used by the spacecraft of the LLCD project consists of high-bandwidth inertial sensors to provide local stabilization by mitigating spacecraft disturbances, such as vibration, a two-axis coarse positioning gimbal that provides a large field-of-regard for acquisition and coarse tracking, and a piezoelectric actuator to modulate the lateral position of the receive fiber in two axes for fine tracking [105]. Moreover, an uplink beacon is emitted from the ground station, which is received by a QPD at the spacecraft. This QPD is used to acquire and track the uplink signal.

As a follow-up effort to LLCD, NASA introduced another ground/satellite-to-satellite/ground FSO communications system, called Laser Communications Relay Demonstration (LCRD) [101]. This system aims to provide high-speed FSO links between two ground terminals by using an optical relay in outer space. The payload of the optical relay is planned to carry two optical transceivers to establish a real-time optical link between two ground stations on Earth. NASA has expressed interest in deep-space optical communications with direct applicability on long-haul FSO communications between Earth and Mars [111].

2) Terrestrial FSO Communications Systems: Terrestrial FSO applications can be used outdoor or indoor. We first detail some outdoor FSO applications and then elaborate on some indoor cases.

a) Outdoor FSO Communications Systems: Building-to-building, or in general, structure-to-structure, FSO communications are a category of outdoor FSO applications in which communicating optical terminals are stationary. The buildings, towers, bridges, or structures where the FSO terminals are installed may experience movements caused by thermal expansion, building sway, or seismic activity [34]. Therefore, to maintain FSO transceivers' alignment, stationary FSO terminals may require ATP mechanisms, which may be relatively less complex than those used in mobile FSO

TABLE I
CAPABILITIES, MAJOR FEATURES, AND THE APPLICATION SCOPE(S) OF THE SURVEYED ATP MECHANISMS

ATP Mechanism	Pointing Resolution (rad)	Field of Regard	Angular Steering Speed	Mechanics	Dimensionality	Application Scope
Gimbal-based	μrad	Wide	Low	Mechanical	2D	Any
Mirror-based	Sub-μrad	Narrow	High	Mechanical, piezoelectric and electromechanical	2D, 3D	Any
Gimbal-Mirror Hybrid	Sub-μrad	Wide	High	Mechanical, piezoelectric and electromechanical	2D, 3D	Any
Adaptive Optics	nrad	Narrow	High	Electromechanical	2D	Outer space communications
Liquid-crystal-based	Sub-μrad	Narrow for one stage	High	Electrical	2D	Terrestrial communications
RF-FSO Hybrid	Sub-μrad	Wide	Low	Mechanical	2D	Any
Rotating Head	Not known	Wide	Low	Mechanical	2D, 3D	Ground/vehicle-to-vehicle/ground
Spherical Node Design	N/A	360°	N/A	No moving parts (spatial re-use)	3D	Ground/vehicle-to-vehicle/ground

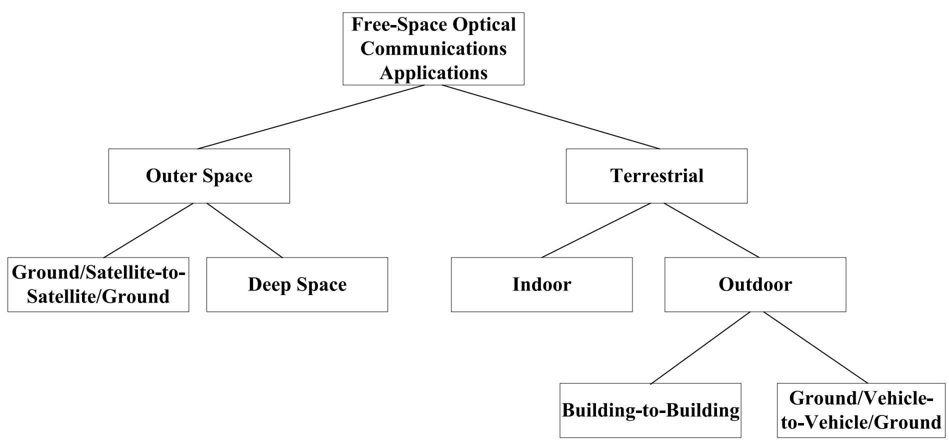


Fig. 11. Classification of FSO communications systems according to use case.

TABLE II
APPLICATIONS OF FSO COMMUNICATIONS SYSTEMS AND CORRESPONDING ATP MECHANISMS

Application	ATP Mechanism(s)
VLC / Indoor	Gimbal-based Mirror-based
Building-to-Building	Mirror-based AO RF-FSO Hybrid
High-Speed Trains	Mirror-based
UAVs	Gimbal-based Mirror-based AO Rotating Head
Balloons	Gimbal-based Mirror-based
Satellites	Gimbal-based Mirror-based AO
Deep Space	Gimbal-based Mirror-based AO

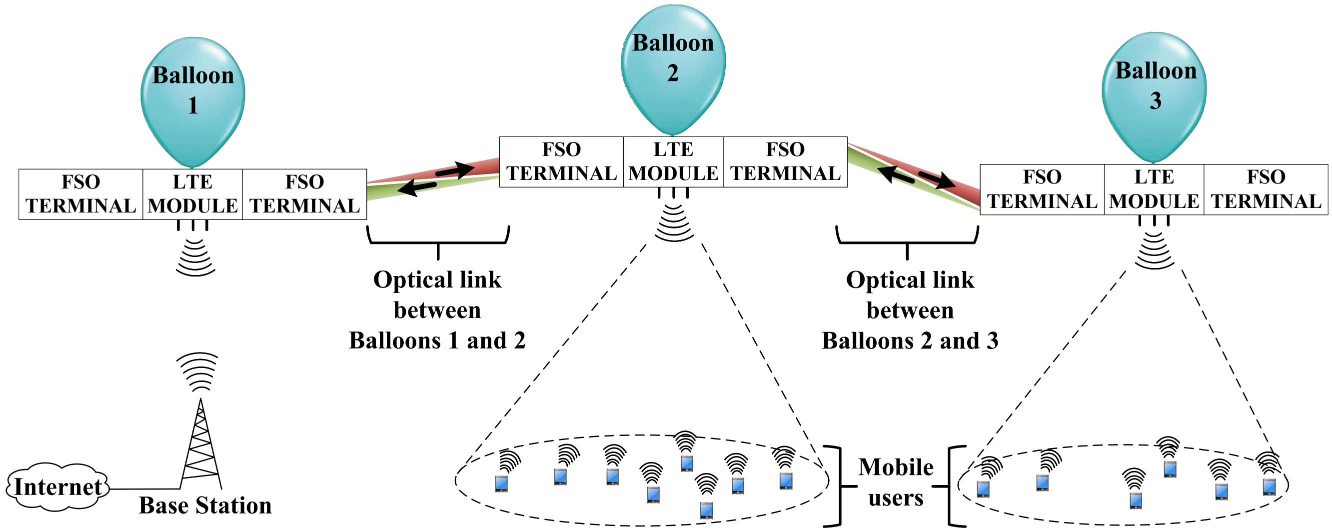
communications with very limited movements of the structures. Some commercial FSO terminals use proprietary auto-tracking mechanisms that do not employ moving platforms but allow the FSO terminals to track the communicating optical terminals over an angular FOV range [112]–[114]. It is worth noting that auto-tracking mechanisms used in stationary optical transceivers may be eliminated or relaxed if the transmitted beam is wide enough to compensate for pointing errors caused by the movements of the structures on which the FSO transceivers are mounted.

FSO communications systems find high applicability in ground/vehicle-to-vehicle/ground to provide high-bandwidth connectivity. A large-scale example is Google's project Loon [109]. This project aims at providing Internet access to people who live in regions that are unreachable or underserved. This project aims to construct a mesh network of high-altitude interconnected stratospheric balloons, placed at an altitude of approximately 20 km. The ground-balloon connectivity in this project, can be considered as a ground/vehicle-to-vehicle/ground terrestrial FSO application. This project uses FSO communications for inter-balloon links and LTE for base-station connectivity and user access. Figure 12(a) shows the structure of this project with three balloons. Balloon 1 is connected to a base station, and Balloons 2 and 3 act as relays and disseminators of the relayed data transmitted from the base station to the mobile users who use LTE-supported mobile devices. The balloons are placed on the stratosphere because there is no obstruction on LOS, and the atmospheric conditions of the stratosphere are well suited for laser propagation. Attenuating factors, such as clouds, fog, aerosols, and turbulence, in the stratosphere are significantly scarcer than at the ground level. The altitude and direction control of balloons are carried out by exploiting the wind layers in the stratosphere, where the balloons float to the east or to the west depending on the wind layer in which the balloon is positioned. Each balloon carries two FSO terminals, one for east-bound and one for west-bound communications. These terminals are used to construct an inter-balloon mesh network. Each FSO terminal of a balloon employs a beacon-assisted ATP mechanism that uses a two-axis gimbal to control the orientation of its FSO transceiver and a CMOS sensor that uses an image processing algorithm to keep track of the beacon image. The GPS position of a target balloon and the attitude of the source balloon collected from the differential GPS are used in the gimbal for initial pointing and signal acquisition. A similar pointing operation is performed on the respective balloon at the other end of the link for a mutual beacon acquisition. When the mutual gimbal pointing between the corresponding FSO terminals is achieved, a beacon search starts on both FSO terminals. After a successful beacon acquisition by both parties, an optical connection is established, and the ATP mechanism switches to the tracking phase to maintain the optical link as the balloons travel. This concept was demonstrated in flight tests, where a bidirectional optical link was established with a full duplex data rate of 130 Mbps, at distances beyond 100 km.

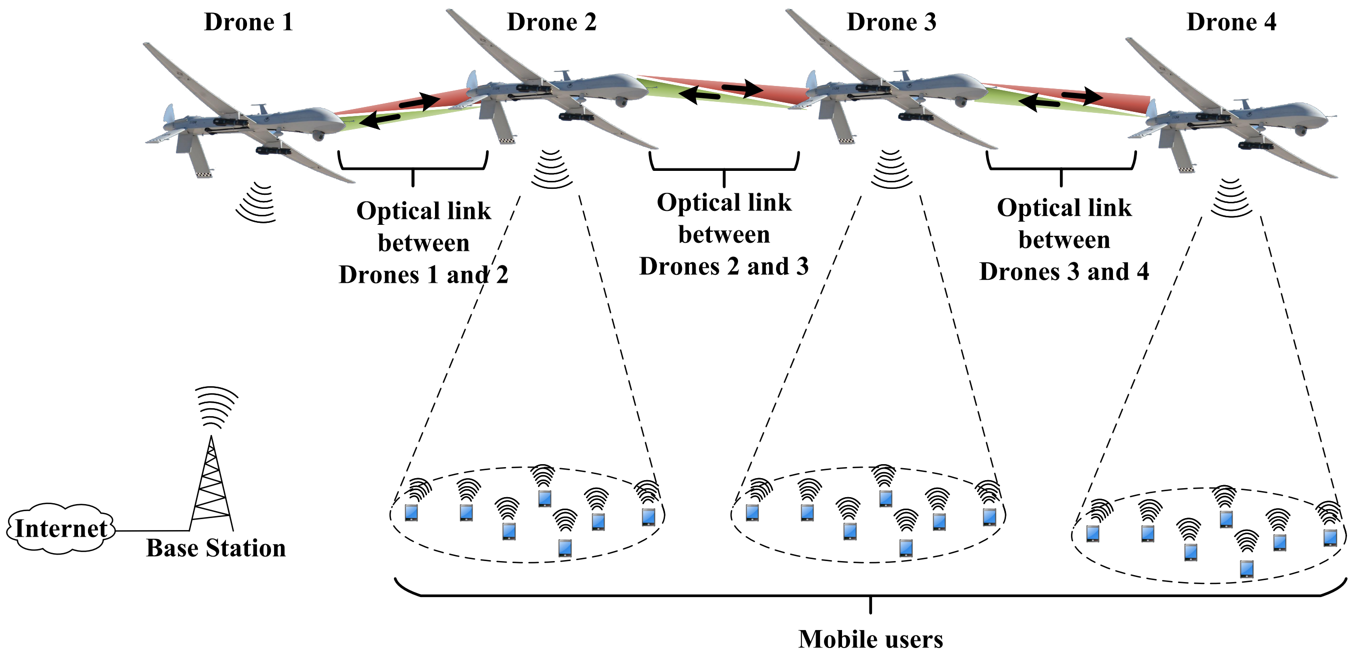
GPS is a widely-used technology for localization and position tracking of mobile FSO stations outdoors [45], [96], [97], [108]. GPS location information is also used to locate a mobile FSO station and point the remote FSO terminal towards the mobile station. GPS may not provide the exact location of a mobile FSO station because of satellite signal blockage due to buildings, bridges, or other opaque objects, lack of GPS signals when GPS is used indoor or underground, or multipath propagation of GPS signals that are reflected off buildings or walls [77]. Location and position tracking becomes more challenging for high-speed moving FSO stations, such as high-speed trains. An inertial measurement unit (IMU), a device used to measure and report three axis acceleration and angular turning rate of a body by using a combination of accelerometers and gyroscopes [115], can complement GPS usage to provide more accurate location and orientation information of a mobile FSO transceiver [108]. Another complementary localization technique to GPS can be a local positioning system, which is defined as a navigation system that works locally and provides location information of a mobile device in a local vicinity. A local positioning system uses signals from cellular base stations, Wi-Fi access points, or radio broadcast towers as beacon signals to calculate the location of a mobile device [116]. Moreover, application-specific localization and position-tracking solutions, such as communications-based train control systems, may provide high-accuracy and high-resolution location of a high-speed train. For instance, the European rail traffic management system is a communications-based train control system used to locate and track high-speed trains in Europe [117].

Internet.org is another initiative that aims to provide Internet service to the parts of the world where people have no Internet access [118], [119]. Similar to Google's project, Internet.org plans to deliver Internet to the developing world via solar-powered high altitude (i.e., 20 km) drones and satellites that are interconnected using FSO links [120]. This project plans to use low-Earth orbit and geosynchronous satellites, and drones equipped with both optical terminals and RF wireless (e.g., LTE) transceivers to provide Internet access to the low-density areas and dense suburban regions, respectively. The drones use FSO communications to establish inter-drone links and to relay data between mobile users and a ground base station. Moreover, the drones use RF wireless transceivers to disseminate data to the regions where they fly over. Similarly, satellites would deliver Internet access to less populated areas, but from higher altitudes. Therefore, the Internet.org project may be considered an application that combines ground/vehicle-to-vehicle/ground terrestrial and outer-space FSO communications. Figure 12(b) shows the structure of the Internet.org project consisting of four drones. In the Internet.org initiative, transceivers use a two-axis gimbal with a field of regard of $\pm 30^\circ$ for air-to-air and air-to-ground laser communications [55]. This hemispherical gimbal is equipped with two servo motors to facilitate rotations in two dimensions and two inner FSMs for fine field-of-regard adjustments. The lightweight design of the selected gimbal provides a wide field-of-regard, and employs an aperture large enough to meet a desired link budget. The link budget estimation of an FSO communications system sums the transmission power with all types of gains and losses affecting the received power at the receiver [121]. Moreover, this ATP employs a coude-path, a system of connecting tubes and relay mirrors required to direct the unexpanded laser beam into a telescope [122], that carries the light between an FSM and the optical bench where acquisition and tracking components are contained. In the same project, a monolithic gimbal design, where the incoming and outgoing beam use the same optical path, is adopted. The optical bench and the coude-path are modular parts that can be customized for different applications. For instance, separate optical paths with dedicated FSMs for each incoming and outgoing beams may be employed in an FSO communications system for fast-moving mobile objects.

b) Indoor FSO Communications Systems: FSO communications systems have also been proposed for both stationary and mobile indoor communications [36], [123]–[127]. In addition to laser diodes, LEDs may be employed for indoor FSO communications. Indoor FSO communications systems are called visible light communications (VLC) systems when the wavelengths used for communications are in the visible range of the spectrum [128]–[130]. The term of optical wireless (OW) is used to represent the superclass that includes both FSO and VLC. There are different channel configurations,



(a) A sample structure of Google's project Loon with three balloons.



(b) A sample structure of Internet.org project by Facebook consisting of four drones.

Fig. 12. Examples of terrestrial FSO communications projects: **(a)** Google's Project Loon and **(b)** Internet.org by Facebook.

such as directed LOS, non-directed LOS, hybrid LOS, directed non-LOS non-directed non-LOS, and hybrid non-LOS, for indoor OW communications systems [39], [130]. In the LOS category, there is a direct LOS path between a transmitter-receiver pair. In the non-LOS category, the transmitted beam may be reflected from surfaces or objects before it arrives at the receiver. Arrival time differences of the optical signals that follow different paths may cause a problem called inter-symbol interference, which may generate distortion on the received signal [128]. For directed configurations, both transmitter and receiver are directed to a specific point or direction. In this configuration, narrow-beam transmitters and narrow FOV receivers may be employed to increase power efficiency and immunity of the optical link against distorting effects, such as ambient and artificial light. For non-directed channel configurations, both transmitter and receiver are not pointed to a specific direction. Instead, they use wide beam transmitters and wide-FOV receivers to establish an optical link between the transmitter and receiver. Moreover, hybrid channels combine different configurations, where the transmitter and receiver may be pointed to different directions. For instance, a narrow-beam transmitter may be pointed to a wide-FOV receiver that is not directed to a particular point in the hybrid channel configuration. In this configuration, the transmitted beam may be bounced from wall(s) before it is received by the receiver. As in outdoor FSO communications systems, indoor OW communications systems using narrow beam(s) may require a tracking system to accommodate user mobility [128]. For such an indoor tracking system, localization of the mobile FSO transceiver within a room is required. GPS cannot be used to locate the mobile device in the room due to the lack of indoor signal coverage of GPS. Angle of arrival and time difference of arrival based localization techniques that employ multiple optical anchors illuminating the mobile FSO transceiver in the room have been proposed to solve this problem [131]–[133].

On the other hand, using multiple beams to cover a whole room as well as employing wide beam systems may relax or eliminate the need for an ATP system. For instance, a non-directed non-LOS configuration, which is also called a diffuse system, is considered as a robust and easy-to-implement system for mobile indoor communications and it does not require an ATP system, even for a mobile optical receiver [39], [134], [135].

A non-mechanical compact transceiver design that provides an angular coverage of 180° by using multiple beams is proposed and implemented for indoor OW communications. This transceiver uses no mechanical parts for tracking a mobile receiver [136]. The proposed design consists of an eight by eight vertical-cavity surface-emitting laser (VCSEL) array as light source, a telescope lens that collects the light emitted from a counter optical terminal, a beam splitter that allows the transceiver to use the same optical path for transmission and receiving, and a CCD sensor that detects the direction of the optical terminal. Figure 13 shows the illustration of the compact transceiver design with four-by-four VCSEL array. One of the laser arrays in this transceiver is selected to communicate with a remote terminal according to the direction of the optical signal received by the CCD. The system is designed to be an optical base station attached to the ceiling of a room. It aims to establish an optical connection with a device in the room equipped with an optical transceiver. By enabling the corresponding laser diode in the array, the proposed transceiver facilitates an optical link with the corresponding optical device no matter where the device is located in the room. Therefore, this approach provides a tracking mechanism for a mobile device without using a moving part, and potentially reduces the size and the power consumption of the FSO communications system. Furthermore, this mechanism allows any two adjacent laser beams in the laser array to be turned on simultaneously to ensure that the laser transmission is not interrupted and to maintain a constant optical intensity at the receiver. The proposed base station design also makes multiple-input and multiple-output optical communications possible for multiple devices in the room, placed in various locations, by providing optical spatial diversity.

Eye safety is a major concern of indoor applications using laser beams because of the spatial coherence of the employed laser beam and the short distance from the transmitter [137]. One possible solution to provide eye safety for indoor FSO applications is to break the spatial coherence of the transmitted laser beam. A collimated laser emitter design for optical wireless communications is proposed to achieve eye safety for indoor FSO applications [137]. In this design, the spatial coherence of the beam is reduced by using a diffuser, which allows to maximize the transmission power of the laser for a constant eye safety level. This communications system com-

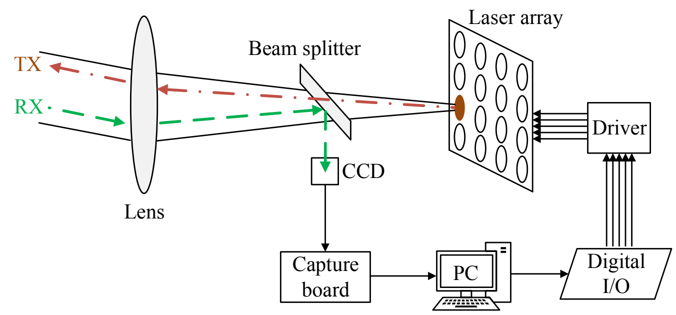


Fig. 13. A non-mechanical compact transceiver design using a four-by-four VCSEL array [136].

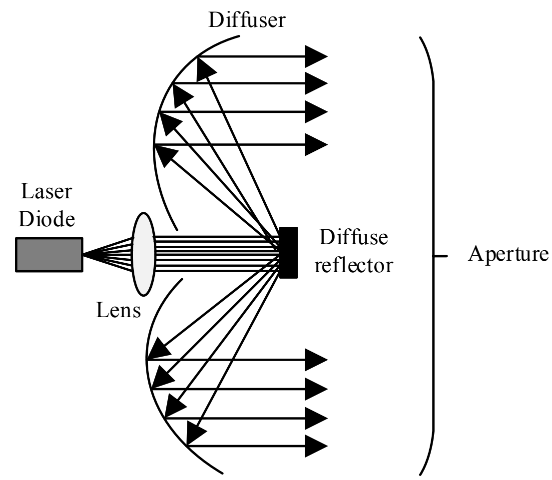


Fig. 14. Basic scheme of an optical configuration of the eye-safe collimated laser emitter design [137].

prises a laser, a diffuser, a diffuse reflector, and a collimating lens, as Figure 14 shows. In this figure, emitted laser light from the laser diode is collimated by a collimating lens and diffused by a diffuse reflector. The diffused laser light is then reflected by the bowl-shaped diffuser and exits the aperture of the transmitter. This design allows emitting 35.9 times more power than that of the laser alone with the same divergence angle owing to the decrease of the spatial coherence of the beam without affecting the eye safety classification.

In addition to the spacial coherence of the laser beam, transmission wavelength of employed laser is another factor that affects eye safety. For instance, 50-65 times more power can be transmitted by using a laser operating at 1520-1600 nm than those of operating at 780-850 nm for the same eye safety classification [34].

There are other examples of specialized applications of indoor FSO communications. A data-center interconnection architecture that uses inter-rack FSO links is proposed [138]. All the FSO links in this proposal are designed to be reconfigurable by a central controller according to the data-center traffic pattern. This approach provides flexibility, reduces the equipment cost, and minimizes the cabling complexity. In such a data center, each rack is equipped with a number of steerable FSO devices, thus allowing multiple inter-rack FSO links at a time. For instance, in a data center network with N racks, Rack 1 can be connected to Rack 2 and Rack N at the same time, if each rack is equipped with two FSO transceivers. A fixed ceiling mirror is used to bounce the transmitted laser beams between any pair of communicating FSO devices, where the space above the racks is exploited to establish obstruction-free optical paths. Two alternative beam steering mechanisms are proposed and compared with respect to latency, degree of flexibility, and cost/power consumption for this optical inter-rack communications system: switchable mirrors and galvanometer mirrors. The first alternative of the proposed beam steering mechanisms for the optical inter-rack communications system is a switchable mirror (SM). An SM is a liquid crystal mirror that can be electrically controlled to rapidly switch between transparent and reflection states [139]. In this configuration, each FSO device is equipped with pre-configured and fixed SMs lined up side-by-side. In the transparent state, an SM lets the beam go through as a regular glass. In the reflection state, an incident beam is reflected to the intended direction by the SM as a mirror. Each SM of an FSO device is aligned during pre-configuration to target a point on a ceiling mirror and thus, an FSO receiver. The link setup is carried out by switching one of the SMs to the mirror state, while leaving the remaining SMs in the transparent state. The transmitted beam first goes through the SMs in the transparent state and hits the SM in the mirror state. The SM in the mirror state then reflects the beam to a target point on the ceiling mirror to allow an intended transceiver on a different rack to receive the reflected beam. The optical link following the path, $source \rightarrow source\ SM \rightarrow ceiling\ mirror \rightarrow destination\ SM \rightarrow destination$ is then established. SMs can be miniaturized as they must be slightly larger than the beam diameter, which has been reportedly selected as 1 cm^2 for inter-rack communications system. Moreover, the power consumption of an SM is currently reported as 40 mW [138]. Reconfiguration and switching latency of the SMs used in this optical inter-rack communications system are reported as 250 and 10-20 ms, respectively. The second alternative of the proposed steering mechanisms for the optical inter-rack communications system is a galvanometer mirror. A galvanometer mirror (GM) is an FSM that moves in response to extremely small currents [140]. GMs can steer the transmitted beam within a desired rectangular cone. In this setting, each FSO device is equipped with a GM to steer the transmitted beam within a desired rectangular cone. An optical link is established by configuring a pair of GMs of two FSO devices that are intended to communicate. The steering latency of the GMs used in this optical inter-rack communications system is linear with respect to the steering angle and less than or equal to 0.5 ms for angles up to $\pm 20°$. Moreover, the power consumption of this off-the-shelf GM is reported as 7W.

IV. Challenges and Future Research

As FSO and VLC technologies advance, their applications are found in broader scopes and markets. This increase of applicability is especially noticeable in mobile systems. As the size of mobile systems (e.g., battery-powered drones) and micro-stations, such as those used in Internet of things, decrease, ATP mechanism are expected to also decrease in size and complexity, calling for new ATP designs. However, many of the recent designs may need to be tailored to the specific type of application.

The recent growing interest in autonomous cars brings out an essential requirement: communications capability for vehicle-to-vehicle, vehicle-to-infrastructure, or vehicle-to-everything communications to create an intelligent transportation system [141]–[143]. A challenge in this application is to keep LOS with vehicles in an urban environment with dense presence of buildings. Such scenarios present a challenge for signal acquisition and tracking.

With the emergence of Internet of Things (IoT), including mobile IoT, small ATPs have not been fully developed. The development of small ATP mechanisms may be challenged by the mobility requirements, which include small weight and size. For example, multiple optical transceivers may be used by an optical terminal to provide omni-directional connectivity and multiple connections at a time and they require larger real estate.

The high mobility and speed of some communicating vehicles, such as cars, high-speed trains or UAVs, may be challenging for FSO technology in the context of V2X communications. Therefore, an agile ATP mechanism that can keep up with the speed of moving vehicle(s) to maintain the optical link between the transceivers of these vehicles is required. For instance, the results of some field experiments showed that a mirror-based ATP mechanism cannot maintain an optical link between a ground station and a vehicle traveling at 270 km/h for more than 6 ms [69].

Other innovative features need to be incorporated in an ATP mechanism suitable for V2X applications are the ability to mitigate vibration, and multi-directional coverage. Therefore, the design of a suitable ATP mechanism that considers the requirements of a V2X communications system is of great interest.

A predictive ATP mechanism for mobile FSO communications, where the laser beam is pointed towards the moving direction of the tracked object may be of research interest. Predictive ATP for mobile FSO communications is a mechanism that may decrease the handover time of a ground-to-vehicle or vehicle-to-ground by having a prior knowledge about the trajectory of the moving vehicle. This technique requires at least two transceivers on a moving vehicle, which are connected to two consecutive base stations, source and target, respectively. If the trajectory and speed of the vehicle are known in advance, the location of the moving vehicle may be estimated at any moment. In case of a handover, the target base station and one of the transceivers of the vehicle can be pointed towards each other without having a connection between them. While the handover is performed, the vehicle can be still connected to the source base station to provide Internet access to the passengers in the vehicle. By means of predictive ATP, the time to locate the location of the vehicle using its GPS position may be eliminated. Therefore, the total handover time may be decreased. One disadvantage of the predictive ATP mechanism is the increased cost because of the extra transceiver(s) in the vehicle and the error caused by mismatch on the expected moving and actual speeds, therefore requiring support from GPS or other localization technique.

V. CONCLUSIONS

An ATP mechanism is a crucial element of an FSO communications system as this communications technology requires LOS between transmitter and receiver. The use of coherent light as in laser beam is mostly applied for communications in moderate-to-long distances. Alignment is required in most cases of FSO communications; small displacements by the receiver or the transmitter can make them fall out of sight for short distances. As the distance between transceivers increases, the required alignment precision for FSO transmitter also increases due to the narrow divergence of the employed beams. In fact, the motion is actually restricted to both communicating stations because full-duplex communication requires the use of transmitters and receivers by both ends. Therefore, designing FSO transceivers with a suitable ATP mechanism is critical for realizing effective FSO communications. We presented a survey on ATP mechanisms for FSO communications systems and categorized the ATP mechanisms according to the working principles and use cases. The technical details of each ATP mechanism have been described to reveal properties, limitations, and challenges. Our overview on the ATP mechanisms used in FSO communications systems for mobile objects also includes indoor (short) distance with visible light and deep-space communications. We also discussed some existing research challenges.

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