Revolutionizing Optical Wireless Communications via Smart Optics

Amr M. Abdelhady, Osama Amin, Mohamed-Slim Alouini, and Basem Shihada

I. Abstract

The heterogeneity of optical wireless networks (OWNs) has expanded over decades in terms of services, node densities, mobility requirements, bandwidth needs, responsiveness, and physical device profile. Consequently, incorporating dynamic reconfigurability into future OWNs can satisfy their diverse realm of objectives. Towards this end, we provide our vision for the potential gains of integrating tunable optical elements in OWNs reflected in energy consumption reduction, coverage customization, data transfer rate boosting, highly accommodating multiple access schemes, enhancing physical layer security, supporting simultaneous services, and interference reduction. Finally, we speculate a roadmap for future research directions in tunable optics aided OWNs and the associated challenges with their deployment and operation.

***Index Terms*—Optical wireless communications (OWC), smart optics, reconfigurable intelligent surfaces, intelligent reflecting surfaces.**

II. Introduction

The ever-growing interest in wireless services has witnessed a surge during the last couple of years due to the widely spreading pandemic. The urge to provide physical-distancing preserving services such as remote education, healthcare, and work has put wireless networks under unprecedented stress levels. Even before the pandemic, the demand for wireless services was climbing very rapidly due to the rising number of applications covering a wide range of daily life aspects. In addition, the staggering number of wireless nodes, mobility and reliability requirements, heterogeneous nature of communicating networks, and energy efficiency objectives have thrust research efforts in the wireless communications field for the past few decades [1].

Amongst the broad electromagnetic spectrum, the optical band has received a paramount portion of research efforts. The license-free wide bandwidth offered by this spectrum is becoming very appealing due to the radio frequency (RF) spectrum crunch. In addition, the impenetrability of optical radiation to the majority of objects in typical environments reinforces information security within indoor spaces. Moreover, optical technologies are electromagnetic interference (EMI) free technologies, and hence, can be used in hospitals, airplane cabins, and factories, i.e., any EMI-sensitive venues. Furthermore, the affordability of the needed components to realize optical links render them cost-effective solutions to cater for the stunning demand increase on the number of wireless communications links. The visible band is of particular interest as it features an abundance of existing infrastructure originally purposed for lighting. In addition, it simplifies the coverage design process due to the visibility of the covered regions. Nonetheless, the optical band is still underutilized due to the limited bandwidth of the optical frontends, in addition to the significant performance degradation in non-line-of-sight (NLOS) scenarios [2].

On a different front, the generation, manipulation, and detection of optical radiation have been the main focus of many academic and industrial studies. The study and development of optical and optoelectronic devices have evolved progressively over decades to develop explanatory theories and engineer devices. Optical radiation propagation was initially studied via geometric optics, which provided explanations for reflection and refraction only [3]. After that, the electromagnetic wave theory of light was introduced by Maxwell and was able to explain phenomena such as diffraction and interference, which were not explainable via geometric optics [3]. Finally, the particle nature of light was unraveled by quantum optics theory, which laid the foundations for understanding optical radiation absorption and emission [3]. Also, the advancements of material fabrication shifted the optics industry from classical refractive bulky devices to modern diffractive optical elements (DOEs) and metasurfaces [4]. Optical devices evolution encompassed the reconfigurability dimension, where devices possessing optical properties sensitive to external stimulation were developed as variable-focus lenses.

Despite the rapid research advancements in optical devices physics and their offered functionalities, corresponding analytical and experimental studies in the wireless communications domain are still lacking. This gap between optical devices physics research and optical wireless communications has motivated us to provide an overview of both fields and the potential gains of the interplay between them. In particular, the dynamic nature of wireless communications networks requirements and operation conditions emphasizes the need for reconfigurable components to achieve energy-efficient and/or performance-optimized operation. The incorporation of tunable lumped elements at the transmitter and receiver sides has been the study subject for many research works in optical wireless communications [5]–[9], where beam steering, beam width adjustment, and field of view (FoV) tuning were considered. Nonetheless, the reconnaissance of reconfigurable intelligent surfaces (RISs) in optical wireless communications (OWC) networks has been very limited to a minority of works [10]–[19], unlike their RF counterpart [20].

In [14]–[17], the authors envisioned the potentials of recon-

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figurable surfaces for free space optical (FSO) communications, light fidelity, and indoor VLC networks, respectively. Differently, in this work, we consider the wider scope of optical wireless communications with emphasis on bridging the gap between physical optical devices research and the communications perspective while speculating novel use cases and highlighting promising research directions at the interface between tunable optics and wireless communications. Towards this aim, we start by giving an overview of OWC and the tunable components. Then, we highlight the role of reconfigurability in adaptive OWC systems by tailoring the coverage, supporting a multitude of different services simultaneously, enhancing physical layer security, reducing the energy consumption, mitigating interference, providing better mobility support, improving multiple access and data transfer rate. In addition, we envision some promising future research directions regarding developing tunable-optics-enabled OWC networks.

III. Overview on Optical Wireless Communications

In this section, we provide a bird's eye view on the current OWC technologies, their main configurations, capabilities, and application areas.

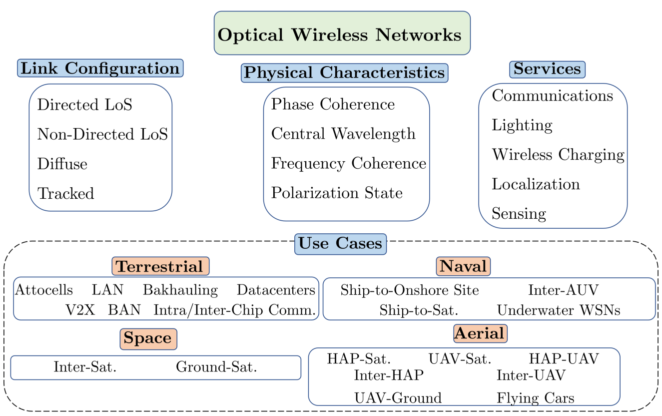


Fig. 1: OWC services and characteristics overview.

A. Link Configuration

OWC systems can be categorized on a link configuration basis into: directed line of sight (LoS), non-directed LoS, diffuse, and tracked links [21]–[23]. In a directed LoS configuration, the transmitter employs a narrow beam to communicate with a high-gain narrow-field of view (FoV) receiver. In such a configuration, the signal-to-noise ratio (SNR), energy efficiency, interference effects, and channel bandwidth are very well conditioned, albeit mobility of receiver is not supported, and the outage is imperative when the LoS is blocked. As for the non-directed LoS configuration, the transmitters' beamwidth and the receivers' FoVs are relatively large, enhancing the coverage area and mobility support in multi-user scenarios. However, the performance gain comes at the expense of reduced energy efficiency, less link bandwidth, high interference levels, lower SNR, and less vulnerability to LoS blockage. The diffuse configuration can be used in indoor scenarios where a wide-beamwidth transmitter is oriented facing the ceiling, and wide FoV receivers mainly capture the first-order reflections. This configuration provides better coverage, mobility support, and less outage/blockage probability while deteriorating the channel bandwidth and SNR due to longer paths between the transmitter and the receivers. As for the tracked configuration, a narrow-beamwidth transmitter and narrow FoV receiver are used where the transmitter orientation tracks the receiver position either mechanically or electronically. This configuration harnesses the directed LoS configuration's merits and alleviates its coverage area and mobility support shortages through added system complexity. Nonetheless, this configuration suffers from outages triggered by LoS blockages.

B. Optical Link Characteristics

The physical characterization of optical wireless links is determined by their coherence status in terms of frequency/wavelength and phase, in addition to their polarization sensitivity and the central frequency of operation. The optical spectrum encompasses the infrared (0.76-300 μm), visible light (390–760 nm), and ultraviolet (10–390 nm) bands [3], [24]. Each of these frequency sub-bands possesses distinctive features that render it favorable for certain wireless applications. The ultraviolet band is distinguished with its atmospheric scattering capability, which enables NLOS communications at large data rates in outdoor scenarios [25]. On the other hand, both the visible light and infrared bands can establish indoor and outdoor OWC links. In indoor scenarios, visible light is favored for the downlink operation, while infrared is better for uplink operation. In outdoor scenarios, depending on the atmospheric attenuation of optical waves due to absorption, fog, haze, rain, and snow, the optical carrier wavelength can be optimized [26]–[29]. It is noted that the visible light band has superiority in underwater communications [30], [31].

The light radiated from a source is composed of a continuum of wavelets possessing their frequency, phase, and polarization [32]. The coherence of such radiation is determined by the degree of variations of the individual wavelet frequencies and phases. The degree of similarity of the individual wavelets' polarization tells whether the radiation is polarized or unpolarized. The three previously mentioned physical characteristics and the spatial phase profile of light beams, also known as spatial mode, represent degrees of freedom that can be exploited in data transfer. Several systems are developed to transfer multiplexed data, such as wavelength division multiplexing [33], phase shift keying [34], polarization division multiplexing [35], and spatial mode multiplexing [36].

C. Collateral Services

OWC systems provide an all-encompassing platform for a multitude of services [37], [38] that can be provided simultaneously.

Illumination: Amongst OWC systems, visible light communication (VLC) systems are of particular interest as they provide indispensable lighting functionality. In such scenarios, it is crucial to maintain lighting quality in terms of spatial uniformity, flickering avoidance, stable chromaticity, and high color rendering index [39].

Wireless Charging: Simultaneous lightwave power and information transfer (SLIPT) systems are crucial for extending the battery life-time of mobile terminals in both indoor and outdoor scenarios. The wireless charging feature is immensely rewarding for wireless sensor networks operating in harsh environments as in underwater systems [40], and in airborne communications [41].

Localization: Location-based services have received lots of attention, such as geofencing, indoor navigation, and location-aware communications [42]. The importance of such services is due to their potential merits in terms of optimized network performance and centimeter positioning accuracy that is not achievable with a global positioning system. Localization algorithms rely mainly on received signal strength, arrival time, and arrival angle information to provide a location estimate. The positioning process might be passive where the device, which needs to be located, does not participate, and the position is inferred through network signaling solely.

Sensing: Although the sensing functionality integration in OWC networks is minimal, the potential of such incorporation is evident [43]–[45]. The interplay between OWC systems and sensing devices creates opportunities for optimized performance based on the acquired cognitive features, resulting in better channel modeling and estimation. In addition, sensing can provide privacy-preserving surveillance services and help create smart environments where detection and object tracking facilities are made available. For instance, the already deployed network transmitters and receivers can exploit the communications signalling in objects recognition [46], which could help robots and machines accomplish their tasks by providing accurate labeled dynamic maps, and enable gesture based control. In addition, it could offer activity recognition as fall detection, and suspicious behaviours detection which could help in proactive crimes prevention or prompt detection and reporting, to name a few. On the other hand, exploiting the sensing functionality offered by other nodes in the environment helps the OWC network to have a better estimation for the NLoS paths, possible blockages and enable them adjust their transmission and the controllable channel elements as reflectors accordingly.

D. OWC Technologies and Use Cases

OWC systems are categorized based on the adopted technology into: LiFi, VLC, optical camera communications (OCC), and FSO [2], [47]. The favorable distinctive features associated with each of the OWC technologies promotes them as promising solutions for a wide range of applications having very different objectives and constraints.

1) Terrestrial Communications

OWC is one of the leading players in a plethora of fixed and mobile terrestrial networks. For the fixed scenarios, FSO is used to realize inter/intra-chip communications in interconnects and inter-rack communications in data centers [48], backhauling, last-mile service in cellular networks, and inter-building links within campuses [49]. As for limited mobility setups, VLC and LiFi[1] provide connectivity for small-scale indoor networks, ranging from body area networks [51], [52], through personal area networks where coverage of few meters is provided, to local area networks [47]. In addition, such technologies aid the heterogeneous cellular networks densification with extremely small cell sizes as in attocells [53]. In outdoor scenarios with more demanding mobility requirements, OCC possesses extraordinary potential, especially in vehicle-to-X communications, where reduced data rates are not crucial for the required data traffic load needed for safety and navigation purposes [54].

2) Aerial Communications

In addition, the extreme directivity along with the massive bandwidth offered by FSO links and the LoS availability in various aerial communications scenarios heavily encourage adopting FSO-based communication links. FSO communications between aerial platforms as unmanned aerial vehicles (UAVs), high altitude platforms (HAPs), and airplanes, could form a vertical backbone structure for global connectivity and complement the existing cellular networks [55]. In addition to their terrestrial coverage extension role (where they serve as relaying nodes or flying base stations), HAPs, UAVs, and satellites can form a hybrid aerial/space network, where UAVs and flying cars act as users to such networks [56], [57]. In such setups, the inter-UAV and flying car communications might benefit from OCC.

3) Underwater and Maritime Communications

Moreover, OWC represents a promising solution for underwater wireless communications [58], especially visible-light-based technologies due to the relative transparency of water for this frequency band [24]. Underwater OWC is particularly interesting as it offers large bandwidth at low latencies compared with underwater acoustic communications. Consequently, inter-autonomous underwater vehicles, Ship-to-onshore site communications, and ship-satellite communications through optical links employing OWC possess high potential in enabling deep-sea explorations and supporting underwater wireless sensor networks [59]. Moreover, it extends broadband connectivity reach to cover the aquatic regions representing the majority of Earth's surface and enhances global connectivity [31].

4) Space Communications

Furthermore, OWC is pivotal to the space communications industry, where FSO technology exhibits clear superiority over RF links in inter-satellite links [29], [60]. The LoS availability, absence of atmospheric turbulence, minimal beam divergence angles, and enormous bandwidth endorse inter-low-Earth orbit, the geostationary orbit, and CubeSat FSO links [61]. Terrestrial satellite communications are realized by RF and FSO links or hybrid RF/FSO links to mitigate the atmospheric adversities. FSO is a crucial technology for the viability of massive satellite constellations being deployed to achieve global coverage and reduce the digital divide.

The outstanding inherent merits of OWC throughout all the previously mentioned application areas immensely certify its

[1]VLC and LiFi impose different restrictions on the used communication band, the link topology, the duplexing nature, and mobility support [50]

candidacy to complement the holistic fabric of global wireless connectivity.

IV. Overview on Tunable Optics

In this section, we provide a brief summary of the optical devices functionalities, highlight the tunable optical properties, the adopted technologies and associated materials to implement tunable optics, their excitation mechanisms and offered capabilities.

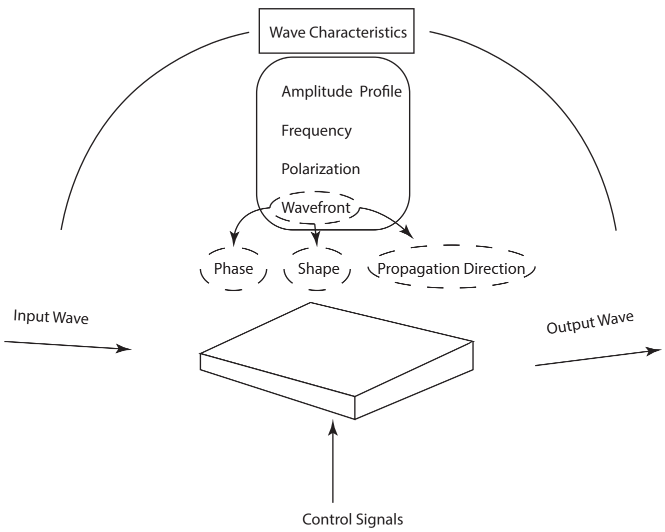


Fig. 2: Functional representation of optical devices operation.

A. Optical Devices Functionalities

The main operations optical radiation experience are broadly classified into generation, manipulation, and detection.

1) Sources

Optical sources vary in their output radiation characteristics in terms of power spectral density profile, radiation pattern, polarization, and phase coherence. In addition, they feature different modulation bandwidths and radiation efficiencies. For instance, light emitting diodes (LEDs) are characterized by a relatively wide emission power spectral density profile, small modulation bandwidth and radiation efficiency compared with laser diodes (LDs). Moreover, LDs emit phase coherent radiation while LEDs do not. Superluminescent diodes hit an intermediate point between LEDs and LDs on the line width, coherence and modulation bandwidth frontier [62]. Achieving full control over the characteristics of optical radiation is attainable through optical antennas [63]. On a different dimension, despite their limited bandwidth, organic light emitting diodes based on flexible substrates [64] accelerates the development of wearable and conformal sources enriching OWC capabilities within the internet of things (IoT) realm.

The offered bandwidth in the optical spectrum is underutilized due to the limited bandwidth of the optical sources. Micro-LEDs arrays offer much higher bandwidth than normal sized ones, where they allow for hundreds of MHz [65], GHz bandwidth for nanowire-based micro-LEDs [66] and even beyond GHz using asymmetric pyramidal structure [67]. On a parallel note, to cater for the exploding per-link data rate requirements, different types of LD technologies featuring promising modulation bandiwdths of tens and hundreds of GHz are being developed such as vertical cavity surface emitting lasers (VCSELs) [68], nanowire lasers [69], and plasmonic nanolasers [70].

2) Manipulators

Optical radiation manipulation is all about introducing changes to one or many of the propagating wave characteristics: amplitude, frequency, phase, polarization, spatial power distribution, propagation direction, and wavefront shape. Accordingly, a light manipulation device can be perceived as a functional vector that maps input wave characteristics into the output wave characteristics. It is worth mentioning that this function might be independent of the input or depends on a subset of the input wave characteristics according to the device's nature.

Optical manipulators can be categorized based on the affected output and the stimulating input wave characteristics as follows:

Propagation direction manipulators: Non-dispersive prisms and flat mirrors alter the incident light propagation direction according to Snell's laws of refraction and reflection, respectively, without being affected by any other parameter of the incident light. Albeit, in dispersive prisms, the direction of refraction depends on the incident light wavelength. It is worth mentioning that the amplitude of the reflected wave from a mirror surface depends on the incident light wavelength, propagation direction and the mirror material.

Wavefront manipulators: Wavefront shape manipulation is exhibited clearly through the operation of lenses and curved mirrors, where incident planar wavefronts are altered to spherical ones either converging to a certain point (focus) or diverging from it, depending on the lens/mirror geometry. In such devices, the incident wavefront experiences different phase shifts due to the device geometry as in lenses and parabolic and hyperbolic mirrors, or electrical phase shifts, as illustrated in the sequel.

Spectral manipulators: Spectral manipulation of radiation encompasses filtering where the output wave power spectral density becomes a masked version of the input wave. In addition, it includes frequency shifting/mixing, which lies under the umbrella of non-linear optics.

Polarization manipulators: The operations provided by polarization-related devices are mainly based on dichroism (polarization-based absorption selectivity) and birefringence (polarization-based propagation), which is responsible for the double refraction phenomenon [71]. For instance, polarizers are used to generate polarized light where the electric field direction status is deterministic, while a depolarizer is used to convert a polarized or partially polarized light into unpolarized light with random electric field direction. Retarders are used to manipulate the polarization state of polarized light, e.g., rotating the electric field direction of a linearly polarized light or converting linear polarization into circular polarization.

Power density manipulators: Another specialty for the light manipulation devices is the re-distribution of the spatial energy distribution. Different optical devices provide this functionality as diffusers, which increase the angular spread of a light beam, beam-splitters, which split the incident beam into many beams carrying different portions of the incident power, and beam combiners used to combine a number of incident light beams into a single collimated beam.

On a different dimension, light manipulators can be categorized according to their underlying operation mechanisms.

Geometric optics based: The previously mentioned manipulators operation is totally governed by refraction and reflection phenomena that are well explain by Snell's law. Such devices are relatively simple to design and fabricate, nonetheless they are bulky and provide limited functionality.

Diffraction based: On the other hand, optical devices that are designed to control the incident wave diffraction phenomenon, namely, diffractive optics and nanophotonics, offer the aforementioned functionalities and even more. Flat lenses and focusing mirrors in addition to vortex beams generators that are implemented using DOEs [72], and super-resolution lenses capable of focusing beyond the diffraction limit [73], are a few examples of the mightiness of diffractive optics in spatial power density control. Such devices are favored for their miniaturized dimensions and light weight, which comes at the complexity of design and stringent conditions for proper operation.

Scattering based: Finally, the full range of light manipulation possibilities can be exploited using metamaterials and metasurfaces. These materials consist of periodic structures of sub-wavelength metallic or dielectric structures that are called atoms [4], [74], [75]. The operation of these materials is governed by the designed particle plasmon and Mie resonances due to light scattering by the sub-wavelength elements.

3) Detectors

Optical detectors are characterized by their spectral response, reception pattern, efficiency, noise figure, and dimensions [22]. The detector bandwidth, responsivity are the two principal features of the spectral detector response, which determines the variation rate limits of the received signal and the generated electrical current due to received optical power, respectively. On the other hand, the detector FoV is the main feature of the reception pattern, which determines limits on the receiving directions. It is well known that the product of the collection area, the FoV of a lossless optical system, is constant (conservation of étendue) [3]. Nonetheless, in the last decade, systems that provide wide FoV at higher gains than expected by the étendue limit were proposed for OWC [76].

The majority of optical detectors used in OWC are p-i-n photodiodes. Avalanche photodiodes are used in optical fiber communications to increase the transmission range where the multiplication gain they provide increases the receiver sensitivity without significant noise enhancement as for ambient noise in the wireless scenario [77]. Single-photon avalanche detectors (SPADs) appeared recently and represented a good candidate for high-sensitivity receivers. In addition, SPADs arrays provide large bandwidth even with a large collection area since each element is small and the overall detector bandwidth is limited by the individual SPAD capacitance [78].

B. Tunable Properties

The previously mentioned optical devices functionalities can be static or dynamic. Adding dynamic tuning capabilities where an externally controlled stimulus parametrizes the device function widens the application areas of optical devices and magnifies their impact. Towards this end, tunability is achieved through materials possessing controllable optical properties or by incorporating an optical device in an incubating system such that the overall optical behavior becomes controllable. The optical response of tunable materials is achieved by altering their geometric profile, dimensions, surrounding structure, intrinsic structural arrangement, or refractive index.

C. Enabling Technologies

A multitude of materials and technologies enables the previously discussed dynamic behaviors. For instance, fluidic droplets possess lensing capabilities due to their spherical shape, and they are easily re-formable through hydraulic, pneumatic, and electrostatic mechanisms. In addition, soft deformable materials, known as elastomers, can change their profile upon applied stress. One promising actuation technology for elastomeric materials is electroactive polymers [79]. Liquid crystals (LCs) are anisotropic materials, where using an external electric field can alter the arrangement of molecules and their alignment. Such arrangement results in a polarization-sensitive refractive index profile for the material [80], [81]. Moreover, micro-electromechanical systems (MEMS) provide in-plane and out-of-plane motion degrees of freedom via electrothermal, electrostatic, electromagnetic, and piezoelectric actuation techniques [82], [83]. Furthermore, such systems can be integrated with photonic crystals to build tunable stretchable photonic crystal devices[2], which provide several optical functions at a reduced volume. Finally, tunable phase-change materials are those that alter their structure between amorphous and crystallized states upon applying external thermal or optical stimulus [84]. Such transitions result in refractive index variations, which can be exploited in many optical functions.

D. Tunable Devices Capabilities

After discussing the optical device functionalities, their tunable properties, and the enabling technologies that support their controllability, we exemplify the tunable device abilities. On the optical radiation generation side, LDs with controllable wavelength and polarization have been demonstrated [85]. Similarly, LEDs with adjustable chromaticity were developed [86]. As for the light manipulation frontier, a plethora of tunable optical devices serving the previously discussed various functionalities [81]. For instance, variable optical attenuators, variable optical axis lenses and mirrors, tunable beam splitters, and tunable beam deflectors offer basic reconfigurable optical manipulation capabilities where the output wave is related to the input wave by a single uncoupled feature variation based on a tunable parameter. Filters, polarization-sensitive

[2]Photonic crystals are materials having periodic variations of the dielectric constants.

devices, diffraction gratings, deformable mirrors which allow for wavefront correction in FSO, and spatial light modulators (SLMs) that achieve wavefront control via phase manipulation, to name but a few, are realizations of more advanced functionalities where an output wave feature is coupled with a different feature of the input wave.

V. Potential of Integrating Tunable Optics and OWC

In this section, we shed the light on some exploitation strategies for reconfigurable optics within OWC systems and discuss the anticipated performance gains.

A. Coverage Tailoring

The positive impact of employing reconfigurable optics on coverage of OWC systems is self-evident. OWC systems suffer from significant performance degradation in the absence of LoS links. Thus, transmitters with a tunable beam shaper can shift the power distribution towards a diffuse reflector that illuminates the intended receiver to mitigate the blockage events. This can be realized by covering the optical source using tunable metasurface [87], which features small profile and fast switching capability suitable for hard mobility requirements whilst increasing costs due to fabrication intricacies. The same functionality could be implemented through geometric optics based solutions as tunable lenses on the expense of larger device profiles and slower response times that is more suitable for indoor setups. Moreover, the diffuse reflections can be focused on an LoS-blocked detector by proper adjustment of the phase profile of a coherent optical array transmitter using an SLM [88]. Another way to reach the LoS-blocked receiver is by employing controllable reflective surfaces, especially those with a tunable focusing capability like the ones proposed in [12]. It is worth mentioning that both ways can provide customized spatial coverage with a designed footprint in the detection plane whose precision depends on the resolution of the employed SLM at the transmitter in the former method or that of the reflecting array.

Thanks to the spatial power distribution capabilities offered by such intelligent transmitters and reflectors, the coverage zones and users' association can be optimized to balance the load and improve the throughput in an unprecedented way. In addition, employing conformal tunable metasurfaces as objects coatings allows for significantly reducing the LoS blockage probability. Such unparalleled feature is exemplified by cloaking optical devices. It is worth mentioning that beam steering and beamwidth tuning has been studied in many previous works as [5] and [89]. Nonetheless, arbitrary transmitter beam shaping enabled by DOEs, as depicted in Fig. 3 (left), is not previously studied analytically. In addition, cloaking effects enabled by exploiting controlled wave diffraction upon incidence on metasurfaces represents a promising direction for future OWC research works.

B. Simultaneous Services

Building wireless networks that offer communications, localization, sensing, lighting, and wireless charging services is foreseen and highly motivated for the next-generation local area and cellular networks. The adoption of tunable optical devices in such systems allows for dynamic dedication of devices to serve different purposes according to the need. For example, an optical source can serve as an anchor for the localization of a specific device or charge another device wirelessly; based on the devices' location. Also, the offered services/functions could be dynamically adapted according to the encountered demand on the simultaneously offered wireless services.

The added degrees of freedom by tunable transmitters, receivers, and controllable channel objects create new opportunities for improving the collateral services offered by OWC systems.For instance, novel iterative algorithms can benefit from coverage tailoring and dynamic direction of reception along with dynamic receiver FoV, experimentally and analytically studied in [19], [8] for LC-based devices, respectively, in achieving extreme localization accuracies. In addition, dedicating the offered degrees of freedom in tunable OWC networks to sensing services will result in better imaging of the OWC surrounding environment without breaching users' privacy. In turn, the accurate knowledge of nodes' positions and the enhanced sensing capabilities will reflect on building better cyber models of the surrounding environment of the OWC system and consequently taking well-informed decisions on resources distribution among different services. Finally, the reconfigurability of sources radiation pattern and the surfaces reflection pattern (defined by their BRDF) alleviates the intricacies incurred in the simultaneous satisfaction of both spatial illumination uniformity requirement and the communications service requirements. The finiteness of available resources at the network side and the conflicting objectives of the aforementioned individual services create inevitable tradeoffs [8], [90]. For example, the tradeoff between communications and illumination has been investigated in [90]. On the other hand, the tradeoff between communications and harvested energy has been studied in [8]. Albeit, generalized multiobjective studies that considers all the possible OWC functionalites together is still lacking, especially when reconfigurable channel components are considered, which are envisioned to offer better Pareto fronts. In addition, the added versatility by reception pattern reconfigurability enabled by metasurfaces, depicted in Fig. 3 (right), and BRDF controllability offered by tunable nanophotonic materials represents an appealing future research direction.

C. Enhanced Physical Layer Security

The importance of securing data transmission in current and next-generation wireless networks is profound due to their high penetration level. With the continuous development of wearable electronics and implantable medical devices, massive personal data traffic will be generated and transmitted wirelessly. Thus, it is imperative to keep such sensitive data away from eavesdroppers using physical layer security techniques. Tunning the optical communication system and environment can enhance the system's security by developing a reliable communication channel between the transmitter and

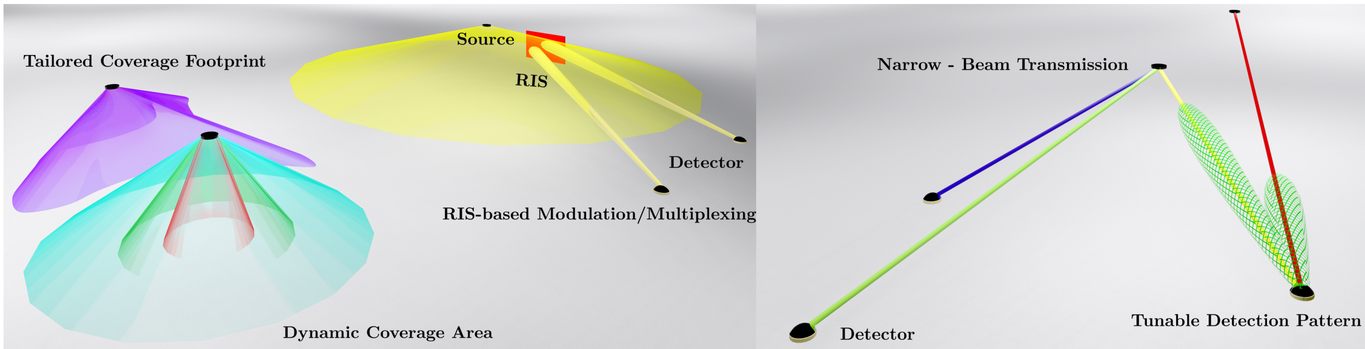


Fig. 3: Main advantages of smart optics aided OWC.

the intended receiver while degrading the channel between the transmitter and the suspected eavesdroppers.

Several adaptive optical techniques can support the physical layer security, such as steerable optical beams and optical power diffusion. The transmitters featuring steerable narrow beam pencil-shaped radiation profiles [91] can be used to reduce the probability of signal interception. Another way to realize such secure links is accomplished by spreading the transmitter power over a broad angular extent. As such, the directly received power by the LoS is imperceptible; thus, reflector arrays can be used to focus the optical energy towards the intended receiver. Along that direction, in [92] the authors studied the secrecy rate maximization problem for a mirror-array aided VLC system via mirror orientations tuning. Studying this problem for metasurfaces based RIS and comparing its performance against the mirror array version is highly encouraged. Moreover, a random sequence of wavelengths can carry the transmitted data stream by employing transmitters with a controllable wavelength as the transmitter proposed in [6] and receivers with a tunable spectral response. In addition, the transmitted data stream can be carried over a random sequence of reflection paths by using an array of reflectors, a steerable narrow-beam transmitter, and an angular diversity receiver. Finally, similar approaches can be employed while exploiting the polarization and wavefront phase profile or spatial mode (as in orbital angular momentum systems). Combining the techniques mentioned above can achieve higher secrecy performance at the expense of increased system hardware complexity.

D. Reduced Energy Consumption

The explosive growth of the number of communication nodes, data traffic demands, and miniaturization of devices with a limited battery lifetime requires dedicating immense efforts to reduce the energy consumption of such networks. Thus, it is necessary to establish precise control over the radiated power spatial profile to address the energy consumption concerns. From a link-level perspective, the radiated beam width should be narrow enough to confine the transmitted power within the receiver aperture to avoid any propagation losses. Similarly, the inverse relation between receiver responsivity and its field of view implies that tuning the FoV to the minimum possible value covering the entire transmitter aperture minimizes the propagation losses. Nonetheless, the energy lost during the pointing process should be taken into consideration. Also, an iterative beam alignment and transmitter beamwidth, receiver FoV tuning techniques should be devised to minimize the overall energy consumption (the transient phase along the steady-state).

It might be even more power-efficient to use an indirect path rather than the direct LoS, which might be partially blocked, experiencing more attenuation, scintillation, and turbulence as in FSO setups. In addition, exploiting the spectral dimension tunability of the transmitter and receiver sides could enhance the system energy consumption performance, where some transmission windows might provide better channel conditions depending on weather conditions. Moreover, adaptive optics as deformable mirrors can correct for wavefront distortions and reduce the energy consumed in repeated transmissions.

One of the most promising research directions in energy consumption reduction enabled by tunable optics is optical passive communications. In such setups the transmitter harvests the ambient light and uses the harvested power to transmit its own data, or directly modulates the ambient radiation using tunable optical elements as LCD shutters [93], retroreflectors [94] for backscattered communicatons. Such technologies alleviates or totally eliminates battery requirements for IoT devices.

E. Interference Mitigation

Interference in multi-source multi-user VLC system setups is brutal due to the illumination spatial uniformity requirements and the fixed FoV nature of the conventional VLC receivers. One way to mitigate the impact of interferences is by utilizing tunable FoV receivers and adjustable detection patterns (either mechanically using MEMS or electrically via a tunable metasurface coating) to minimize the reception of any unintended transmissions. Another way is by relying on secondary objects coated with tunable metasurfaces to focus the light beam of the associated transmitter only on the detector surface and achieve a high signal to interference plus noise ratio. Moreover, using tunable polarizers and polarization-sensitive detectors, different transmitters can employ orthogonal polarization states to minimize interference experienced by each receiver. Furthermore, generating vortex beams in laser-based VLC setups utilizing diffusers represents a promising interference avoidance solution. This laser-based system provides a proper illumination coverage, where the transmitters use orthogonal spatial modes, and the detectors operate at tunable spatial modes. In multi-source multi-user OWC systems that do not support lighting as in the IR-based ones, the wavelength dimension can be exploited efficiently to mitigate interference. The transmitter side employs tunable diffraction metagratings with controllable shutter devices serving as modulators for each dispersed beam aimed at different users.

F. Improved Mobility Support

The advent of tunable surfaces covering moving objects within an OWC network opens the floor for opportunistic passive relaying. In such scenarios, the unintended impinging optical signal on a moving object can be redirected onto its intended receiver by adjusting the control parameters of the surface using a different wireless channel, e.g., RF control signaling. Also, it could act as an interference blocker for undesired signals reaching non-intended receivers. In addition, the collaborative role of static or dynamic nodes in providing extended coverage to other moving nodes can reduce the need for handovers significantly. Moreover, soft handovers can be achieved with the aid of such collaborative nodes. The effectiveness of integrating smart optics with OWC in supporting mobility can be easily speculated thanks to the achievable spatial diversity of signal transmission amongst constellations of HAPs and swarms of UAVs employing FSO links. In such scenarios, atmospheric conditions affecting the directed LoS link might be compensated by receiving the same signal from other nodes within the constellation/swarm having LoS with the communicating pair. Furthermore, it is evident that employing tunable metasurfaces with ultrathin profiles and extremely light weights indirectly supports the limited UAVs batteries.

G. Increased Data Rates

The offered degrees of freedom by tunable optics can significantly enhance the link-level throughput in two ways. The direct one involves increasing the spectral efficiency via exploiting more orthogonal dimensions for signaling. In comparison, the second one entails enhancing the channel conditions by reducing the inter-symbol interference and outage probability, which can support higher data rates. The former approach can be realized via polarization division multiplexing (PDM) or spatial modulation through multi-element transmitters. In [95], the authors experimentally demonstrated a PDM VLC system where two parallel data streams were transmitted simultaneously with the aid of polarizers, polarization beam splitters (PBSs). This idea could be further generalized to multiplex more polarization states on the Poincaré sphere with the aid of tunable polarizers and PBSs. The other realizations encompass modulating the response of the integrated smart surfaces within the environment, and spatial mode multiplexing where different phase profile beams are combined with each of which being modulated with different data streams. It is evident that combining these schemes together can result in extreme spectral efficiency values. The latter approach involves delay spread optimization by precise control over the propagation paths through proper choice of the activated elements within the reflector arrays in directed NLOS scenarios or by tuning the topology of the reflector via deformable optics. Finally, using coherent array transmitters, ordinary diffuse reflections control, and radiation pattern control to shape the reflection spot can limit the spread of channel delay in such scenarios.

Multiple-Input-Multiple-Output (MIMO) OWC systems performance can be enhanced significantly by employing intermediate controlled reflecting elements between the transmitter and the receiver as it will reduce the correlation of the channel matrix.

As for the aggregate network throughput, the integration of tunable components at the transmitters sides, receivers sides and within the surrounding environment allows for unprecedented collaboration chances. For instance, adopting the pencil beam profile for transmission aided with receiver tracking capabilities extends the reach of each transmitter creates an opportunity for efficient cooperative communications and increases the overall network spectral efficiency.

H. Improved Multiple Access

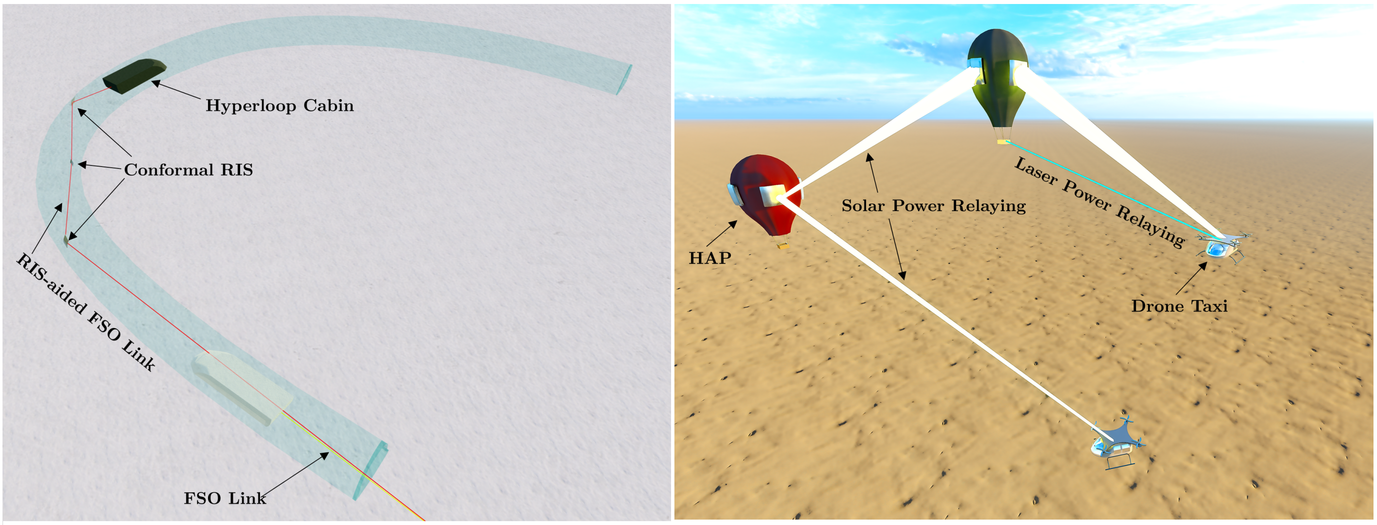
The previously mentioned degrees of freedom offered by reconfigurable OWC systems can be exploited to accommodate a large number of devices while providing orthogonal access. Spatial division multiple access can be further improved through the exploitation of controllable reflecting surfaces. The main idea is to use the optical radiation source as a pure, unmodulated carrier. At the same time, the modulation of different user streams is done at the controllable reflection nodes using tunable shutters. Then, the modulated beams are directed towards their intended users by any of the previously discussed means. On a different dimension, non-orthogonal multiple access (NOMA) for RIS-aided VLC systems is studied in [96]. One possible future extension for this work is to consider rate splitting multiple access for RIS-aided optical networks.

VI. Future Research Directions

In this section, we envision some foreseen research areas to harness the full potential of smart optics integrated OWC networks.

A. Multi-Source, -RIS, -Detector Systems

Motivated by the previously discussed potential gains of tunable optics in supporting OWCs, studying the general setting where many sources are serving a population of users with the aid of a set of intermediate passive nodes is self suggestive. In [97], the multi-source multi-detector single mirror array reflector was considered, where sum rate maximization was targeted by tuning the mirrors orientations under point source assumption. In [98], the authors generalized the problem to account for user association and power allocation optimization. Nonetheless, solving these problems for extended source and multi-RIS cases is yet to be addressed. Moreover, the multi-RIS scenario is recently considered only in a performance



(a) IRS-enabled hyperloop communications

(b) Aerial solar power relaying

Fig. 4: Futuristic applications as intelligent transportation systems and power relaying.

analysis study in a single-source single-detector setup to achieve spatial diversity in [99]. In addition, the distortive effect of a directed tuned beam into the power distribution of unintended receivers should be carefully studied and addressed in future works. The availability of multiple intermediate nodes raises a matching problem. The transmitters need to decide how they would distribute their power among different intermediate nodes. In other words, the design performance metric should be defined earlier, such as spectral efficiency, energy efficiency, minimum SINR, and maximum per-user delay spread. In addition, the multi-purpose nature of the next generation optical wireless networks promotes studying resources-services assignment problems to achieve a reasonable level of quality for each of the provided services.

B. Multi-hop RIS Systems

Installing multiple RISs within the communications environment creates opportunities for multi-hop transmission of directed power. In this way, even in highly crowded spaces, a directed NLOS link can be established. The feasibility of this approach depends heavily on the performance of the employed reflecting surfaces, as the beam will be attenuated after each hop. Hence, accurate channel modeling and proper design of these scenarios should be investigated to provide an idea about the maximum number of hops to achieve a targeted performance metric. On a different dimension, the multi-hop facility will deteriorate the physical layer security performance of the system as the number of possible signal delivery paths increases. In addition, such a link configuration versatility could increase the reliability of highly dense aerial swarm networks and enable hybrid terrestrial-aerial-space connectivity.

C. Machine Learning Impact

Incorporating deep learning and reinforcement learning can improve resource allocation in smart-optics aided OWC setups by computational complexity reduction and/or improved optimality of the allocation strategies. On the one hand, the online optimized network parameters computation could be implemented using deep neural networks (DNNs) whose inputs are the channel conditions and constraints parameters, while their outputs are the optimized network parameters of interest, e.g., resource allocation variables. These DNNs are offline-trained using traditional iterative optimization techniques using a sampled set of the possible channel condition parameters values. The sampling methodology of the training set along with the DNN architecture has great impact on the online performance quality of the DNNs. On the other hand, deep reinforcement learning algorithms are good candidates for solving more complicated parameter optimization problems arising from the inherent non-linearities associated with the generalized Snell's law of reflection and refraction that governs metasurfaces operation. This is motivated by the incapability of handling such problems with iterative optimization approaches as successive convex approximation as the objective function and/or as the surrogate convex/concave functions composing the approximate problem of each iteration are not easily attainable. The huge expected number of communicating devices and intermediate nodes promotes employing distributed optimization techniques. Towards this end, federated learning-based control over such networks represents a promising solution for delay-intolerant scenarios where robotic systems are involved. In addition, it offers individual nodes data-privacy preserving where the only shared information between the individual nodes are the model parameters i.e., DNNs weights and biases.

D. Novel RIS Architectures

The comparison made between tunable metasurface-based focusing reflectors and their mirror array counterpart in [12] indicated that the superior system depends on the application scenario. Consequently, building a hybrid structure of tunable metasurface units and controllable mirrors could improve performance at the expense of increased system complexity. Designing such a system entails several questions regarding the portions of metasurface parts and mirror parts of the whole setup, their geometric layout, and its optimization to be addressed by future works. Inspired by the angular beam compression capability of metasurface patches, clearly highlighted by the beam spread ratio metric in [12], we propose installing the metasurface patches on a two rotational degrees of freedom bases to harness the non-linearity gain of metasurfaces and orientation alignment of mirror arrays, to be studied in detail in a future work. In addition, studying the impact of RIS topology optimization represents a totally unexplored territory and the potential impacts of topology tunability along with the phase gradient design of metasurface patches and orientation on OWC different performance metrics, represent an interesting question to be addressed by future studies. One promising architecture that has been proposed in RF wireless systems, so would be its optical counterpart, consists of a non-tunable metaprism excited by an OFDM signal to realize beam steering functionality by electronically adjusting the OFDM signal [100]. The merit of this architecture is shifting the complexity towards the signal processing side which is much simpler compared with hardware complexity of tunable metasurfaces. The offered complexity reduction comes at the cost of deteriorated performance compared with their RIS counterparts [100].

E. Tradeoffs

The incorporation of smart optics within OWC networks entails some fundamental tradeoffs. For instance, increasing the number of controllable elements of a tunable reflecting array increases the power focusing capability and power transfer efficiency. Though, it comes at the cost of increased hardware complexity, which translates into increased operational energy costs and processing delays. Similarly, although expanding the reflector area increases the captured power, it also increases the blockage probability for other links and possibly the delay spread. In addition, adopting multihop setups increases the network accessibility at increased deployment, operation cost, and visual pollution (reflections of impinging waves from unintended sources).

F. Duplexing

The use of backscattering retroreflectors for uplink realization in OWC links has been studied thoroughly. Nonetheless, studying bidirectional OWC links involving intermediate passive relaying nodes represents a new area to be explored in future research works. In principle, employing mirror array-based intermediate nodes enables utilizing the same elements for both transmission and reception, albeit self-interference must be accounted for at the transmitters. On the other hand, using metasurface-based intermediate nodes necessitates splitting the downlink and uplink paths due to reciprocity lack of the generalized Snell's law of reflection for full duplexing operation.

G. RIS Assisted Laser-based VLC

The favorable properties of laser sources as energy efficiency, coherency, narrow linewidth, and high polarizability, promote it as an elegant communications transmitter. In addition, operating in the visible frequency range and incorporating diffusers in these systems have pushed their potential use in lighting purposes. Nonetheless, the offered lighting quality in terms of color rendering index still lacks due to interference issues. Consequently, integrating tunable optical devices represents a promising solution for interference management in laser-based VLC systems. This claim is justified by the ability of such devices to manipulate impinging light properties as front end, amplitude spatial profile, polarization, and even wavelength. To this end, future research efforts should be dedicated to investigating this whole new field to harness the potential gains on both illumination and communications frontiers while keeping energy consumption at minimal levels.

H. Hyperloop Communications

Providing broadband connectivity to railway passengers during their travel time is an already challenging task due to the time-varying nature of the communication channel. These channel intricacies significantly limit the maximum supported transmission rate, and as the train speed increases, the performance degradation becomes severer. In a recent work [101], the authors studied mirror-based RIS-assisted dual-hop FSO network to provide broadband connectivity to a high speed train. The Hyperloop environment where cabins travel in vacuum tubes at extreme speeds exceeding 1000 km/h makes broadband wireless coverage a very elusive objective [102]. To this end, addressing this problem using adaptive inter-cabin and infrastructure-cabin FSO links based on electronically- or even optically tunable optical reflective materials represents a promising direction for future research. This approach is motivated by the abundant bandwidth offered by FSO links and the well-defined trajectory and dynamics of Hyperloop, which enables proper planning and control over the tunable components of the system with minimized aiming errors. In addition, tunable wavelength lasers and photodetectors with tunable spectral response can help compensate for the inevitable severe Doppler effect at such extreme speeds.

I. RIS-assisted Power Relaying

Remotely operated mobile platforms that are battery-powered are consistently receiving growing attention. The quality of services offered by such platforms is fundamentally limited by the battery lifetime, which can be extended via wireless charging. The versatility provided by tunable optics offers promising solutions for efficient power transfer between moving platforms. For instance, LEO satellite constellations can exploit reconfigurable power focusing devices to direct the available solar power towards a subset of the satellites experiencing power shortage. Recently, in [103], the authors proposed using inter-satellite optical links to empower cubesats, hence, the available solar power for large satellites is harvested then delivered to the cubesats via laser beams.

Similarly, a powerful laser source on a ground station can indirectly power a drone through an intermediate one having a LoS with the ground station. This vertical architecture can also be realized by splitting the laser power of the ground station between some intermediate nodes to deliver it to the intended recipient UAV. Similarly, power relaying strategies can be adopted within OWC networks supporting different use cases as underwater AUVs, aerial networks of HAPs as depicted in Fig. 4b, drone-taxis, unmanned operated vehicles used in industrial facilities, and inter-networks power transfer between terrestrial, navy, aerial, and space networks. For indoor use cases, rigid geometric optics based devices having mechanical tunability can be tolerated. Nonetheless, for satellites and flying platforms, moving at large velocities and possessing limited onboard space, tunable metasurfaces with electronic or even optical stimulation is a much better choice despite the costs.

1) Solar power relaying gain between two airships

In this subsection, we exemplify by simulation on the potential gains of optical power relaying enabled by smart optical elements. Towards this end, we consider the single-hop solar irradiance focusing problem between two airships featuring 150 m length, and 34 m diameter [104]. In this study the incident solar irradiance on a one of the two HAPs is focused towards the solar cell array of the other via an element-orientation tunable mirror array. In this study, the number of array elements takes the values 1, 10, 100, 1000, and 10,000, while the separation distance between the two HAPs is changed from 3 Km to 10 Km. It is assumed that the reflected light rays hit the solar cell array of the HAP being charged normally. In addition, the number of mirror array elements is increased whilst keeping the overall area constant of the whole reflector which represents $\frac{1}{8}$ of the HAP lateral area. It can be seen in Fig. 5 that as the separation distance increases irradiance focusing gain decreases due to solar beam divergence of the individual reflecting elements. Moreover, it can be observed that for a distance of 5 Km, the solar relayed power is almost equal to its directly received counterpart. In addition, it is clear that, as the number of elements increases the focusing gain increases till a saturation point. This behavior is justified by the fact the small reflecting element area does not affect the solar beam divergence anymore, which is totally determined by the sun subtended solid angle as measured from the HAP.

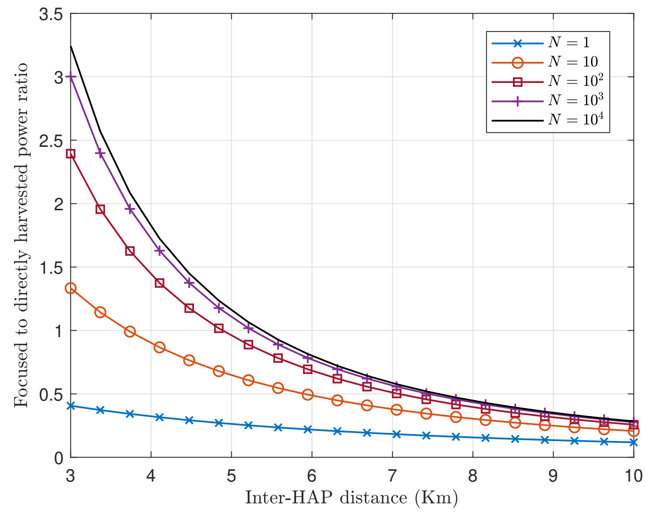


Fig. 5: Solar Power Relaying Gain.

J. RIS-assisted Resonant Beams

Resonant beam communications is another area where tunable optics can provide an added value. This technology offers significant improvements for efficient wireless charging of mobile receivers without the need for receiver tracking due to the improved path loss characteristics compared with direct LoS LED-based links [105]. Nonetheless, it requires a LoS between the transmitter and receiver to achieve resonance. Incorporating tunable reflecting surfaces in such a system allows for a directed NLOS path creation and, consequently, resonance realization. The efficiency of energy transmission in such a system setup opens the floor for future research works.

VII. Challenges

In this section, we pinpoint the main impediments that confront the integration of tunable optics in OWC.

A. Intermediate Nodes Deployment

It is evident that the proper deployment of tunable optical elements in OWC networks involves several intricacies as locations selection, dimensions, and topology design, deployment density, to name but a few. The placement of tunable optical elements serving as intermediate nodes between sources and destinations represents a challenging problem with respect to several aspects. The first of which is defining proper metrics to evaluate the goodness of a placement strategy. These metrics are not straightforward due to the simultaneity of offered services and their conflicting objectives. In addition, it is not easy to tell beforehand whether such metrics should be defined on an ensemble average or worst-case basis. Another issue associated with deployment location choice is the blockage chances minimization.

Moreover, selecting the dimensions of intermediate nodes raises similar concerns to those is associated with numerous tradeoffs as the delay-spread vs. received power and blockage probability vs. received power, to name but a few. It is evident that the received power is proportional to the intermediate node area where the two former quantities are varies inversely with it. In addition, increasing the intermediate node area contradicts the aesthetic aspects of the hosting environment of the OWC system. Furthermore, the tunable optical elements topology choice significantly affects the delay spread and the amplitude profile of the optical field.

B. Operation

Optimizing the operation of such customizable optical devices is not straightforward and involves several issues. The first one is developing activation strategies of the atomic elements of the optical device array. Such strategies need to consider the delay spread control and balance between different performance metrics. For example, the design should balance energy consumption reduction, data rate improvement, and response time minimization. Also, the adaptive tuning function optimality is questionable, where it changes with the channel realization. Moreover, defining the optimization problems responsible for managing the tunable optical elements-aided OWC networks is extremely convoluted due to the variations of user preferences regarding the tradeoffs of provided services by the network.

C. Computational Complexity Handling

Building tunable optical devices possessing superior resolutions to enable precise control over the previously discussed optical functionalities incurs inevitably excessive computational complexity. Some powerful approaches can handle computational concerns, such as federated learning, distributed optimization, and photonic integrated circuits.

D. Channel Estimation

The massive number of tunable atomic elements makes traditional channel estimation techniques as pilots transmission a very challenging approach. In addition, such techniques requires adopting semi-passive intermediate nodes equipped with sensing functionality. To maintain affordable complexity, in such setups the atomic elements are divided into subgroups having highly correlated channels, then a single channel coefficient becomes representative for those of this group. Along similar lines, the sparsity of channel representation can be exploited by compressive sensing techniques to reduce the channel estimation process [106]. A different approach, is to consider the overall cascaded channel (source - intermediate node(s) - the detector). This approach enables totally passive intermediate nodes operation. As for OWC deployments in quasi-static environments with dominant LoS and directed NLoS link components, localization and orientation estimation are sufficient to have a very accurate estimate of the channel coefficients.

E. Human Safety

The sensitivity of human body cells to electromagnetic radiation at optical frequencies implies that great care should be taken in the design and operation of optical sources and manipulators. Eye parts vulnerability to injuries due to optical radiation incidence depends significantly on the impinging radiation wavelength. For instance, eye retina is most sensitive to visible light band. Nonetheless, eye cornea and lens are more affected by infrared radiation, whereas human skin is more sensitive to ultraviolet radiation [107]. The exposure thresholds on irradiance are usually set based on the tissue damage energy threshold and the pain reaction time. Exposure thresholds for different body part injuries are presented in [107] and [108, Ch. 4.5.3] for incoherent and laser sources, respectively. That being said, the exposure limits quantified in terms of irradiance for each optical frequency band should be considered when power focusing RISs are used such that the worst case exposure does not result in an injury. This can be controlled by controlling the number of RIS elements contributing to power focusing at a given point.

VIII. Conclusion

Throughout this article, we provided a high-level perspective of tunable optics aided OWC while giving a brief survey on tunable optical devices and the potential of adaptive OWC networks employing tunable optical elements. The proposed adaptive OWC networks can significantly enhance several aspects, such as tailored spatial coverage, spatial multiplexing, security, energy consumption, and interference mitigation. Moreover, we unveiled several future research directions, such as the scalability of reconfigurable OWC networks and optimizing the components' architecture. Finally, we highlighted some foreseen challenges for deploying, operating and sustaining tunable-optics-assisted OWC networks.

References

[1] S. Dang, O. Amin, B. Shihada, and M.-S. Alouini, "What should 6G be?" *Nature Electronics*, vol. 3, no. 1, pp. 20–29, 2020. [Online]. Available: https://doi.org/10.1038/s41928-019-0355-6

[2] H. Haas, J. Elmirghani, and I. White, "Optical wireless communication," *Phil. Trans. R. Soc. A.*, vol. 378, 2020.

[3] B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics*. John Wiley & Sons, 2019.

[4] S. M. Kamali, E. Arbabi, A. Arbabi, and A. Faraon, "A review of dielectric optical metasurfaces for wavefront control," *Nanophotonics*, vol. 7, no. 6, pp. 1041–1068, 2018.

[5] M. B. Rahaim, J. Morrison, and T. D. Little, "Beam control for indoor FSO and dynamic dual-use VLC lighting systems," *Journal of Communications and Information Networks*, vol. 2, no. 4, pp. 11–27, 2017.

[6] H.-H. Chou and W.-T. Huang, "Wavelength tunable asymmetric B-OWC system based on self-injection locking for TDM-PONs," *IEEE Photonics Technology Letters*, vol. 33, no. 7, pp. 370–372, Apr 2021.

[7] H.-W. Rhee, J.-B. You, H. Yoon, K. Han, M. Kim, B. G. Lee, S.-C. Kim, and H.-H. Park, "32 Gbps data transmission with 2D beam-steering using a silicon optical phased array," *IEEE Photonics Technology Letters*, vol. 32, no. 13, pp. 803–806, 2020.

[8] A. M. Abdelhady, O. Amin, B. Shihada, and M. Alouini, "Spectral efficiency and energy harvesting in multi-cell SLIPT systems," *IEEE Transactions on Wireless Communications*, p. 1, 2020.

[9] I. Abdalla, M. Rahaim, and T. Little, "Impact of receiver fov and orientation on dense optical networks," in *2018 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2018, pp. 1–6.

[10] M. Najafi, B. Schmauss, and R. Schober, "Intelligent reflecting surfaces for free space optical communication systems," *IEEE Transactions on Communications*, 2021.

[11] H. Ajam, M. Najafi, V. Jamali, and R. Schober, "Channel Modeling for IRS-Assisted FSO Systems," *arXiv preprint arXiv:2010.00528*, 2020.

[12] A. M. Abdelhady, A. K. Salem, O. Amin, B. Shihada, and M.-S. Alouini, "Visible light communications via intelligent reflecting surfaces: Metasurfaces vs mirror Arrays," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1–20, 2021.

[13] A. M. Abdelhady, O. Amin, A. K. Sultan, M.-S. Alouini, and B. Shihada, "Channel characterization of IRS-based visible light communication systems," *IEEE Trans. Wireless Commun.*, 2022.

[14] M. A. Arfaoui, A. Ghrayeb, and C. Assi, "Integration of irs in indoor vlc systems: Challenges, potential and promising solutions," *arXiv preprint arXiv:2101.05927*, 2021.

[15] S. Sun, T. Wang, F. Yang, J. Song, and Z. Han, "Intelligent reflecting surface-aided visible light communications: Potentials and challenges," *IEEE Vehicular Technology Magazine*, 2021.

[16] H. Abumarshoud, L. Mohjazi, O. A. Dobre, M. Di Renzo, M. A. Imran, and H. Haas, "LiFi through reconfigurable intelligent surfaces: A new frontier for 6G?" *IEEE Vehicular Technology Magazine*, 2021.

[17] V. Jamali, H. Ajam, M. Najafi, B. Schmauss, R. Schober, and H. V. Poor, "Intelligent reflecting surface-assisted free-space optical communications," *arXiv preprint arXiv:2105.13297*, 2021.

[18] A. R. Ndjiongue, T. M. Ngatched, O. A. Dobre, and H. Haas, "Toward the use of re-configurable intelligent surfaces in VLC systems: Beam steering," *IEEE Wireless Communications*, vol. 28, no. 3, pp. 156–162, 2021.

[19] ——, "Re-configurable intelligent surface-based VLC receivers using tunable liquid-crystals: The concept," *Journal of Lightwave Technology*, vol. 39, no. 10, pp. 3193–3200, 2021.

[20] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. De Rosny, and S. Tretyakov, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 11, pp. 2450–2525, 2020.

[21] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling with Matlab®*. CRC press, 2019.

[22] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265–298, Feb. 1997.

[23] F. R. Gfeller and U. Bapst, "Wireless in-house data communication via diffuse infrared radiation," *Proceedings of the IEEE*, vol. 67, no. 11, pp. 1474–1486, Nov. 1979.

[24] M. Z. Chowdhury, M. T. Hossan, A. Islam, and Y. M. Jang, "A comparative survey of optical wireless technologies: Architectures and applications," *IEEE Access*, vol. 6, pp. 9819–9840, 2018.

[25] Z. Xu and B. M. Sadler, "Ultraviolet communications: Potential and state-of-the-art," *IEEE Communications Magazine*, vol. 46, no. 5, pp. 67–73, 2008.

[26] A. Prokes, "Atmospheric effects on availability of free space optics systems," *Optical Engineering*, vol. 48, no. 6, p. 066001, June 2009.

[27] C. C. Chen, "Attenuation of electromagnetic radiation by haze, fog, clouds, and rain," RAND corp. Santa Monica CA, Tech. Rep., 1975.

[28] R. Ramirez-Iniguez, S. M. Idrus, and Z. Sun, *Optical wireless communications: IR for wireless connectivity*. CRC press, 2008.

[29] H. Kaushal and G. Kaddoum, "Optical communication in space: challenges and mitigation techniques," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 57–96, 2016.

[30] M. Uysal, C. Capsoni, Z. Ghassemlooy, A. Boucouvalas, and E. Udvary, *Optical Wireless Communications: an Emerging Technology*. Springer, 2016.

[31] B. Shihada, O. Amin, C. Bainbridge, S. Jardak, O. Alkhazragi, T. K. Ng, B. Ooi, M. Berumen, and M.-S. Alouini, "Aqua-fi: Delivering internet underwater using wireless optical networks," *IEEE Communications Magazine*, vol. 58, no. 5, pp. 84–89, 2020.

[32] M. Born and E. Wolf, "Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light," 1999.

[33] K. Wang, A. Nirmalathas, C. Lim, and E. Skafidas, "4 × 12.5 Gb/s WDM optical wireless communication system for indoor applications," *Journal of Lightwave Technology*, vol. 29, no. 13, pp. 1988–1996, 2011.

[34] L. G. Kazovsky, G. Kalogerakis, and W.-T. Shaw, "Homodyne phase-shift-keying systems: Past challenges and future opportunities," *Journal of lightwave technology*, vol. 24, no. 12, pp. 4876–4884, 2006.

[35] V. Dhasarathan, M. Singh, and J. Malhotra, "Development of high-speed fso transmission link for the implementation of 5g and internet of things," *Wireless Networks*, pp. 1–10, 2019.

[36] A. Trichili, K.-H. Park, M. Zghal, B. S. Ooi, and M.-S. Alouini, "Communicating using spatial mode multiplexing: Potentials, challenges, and perspectives," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 4, pp. 3175–3203, 2019.

[37] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE communications surveys & tutorials*, vol. 17, no. 4, pp. 2047–2077, 2015.

[38] H. G. Sandalidis, A. Vavoulas, T. A. Tsiftsis, and N. Vaiopoulos, "Illumination, data transmission, and energy harvesting: the threefold advantage of VLC," *Applied optics*, vol. 56, no. 12, pp. 3421–3427, 2017.

[39] M. S. Rea, *The IESNA lighting handbook: reference & application*. IESNA, 2000.

[40] J. I. de Oliveira Filho, A. Trichili, B. S. Ooi, M.-S. Alouini, and K. N. Salama, "Toward self-powered internet of underwater things devices," *IEEE Communications Magazine*, vol. 58, no. 1, pp. 68–73, 2020.

[41] P. D. Diamantoulakis, K. N. Pappi, Z. Ma, X. Lei, P. C. Sofotasios, and G. K. Karagiannidis, "Airborne radio access networks with simultaneous lightwave information and power transfer (slipt)," in *2018 IEEE Global Communications Conference (GLOBECOM)*. Abu Dhabi: IEEE, 2018, pp. 1–6.

[42] Y. Zhuang, L. Hua, L. Qi, J. Yang, P. Cao, Y. Cao, Y. Wu, J. Thompson, and H. Haas, "A survey of positioning systems using visible LED lights," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 1963–1988, 2018.

[43] S. Hu, Q. Gao, C. Gong, and Z. Xu, "Efficient visible light sensing in eigenspace," *IEEE Communications Letters*, vol. 22, no. 5, pp. 994–997, 2018.

[44] H. Hosseinianfar and M. Brandt-Pearce, "Cooperative passive pedestrian detection and localization using a visible light communication access network," *IEEE Open Journal of the Communications Society*, vol. 1, pp. 1325–1335, 2020.

[45] ——, "A cooperative physical layer scene-awareness scheme for visible light communications," in *2020 IEEE 17th Annual Consumer Communications & Networking Conference (CCNC)*. IEEE, 2020, pp. 1–2.

[46] E. A. Jarchlo, X. Tang, H. Doroud, V. P. G. Jimenez, B. Lin, P. Casari, and Z. Ghassemlooy, "Li-tect: 3-d monitoring and shape detection using visible light sensors," *IEEE Sensors Journal*, vol. 19, no. 3, pp. 940–949, 2018.

[47] S. Dimitrov and H. Haas, *Principles of LED Light Communications: Towards Networked Li-Fi*. Cambridge University Press, 2015.

[48] A. S. Hamza, J. S. Deogun, and D. R. Alexander, "Wireless communication in data centers: A survey," *IEEE communications surveys & tutorials*, vol. 18, no. 3, pp. 1572–1595, 2016.

[49] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE communications surveys & tutorials*, vol. 16, no. 4, pp. 2231–2258, 2014.

[50] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is lifi?" *Journal of lightwave technology*, vol. 34, no. 6, pp. 1533–1544, 2015.

[51] A.-A. A. Boulogeorgos, S. E. Trevlakis, and N. D. Chatzidiamantis, "Optical wireless communications for in-body and transdermal biomedical applications," *IEEE Communications Magazine*, vol. 59, no. 1, pp. 119–125, 2021.

[52] I. Sohn, Y. H. Jang, and S. H. Lee, "Ultra-low-power implantable medical devices: Optical wireless communication approach," *IEEE Communications Magazine*, vol. 58, no. 5, pp. 77–83, 2020.

[53] H. Haas, "Lifi is a paradigm-shifting 5g technology," *Reviews in Physics*, vol. 3, pp. 26–31, 2018.

[54] T. Yamazato, I. Takai, H. Okada, T. Fujii, T. Yendo, S. Arai, M. Andoh, T. Harada, K. Yasutomi, K. Kagawa *et al.*, "Image-sensor-based visible light communication for automotive applications," *IEEE Communications Magazine*, vol. 52, no. 7, pp. 88–97, 2014.

[55] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M.-S. Alouini, "Fso-based vertical backhaul/fronthaul framework for 5g+ wireless networks," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 218–224, 2018.

[56] A. Kasliwal, N. J. Furbush, J. H. Gawron, J. R. McBride, T. J. Wallington, R. D. De Kleine, H. C. Kim, and G. A. Keoleian, "Role of flying cars in sustainable mobility," *Nature communications*, vol. 10, no. 1, pp. 1–9, 2019.

[57] N. Saeed, T. Y. Al-Naffouri, and M.-S. Alouini, "Wireless communication for flying cars," 2020.

[58] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, "A survey of underwater optical wireless communications," *IEEE communications surveys & tutorials*, vol. 19, no. 1, pp. 204–238, 2016.

[59] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Underwater optical wireless communications, networking, and localization: A survey," *Ad Hoc Networks*, vol. 94, p. 101935, 2019.

[60] G. Maral, M. Bousquet, and Z. Sun, *Satellite communications systems: systems, techniques and technology*. John Wiley & Sons, 2020.

[61] N. Saeed, A. Elzanaty, H. Almorad, H. Dahrouj, T. Y. Al-Naffouri, and M.-S. Alouini, "Cubesat communications: Recent advances and future challenges," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 3, pp. 1839–1862, 2020.

[62] E. F. Schubert, *Light-Emitting Diodes*. Cambridge University Press, 2006.

[63] P. Bharadwaj, B. Deutsch, and L. Novotny, "Optical antennas," *Advances in Optics and Photonics*, vol. 1, no. 3, pp. 438–483, 2009.

[64] A. Dodabalapur, "Organic light emitting diodes," *Solid state communications*, vol. 102, no. 2-3, pp. 259–267, 1997.

[65] S. Rajbhandari, J. J. McKendry, J. Herrnsdorf, H. Chun, G. Faulkner, H. Haas, I. M. Watson, D. O'Brien, and M. D. Dawson, "A review of gallium nitride LEDs for multi-gigabit-per-second visible light data communications," *Semiconductor Science and Technology*, vol. 32, no. 2, p. 023001, 2017.

[66] R. Koester, D. Sager, W.-A. Quitsch, O. Pfingsten, A. Poloczek, S. Blumenthal, G. Keller, W. Prost, G. Bacher, and F.-J. Tegude, "High-speed gan/gainn nanowire array light-emitting diode on silicon (111)," *Nano letters*, vol. 15, no. 4, pp. 2318–2323, 2015.

[67] Z. Tian, Q. Li, X. Wang, M. Zhang, X. Su, Y. Zhang, Y. Li, F. Yun, and S. W. R. Lee, "Phosphor-free microleds with ultrafast and broadband features for visible light communications," *Photon. Res.*, vol. 9, no. 4, pp. 452–459, Apr 2021. [Online]. Available: http://www.osapublishing.org/prj/abstract.cfm?URI=prj-9-4-452

[68] A. Liu, P. Wolf, J. A. Lott, and D. Bimberg, "Vertical-cavity surface-emitting lasers for data communication and sensing," *Photonics Research*, vol. 7, no. 2, pp. 121–136, 2019.

[69] G. Koblmüller, B. Mayer, T. Stettner, G. Abstreiter, and J. J. Finley, "Gaas–algaas core–shell nanowire lasers on silicon: invited review," *Semiconductor Science and Technology*, vol. 32, no. 5, p. 053001, 2017.

[70] S. I. Azzam, A. V. Kildishev, R.-M. Ma, C.-Z. Ning, R. Oulton, V. M. Shalaev, M. I. Stockman, J.-L. Xu, and X. Zhang, "Ten years of spasers and plasmonic nanolasers," *Light: Science & Applications*, vol. 9, no. 1, pp. 1–21, 2020.

[71] F. L. Pedrotti, L. M. Pedrotti, and L. S. Pedrotti, *Introduction to optics*. Cambridge University Press, 2017.

[72] V. A. Soifer, *Diffractive optics and nanophotonics*. CRC Press, 2017.

[73] I. Minin and O. Minin, "Diffractive optics and nanophotonics," *Springer International Publishing*, vol. 10, pp. 978–3, 2016.

[74] B. Liu, K. Song, and J. Xiao, "Two-dimensional optical metasurfaces: From plasmons to dielectrics," *Advances in Condensed Matter Physics*, vol. 2019, 2019.

[75] N. Meinzer, W. L. Barnes, and I. R. Hooper, "Plasmonic meta-atoms and metasurfaces," *Nature Photonics*, vol. 8, no. 12, p. 889, 2014.

[76] S. Collins, D. C. O'Brien, and A. Watt, "High gain, wide field of view concentrator for optical communications," *Optics letters*, vol. 39, no. 7, pp. 1756–1759, 2014.

[77] S. Hranilovic, *Wireless optical communication systems*. Springer Science & Business Media, 2006.

[78] D. O'Brien, S. Rajbhandari, and H. Chun, "Transmitter and receiver technologies for optical wireless," *Philosophical Transactions of the Royal Society A*, vol. 378, no. 2169, p. 20190182, 2020.

[79] F. Carpi, G. Frediani, S. Turco, and D. De Rossi, "Bioinspired tunable lens with muscle-like electroactive elastomers," *Advanced Functional Materials*, vol. 21, no. 21, pp. 4152–4158, 2011.

[80] D.-K. Yang and S.-T. Wu, *Fundamentals of liquid crystal devices*. John Wiley & Sons, 2014.

[81] H. Zappe and C. Duppé, *Tunable micro-optics*. Cambridge University Press, 2016.

[82] M. C. Wu, O. Solgaard, and J. E. Ford, "Optical MEMS for lightwave communication," *Journal of Lightwave Technology*, vol. 24, no. 12, pp. 4433–4454, 2006.

[83] G. Zhou and C. Lee, *Optical MEMS, Nanophotonics, and Their Applications*. CRC Press, 2017.

[84] S. Abdollahramezani, O. Hemmatyar, H. Taghinejad, A. Krasnok, Y. Kiarashinejad, M. Zandehshahvar, A. Alù, and A. Adibi, "Tunable nanophotonics enabled by chalcogenide phase-change materials," *Nanophotonics*, vol. 9, no. 5, pp. 1189–1241, 2020.

[85] F. J. Duarte, *Tunable Laser Optics*. CRC Press, 2017.

[86] Y. J. Hong, C.-H. Lee, A. Yoon, M. Kim, H.-K. Seong, H. J. Chung, C. Sone, Y. J. Park, and G.-C. Yi, "Visible-color-tunable light-emitting diodes," *Advanced Materials*, vol. 23, no. 29, pp. 3284–3288, 2011.

[87] C. Valagiannopoulos, T. A. Tsiftsis, and V. Kovanis, "Metasurface-enabled interference mitigation in visible light communication architectures," *Journal of Optics*, vol. 21, no. 11, p. 115702, oct 2019.

[88] Z. Cao, X. Zhang, G. Osnabrugge, J. Li, I. M. Vellekoop, and A. M. J. Koonen, "Reconfigurable beam system for non-line-of-sight free-space optical communication," *Light: Science & Applications*, vol. 8, no. 1, pp. 1–9, 2019.

[89] A. T. Hussein, M. T. Alresheedi, and J. M. Elmirghani, "20 gb/s mobile indoor visible light communication system employing beam steering and computer generated holograms," *Journal of lightwave technology*, vol. 33, no. 24, pp. 5242–5260, 2015.

[90] A. M. Abdelhady, O. Amin, A. Chaaban, B. Shihada, and M. Alouini, "Spectral-efficiency—illumination Pareto front for energy harvesting enabled VLC systems," *IEEE Transactions on Communications*, vol. 67, no. 12, pp. 8557–8572, dec 2019.

[91] T. Koonen, K. Mekonnen, Z. Cao, F. Huijskens, N. Q. Pham, and E. Tangdiongga, "Ultra-high-capacity wireless communication by means of steered narrow optical beams," *Philosophical Transactions of the Royal Society A*, vol. 378, no. 2169, p. 20190192, 2020.

[92] L. Qian, X. Chi, L. Zhao, and A. Chaaban, "Secure visible light communications via intelligent reflecting surfaces," in *ICC 2021-IEEE International Conference on Communications*. IEEE, 2021, pp. 1–6.

[93] R. Bloom, M. Z. Zamalloa, and C. Pai, "Luxlink: creating a wireless link from ambient light," in *Proceedings of the 17th Conference on Embedded Networked Sensor Systems*, 2019, pp. 166–178.

[94] J. Li, A. Liu, G. Shen, L. Li, C. Sun, and F. Zhao, "Retro-vlc: Enabling battery-free duplex visible light communication for mobile and iot applications," in *Proceedings of the 16th International Workshop on Mobile Computing Systems and Applications*, 2015, pp. 21–26.

[95] P. Chvojka, A. Burton, P. Pesek, X. Li, Z. Ghassemlooy, S. Zvanovec, and P. A. Haigh, "Visible light communications: increasing data rates with polarization division multiplexing," *Optics Letters*, vol. 45, no. 11, pp. 2977–2980, 2020.

[96] H. Abumarshoud, B. Selim, M. Tatipamula, and H. Haas, "Intelligent reflecting surfaces for enhanced NOMA-based visible light communications," *arXiv preprint arXiv:2111.04646*, 2021.

[97] S. Sun, F. Yang, and J. Song, "Sum rate maximization for intelligent reflecting surface-aided visible light communications," *IEEE Communications Letters*, vol. 25, no. 11, pp. 3619–3623, 2021.

[98] S. Sun, F. Yang, J. Song, and Z. Han, "Joint resource management for intelligent reflecting surface–aided visible light communications," *IEEE Transactions on Wireless Communications*, 2022.

[99] H. Wang, Z. Zhang, B. Zhu, J. Dang, L. Wu, L. Wang, K. Zhang, Y. Zhang, and G. Y. Li, "Performance analysis of multi-branch reconfigurable intelligent surfaces-assisted optical wireless communication system in environment with obstacles," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 10, pp. 9986–10 001, 2021.

[100] D. Dardari and D. Massari, "Using metaprisms for performance improvement in wireless communications," *IEEE Transactions on Wireless Communications*, vol. 20, no. 5, pp. 3295–3307, 2021.

[101] P. Agheli, H. Beyranvand, and M. J. Emadi, "High-speed trains access connectivity through ris-assisted fso communications," *arXiv preprint arXiv:2110.12804*, 2021.

[102] W. Hedhly, O. Amin, B. Shihada, and M.-S. Alouini, "Hyperloop communications: Challenges, advances, and approaches," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2413–2435, 2021.

[103] M. Qaraqe, M. Usman, A. Serbes, I. S. Ansari, and M.-S. Alouini, "Power hotspots in space: Powering cubesats via inter-satellite optical wireless power transfer," 2021.

[104] G. K. Kurt, M. G. Khoshkholgh, S. Alfattani, A. Ibrahim, T. S. Darwish, M. S. Alam, H. Yanikomeroglu, and A. Yongacoglu, "A vision and framework for the high altitude platform station (HAPS) networks of the future," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 2, pp. 729–779, 2021.

[105] M. Xiong, Q. Liu, G. Wang, G. B. Giannakis, and C. Huang, "Resonant beam communications: Principles and designs," *IEEE Communications Magazine*, vol. 57, no. 10, pp. 34–39, 2019.

[106] B. Zheng, C. You, W. Mei, and R. Zhang, "A survey on channel estimation and practical passive beamforming design for intelligent reflecting surface aided wireless communications," *arXiv preprint arXiv:2110.01292*, 2021.

[107] R. Protection and I.-I. Protection, "Guidelines on limits of exposure for broad-band incoherent optical radiation (0.38 to 3 μm)," *Health Phys*, vol. 73, no. 3, pp. 539–597, 1997.

[108] D. H. Sliney and J. Mellerio, *Safety with lasers and other optical sources: a comprehensive handbook*. Springer Science & Business Media, 2013.