Advancements in Laser and LED-based Optical Wireless Power Transfer for IoT Applications: A Comprehensive Review

Kimia Ahmadi, *Student Member, IEEE*, Wouter A. Serdijn, *Fellow, IEEE*

***Abstract*—Optical wireless power transfer (OWPT) has emerged as a promising technology for efficient wireless power transfer (WPT), offering advantages such as directionality, suitability for far-field applications, and the ability to transfer power and data simultaneously. This comprehensive review classifies OWPT systems into laser power transfer (LPT) and LED-based OWPT. LPT uses the narrow divergence of laser beams for high-density, long-distance energy transfer, making it suitable for applications such as satellites, autonomous drones, and electric vehicle charging. In contrast, LED-based OWPT offers a safer, more cost-effective solution for low-power applications, especially in the Internet of Things (IoT) domain. It offers advantages such as lower power consumption and fewer safety restrictions compared to LPT.**

Innovations in LPT, such as high-intensity laser power beaming, distributed laser charging, adaptive distributed laser charging, simultaneous lightwave information and power transfer, and resonant beam charging are discussed. Also, recent advancements in LED-OWPT, including single-lens and double-lens systems, collimation techniques, and multi-LED arrays, are explored for their potential in powering IoT devices, wearable electronics, and smart infrastructure.

First, we present a radar chart comparing various WPT techniques with respect to performance criteria. After reviewing the methods of LPT and LED-OWPT in detail, a comparison of these techniques is provided, evaluating their strengths, limitations, and application suitability. A concluding radar chart offers insights for optimizing OWPT systems tailored to specific applications. Future research directions are identified, emphasizing the need for further advancements in beam alignment, safety protocols, and hybrid systems to enhance OWPT's scalability and practicality in real-world scenarios.

***Index Terms*—Internet of Things (IoT), laser power transmission (LPT), optical wireless power transfer (OWPT), light-emitting diodes (LED), and simultaneous wireless information and power transfer (SWIPT).**

I. INTRODUCTION

ALL modern electronic devices, such as consumer products like smartphones, computers, vehicles, drones, robots, and even body-implanted medical devices, depend on electric power sources ranging from milliwatts up to kilowatts. Traditionally, electric power is supplied to all of these electronic devices, usually through mains electricity or by batteries. Nowadays, however, wireless power transfer (WPT) has emerged as a compelling alternative, particularly in scenarios where wired connections are impractical or unsafe. Examples include underwater equipment and implanted medical devices [1], [2]. Research in the WPT field is mostly taking place to solve such problems as long transmission distances, limitation in the transmitters and receivers sizes, improving safety, power transfer efficiency (PTE), the amount of the power delivered to the load (PDL), etc. [3]. Wireless recharging of batteries or supercapacitors holds great promise for portable and autonomous systems but is still one of the important scientific and engineering challenges yet to be overcome [4]. Despite the lower PTE compared to the wired options, rapid adoptions of WPT techniques have been seen recently since its origination due to its adaptability and convenience. Advances in research of high-performance WPT systems towards increasing transmission distance and further improving PTE remain active pursuits [5], [6].

The progression of WPT technology is mainly evolving along two different pathways namely near-field techniques and far-field techniques. The former is characterized by small transmission distances in comparison to the wavelength used, which ranges from a few millimeters to a few meters, while the latter coverage is equal to or greater than a typical personal area network. Near-field WPT includes capacitive power transfer (CPT) [1], [7]–[10], and inductive power transfer (IPT) [11]–[15]including resonant inductive WPT [16]–[18] and magnetic resonance coupling [19]–[22]. Far-field WPT consists of the radiofrequency power transfer (RF WPT) [17], [23]–[27] and optical wireless power transfer (OWPT) [28]–[34] [35] techniques. There are other types of WPT techniques classification in the literature which include radiative and non-radiative or electromagnetic (EM)-based WPT and non-EM techniques [36]–[40].

Despite their maturity in applications like consumer electronics and industrial automation, near-field WPT techniques struggle with efficiency, misalignment, and scalability over relatively longer transmission distances. In contrast, far-field methods, including RF WPT [23], [24], enable power transfer across several meters to even a few kilometers but suffer from exponential attenuation and reduced PTE due to free-space path loss. This has prompted increasing interest in OWPT utilizing light as a medium for wireless power transfer, offering distinct advantages such as lower attenuation and narrow beam divergence as a far-field solution capable of overcoming many limitations of RF-based approaches.

Nevertheless, far-field WPT methods generally exhibit lower PTE compared to near-field techniques [28], [29]. When it comes to scalability, OWPT systems are versatile enough to support diverse applications ranging from IoT and smart cities to space exploration and healthcare, although their operation depends on adherence to stringent safety protocols [29].

Figure 1 illustrates the feasible transmission power versus transmission distance for various WPT methods, with different colored regions representing specific applications, as shown in the accompanying table (based on [41]). The solid black curve represents the exponential decay of power transfer efficiency as the transmission distance increases [42], highlighting the inherent limitation of most WPT methods. As the distance grows, the efficiency of techniques such as inductive coupling, magnetic resonant coupling, and microwave significantly decreases. However, one important conclusion that can be drawn from Figure 1 is that optical wireless power transfer, unlike other WPT techniques, can effectively accommodate a wide range of distances and power levels, making it a versatile solution for various applications.

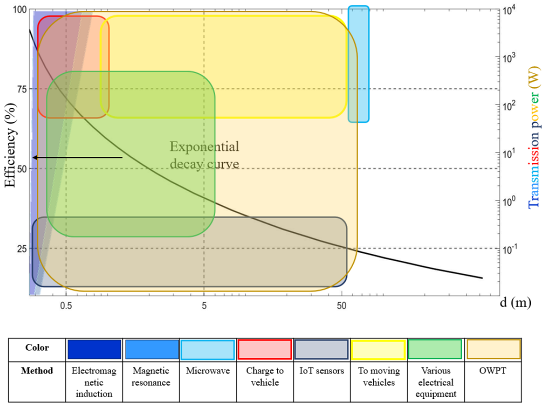


Fig. 1: schematic graph and presentation of the applicable range and transmission power levels of wireless power transmission [41], [42].

The radar chart in Figure 2 compares various WPT methods across important criteria such as transmission distance, efficiency, misalignment sensitivity, safety restrictions, and receiver complexity based on the corresponding state-of-the-art references. The chart highlights the strengths and weaknesses of each technique, offering an insightful way to visualize their relative performance. While near-field WPT techniques offer higher PTE, PDL, and benefit from mature literature, they are limited by short transmission distances and sensitivity to misalignment, making them unsuitable for dynamic applications like IoT. Far-Field OWPT, represented by the yellow chart, excels in areas such as transmission distance, receiver simplicity, and adaptability to dynamic IoT environments with minimal environmental sensitivity. Despite challenges like safety restrictions, OWPT's unique position as a versatile solution that balances various trade-offs makes it a promising candidate for overcoming the limitations of other WPT technologies. This comparison lays the groundwork for exploring OWPT in detail throughout the paper, highlighting its potential as a cutting-edge WPT method.

OWPT also can harvest energy from ambient lighting for self-powering; this feature makes them particularly suitable for applications like biosensors, wearable devices, and certain IoT technologies. Their straightforward electronic designs and compatibility with simultaneous wireless information and power transfer (SWIPT) expand their range of practical uses [29], [61], [62]. Moreover, OWPT systems are effective in underwater applications, where they can reliably power autonomous underwater vehicles (AUVs), seafloor explorations, and robotic systems [34], [63], [64].

Research on OWPT encompasses system concepts, [3], [65], [66], performance evaluation [67], [68], [69], device-level demonstration and system experiments [30], [70], [71]. One of the notable advances includes Wi-Charge's exploration of OWPT for consumer electronics [72] and a laser-based smartphone charging system developed at the University of Washington [73]. Despite its potential, OWPT technology remains in its developmental stages, with key challenges including beam alignment, safety considerations, and performance limitations under adverse conditions, such as environmental factors, misalignment, and dynamic operational settings. Furthermore, the dominance of traditional WPT methods and the technical complexity of OWPT systems have affected their adoption in many applications. However, recent advances in material science have significantly improved photovoltaic conversion efficiencies, while their simple electrical interface has rejuvenated interest in OWPT as a viable and innovative solution for next-generation wireless power delivery [3], [41].

Efficient OWPT systems demand a stable light source,

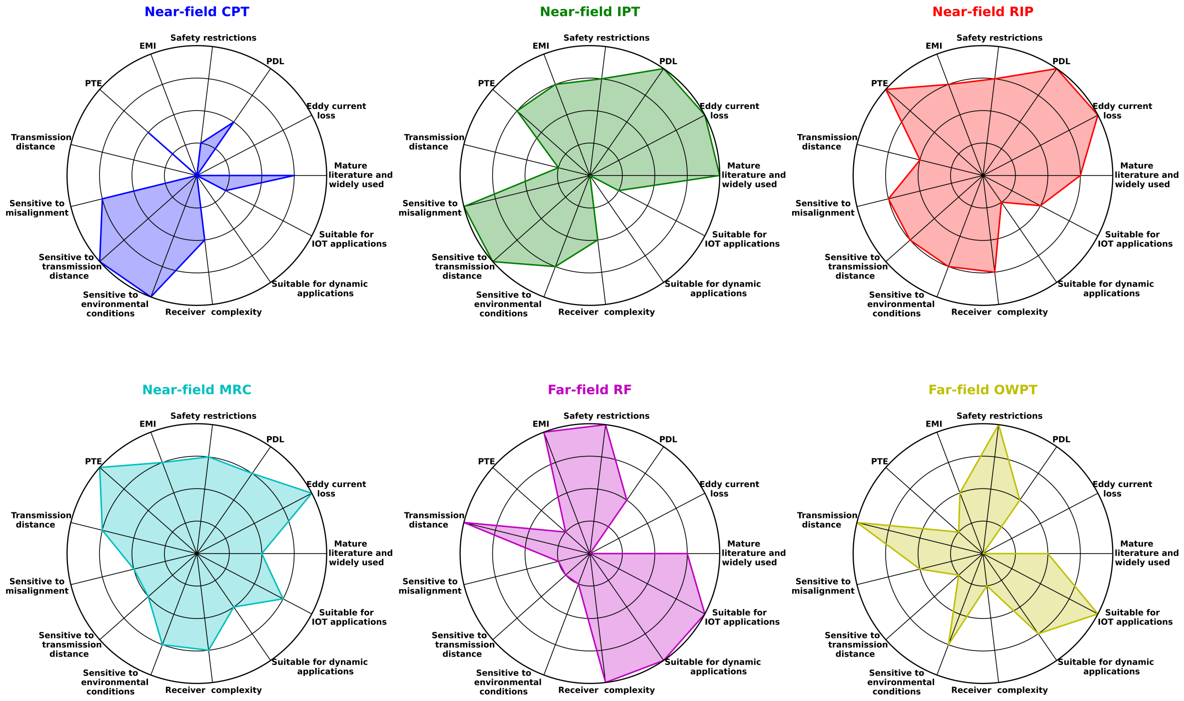


Fig. 2: Radar chart comparison of WPT technologies [30], [36]–[38], [43]–[60].

precise beam control, optimized photovoltaic (PV) cell receivers, while considering safety restriction. Among PV materials, silicon (Eg = 1.12 eV) and gallium arsenide (Eg = 1.43 eV) dominate OWPT applications for their practicality and high power conversion efficiency (PCE). While InP-based photodetectors suit longer wavelengths, their efficiency remains limited, restricting broader adoption. Emerging materials like perovskites show promise for achieving high PTE but face challenges related to performance degradation and sensitivity to misalignment [30]. Although research on blue and UV wavelengths is sparse due to low solar power relevance, Si and GaAs remain standard for OWPT systems [41].

This paper provides a comprehensive review of state-of-the-art advancements in OWPT technologies, categorizing them based on their optical transmitter into laser power transfer (LPT) and LED-based OWPT (LED-OWPT). LPT leverages laser diodes (LDs) to achieve precise, high-density power transfer over long distances, making it suitable for high-power applications such as satellite communication and autonomous drones [31], [36] or challenging environments like highways [29]. On the other hand, LED-OWPT provides a safer, cost-effective solution for vast low-power applications for indoor and outdoor use, including use in healthcare applications, for powering medical monitoring [36], wearable devices, and consumer electronics. It is particularly advantageous due to its lower sensitivity to alignment and the ease of meeting its safety requirements compared to LPT [35], [74], [75]. The key contributions of this paper are as follows:

- **Comprehensive Categorization:** A systematic classification of OWPT systems into LPT and LED-based techniques, with a detailed analysis of their strengths, limitations, and application domains.
- **State-of-the-Art Evaluation:** An evaluation of state-of-the-art innovations in OWPT systems, including high-efficiency collimation systems, safety mechanisms, and performance optimizations for diverse applications such as IoT, healthcare, and smart cities.
- **Comparative Analysis:** A quantitative and qualitative assessment of OWPT compared to other WPT methods, supported by visual tools and comparative tables to highlight key metrics, advantages, and potential challenges of each technique to create a comprehensive perspective for the reader.
- **Application-Focused Insights:** An exploration of OWPT's potential across various domains, emphasizing the practicality and scalability of LED-based OWPT for low-power applications for the IoT era.
- **Future Directions:** Identification of current challenges and research gaps, proposing pathways for ad-

vancing OWPT, such as hybrid systems, intelligent reflecting surfaces (IRS), and dynamic beam alignment.

The rest of the paper is organized as follows: Section II delves into LPT techniques, discussing their principles, advancements, and applications, including High-Intensity Laser Power Beaming (HILPB), Distributed Laser Charging (DLC), Adaptive Distributed Laser Charging (ADLC), Simultaneous Lightwave Information and Power Transfer (SLIPT), and Resonant Beam Charging (RBC). Section III focuses on LED-OWPT, analyzing its practical implementations and potential for IoT. Finally, Section IV concludes the paper by explaining the key findings and discussing opportunities for future research.

II. LASER POWER TRANSFER

Laser power transfer consisting of a laser diode, a gain medium, and a PV cell receiver is a promising long-range WPT technology for powering UAVs, satellites, and mobile devices [65], [76]–[79]. While LPT faces challenges with low PTE, minimizing laser dispersion and optimizing heat dissipation in LDs can enhance their output power and range [80]. Advances in semiconductor lasers have increased their conversion efficiency to 70% at wavelengths around 0.9 µm, while Vertical Cavity Surface Emitting Lasers (VCSELs), with efficiencies up to 60% in the 0.8–1.1 µm range, align well with the peak responsivity of Si and GaAs solar cells, supporting efficient energy conversion [41]. Yet, optimizing PV cells for uniform illumination remains difficult due to the Gaussian beam profile of lasers.

Efficiency improvements in LDs focus on structural design and driver adjustments, with continuous wave (CW) or pulse mode operation tailored to specific application requirements [43]. High-power LDs are more efficient, compact, and cost-effective than Diode-Pumped Solid-State Lasers (DPSSLs) but are currently limited to short-range applications. For more on ”Methods to Improve the Efficiency of the LD” and ”LD Drivers”, the interested reader is referred to [43].

Semiconductor lasers excel in OWPT for generating collimated light. VCSELs, favored for their scalability and 2D array output over external cavity emitting lasers, achieve 40%-60% efficiency and power outputs up to 1 kW. However, challenges in heat dissipation and cooling above a few hundred watts highlight the need for further research and innovation [81], [82].

In [41], the feasibility and challenges of using VCSELs in OWPT are explored. By connecting VCSELs in series, PTE can be enhanced. The system shown in Figure 3 features a high-power VCSEL array (975 nm) paired with a high-efficiency single-crystal Si solar cell. Results indicate VCSEL and solar cell outputs of 18.7 W and 6.38 W, respectively, with 34.1% conversion efficiency and an overall PTE of 6.32%.

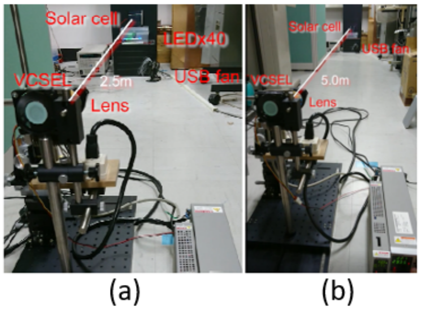


Fig. 3: Demonstration of OWPT using VCSELs: (a) 2.5 m transmission distance, (b) 5 m transmission distance (Picture adopted from [41], with permission).

Also in [64], a VCSEL resonator was developed for laser wireless charging. By optimizing optical elements, the study demonstrated stable laser oscillation over distances beyond 400 cm, suitable for indoor applications. This research achieved a 200 cm air cavity laser, reported a first of its kind, with a maximum output power of 86.3 mW, a Gaussian beam profile, and a low divergence angle of 6.87°. This extended cavity design enhances alignment between the laser beam and the charging terminal, making it ideal for wireless charging applications.

In the rest of this section, we systematically investigate the different LPT techniques presented in the literature. Figure 4 provides an overview of the discussed LPT methods in this section, highlighting their key features and challenges. These methods are arranged from left to right, from long-range power transmission, suitable for satellites, to short-to-medium-range applications tailored for IoT devices.

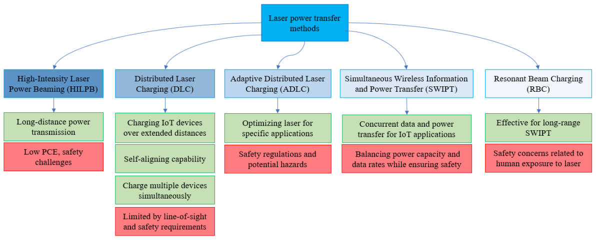


Fig. 4: Overview of discussed LPT methods, and their key features (in green) and challenges (in red).

A. High-Intensity Laser Power Beaming (HILPB)

HILPB technology enables energy transmission to distant mobile devices, such as electric vehicles [29], [83], UAVs, robots, and orbiting satellites [83]–[86]. It also holds promise for connecting power plants, landing sites, and lunar habitats. As shown in Figure 5, HILPB relies on a high-power LD source for its compact size, reliability, and high PCE. The LD generates a monochromatic beam directed toward a PV panel via a beam director. Although theoretically capable of transmitting unlimited power over vast distances, practical and safety constraints limit HILPB PTE and PDL [3].

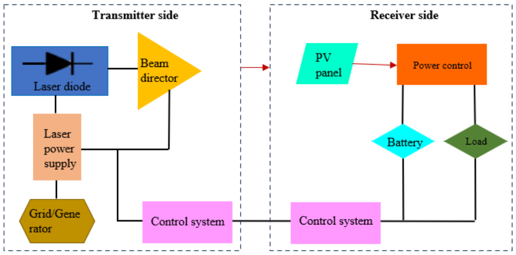


Fig. 5: Block diagram of a HILPB system [3].

Currently, the practical transmission distance of HILPB systems is restricted by the output power of LDs. However, with much better efficiency, the combination of LDs with GaAs PV cells is a favorable structure for HILPB systems [43]. Despite improvements, the overall efficiency has stayed around 10%-20%, which has obstructed its commercialization [43].

The versatility of HILPB systems makes them attractive for different applications, particularly in environments with high voltage, RF, EMI, or magnetic fields [43]. Research into HILPB gained momentum in the 2000s following advancements in LPT projects [3]. Future developments in OWPT technologies are expected to enhance power handling and conversion efficiencies, further advancing the feasibility of HILPB systems, but safety restrictions still remain.

B. Distributed Laser Charging (DLC)

DLC's self-aligning capability allows for the seamless powering of IoT devices without special positioning as long as a line-of-sight (LOS) path exists. Compact DLC receivers can be embedded into sensors, smartphones, or similar devices, while transmitters can be installed on walls or ceilings to charge multiple devices simultaneously. Unlike traditional systems, DLC employs PV cells instead of bulky collecting lenses, offering a lightweight, cost-effective solution [3].

The performance of DLC systems depends on factors such as laser wavelength, PV cell characteristics, and optoelectrical conversion efficiency. While DLC offers advantages like a compact design and extended transmission range, it also faces challenges, including propagation attenuation, PCE concerns, laser safety hazards, LOS dependence, and transmission distance limitations due to path-loss constraints [3].

To enhance DLC's practicality, experiments have combined DLC with diverging angular dispersion [87]. The block diagram in Figure 6 demonstrates how angular dispersion and DLC resonance improve WPT while reducing hazards. The transmitter features a gain medium for power amplification, a diffraction grating for angular dispersion, and a telescope for a wide field-of-view (FOV). Two perpendicular diffraction gratings enable spatially distributed resonance, directing laser energy across a 2D FOV to the receivers [88], [89]. The receiver employs retroreflectors and beam splitters to establish resonant cavities that efficiently reflect the beam back to the transmitter, optimizing power transfer. Safety mechanisms are integrated to stop resonance if LOS is disrupted, but the system is constrained by International Electrotechnical Commission (IEC) maximum permissible exposure (MPE) guidelines, which limit high-power radiation [90].

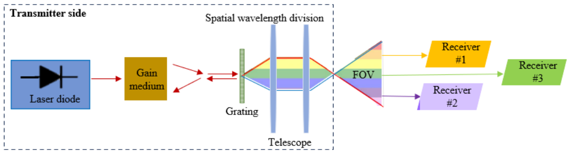


Fig. 6: A block diagram of the DLC OWPT system proposed in [87].

C. Adaptive Distributed Laser Charging (ADLC)

Effective power control to prevent undercharging or overcharging in DLC systems using batteries is crucial for safety and optimal performance. One approach to address these issues is ADLC, also known as adaptive resonant beam charging (ARBC). In ADLC, adaptive power transmission occurs based on feedback from the ADLC receiver, significantly improving energy utilization. According to [91], using adaptive DLC will cause up to 61% power savings in battery charging. For battery charging performance and PTE optimization, [92] demonstrated ARBC system and its fundamental block diagram is presented in Figure 7, showcasing a power supply and gain medium at the transmitter side, and a PV cell, a battery, and a DC-to-DC converter at the receiver. The feedback system involves a power controller and a power monitor. The PV cell output power and battery charging profile determine the laser power requirements. The transmitter's power controller oversees the feedback information. Also, Infra-communication (enabling data transfer through infrared technology), Bluetooth, or Wi-Fi can be utilized in the feedback information system. Future investigations in ADLC must address various challenges, including the system's susceptibility to temperature fluctuations and the impact of resonating laser beam propagation loss [92].

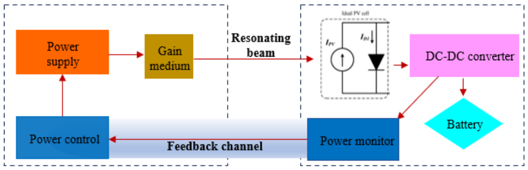


Fig. 7: Block diagram of an ADLC system [3], [92].

D. Simultaneous Wireless Information and Power Transfer (SWIPT)

SWIPT has emerged as a pivotal technology driving the IoT era [93], [94]. Building on this, simultaneous lightwave information and power transfer (SLIPT) integrate communication and networking modules into DLC transceivers [95]. SLIPT enables the use of visible or other parts of the light spectrum for data transfer alongside DLC implementation [96], [97]. By combining WPT and control signaling within a unified resonating beam, SLIPT eliminates the need for radio communication dependencies such as Bluetooth or Wi-Fi, paving the way for robust wireless networks [98]. Additionally, optical sources, such as indoor lighting, can facilitate concurrent data and energy transfer [99].

This approach supports applications like wireless battery recharging in IoT, Intelligent IoT, and Internet of Underwater Things (IoUT) [100], [101]. SLIPT has recently gained attraction as a cost-effective solution for powering remote sensors and self-sustaining devices [3], offering a crucial trade-off between data rates and energy harvesting [102], [103]. For example, experiments in [104] demonstrated a 1 Gb/s data rate using a VCSEL and GaAs PV cell, highlighting its potential for next-generation backhaul connectivity.

Intelligent Reflecting Surface technology [105] has emerged as a promising solution for optimizing channels in SWIPT applications [106]. In [107], the integration of SLIPT within a Visible Light Communication (VLC) system was investigated. By adjusting the interaction between an Optical IRS (OIRS) and transceivers, the system maximizes harvested energy while maintaining optimal data rates. Simulations reveal that OIRS significantly enhances VLC system performance compared to setups without OIRS.

An OIRS-assisted SLIPT system is schematically illustrated in Figure 8, where sets L, K, and N represent the indices of LEDs, users, and OIRS elements, respectively. The system serves K users using L LEDs, with an OIRS consisting of N reflective elements mounted on the wall to amplify reflective channel gain. Each LED corresponds to a single user, requiring L to be at least equal to K. Furthermore, the positions of LEDs, users, and the OIRS are assumed to be known beforehand [107].

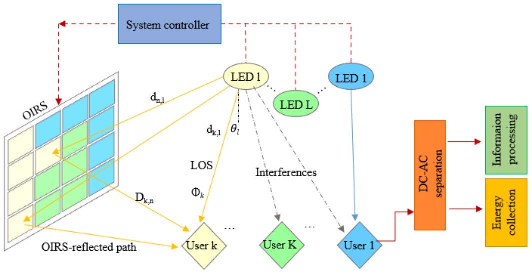


Fig. 8: The system-level schematic of an OIRS-assisted SLIPT [107].

Radiation exposure safety, alongside achieving acceptable transmission distances and power capacity, remains a major challenge in SLIPT systems [108]. SLIPT technologies can be categorized into two main types: (1) wide-area omnidirectional and (2) narrow-beam orientation. Wide-area approaches, such as broadcasting radio waves, provide long-range and omnidirectional coverage but face energy dissipation challenges, limiting high-power transmission [109]–[111]. In contrast, narrow-beam orientation, exemplified by beamforming LEDs/LDs, enables high-energy-density transmission [112], [113].

An advancement in [114] incorporates retroreflectors, a gain medium, and an internal modulator within a telescope to generate a resonant beam, achieving high-power and high-data-rate SLIPT. The Laser Simultaneous Wireless Information and Power Transfer (LSWIPT) [115] system emerges as a promising technology with great potential in the field of consumer electronics. [116], reported a pulsed current source with a switching frequency equal to the data modulation frequency that drives an LD to reach high efficiency at elevated data rates. A significant challenge in LSWIPT systems stems from the interdependence of transmitted power and data rate. To address this, a multi-degree-of-freedom data modulation method is proposed by a combination of amplitude and pulse-width modulation, enabling high-power enhanced data rates in LSWIPT [115].

SLIPT systems integrate power transfer and data transmission seamlessly under dynamic variations of the surrounding light. Using VLC or laser channels, for example, photodetectors and PV cells perform simultaneous energy harvesting and extraction of data signals. Further integration is achieved by the use of hybrid VLC/RF settings, where the AC signal (RF) is used for carrying data and the DC component is employed for power, thus allowing dynamic balancing between data rate and energy harvesting with time-switching (TS) and power-splitting (PS) mechanisms [117], [118]. Adaptive algorithms, such as reinforcement learning (RL), optimize parameters like receiver alignment and power-splitting ratios to keep operations stable in fluctuating environments—from indoor spaces to underwater conditions [119], [120]. Innovations like Low-High Keying enable energy-efficient coding for continuous power and data integration in IoT applications [93].

SLIPT using LEDs has also been investigated, where white LEDs are combined with Si PV cells [121], [122]. Furthermore, methods such as low-directivity LEDs and code shift keying (CSK) will also make SLIPT adaptable in the most difficult scenarios, including underwater communications facing mobility or turbidity dispersion in light endurance [107], [123]. These developments make SLIPT a robust solution for dependable energy and data transfer in the face of diverse applications and changing lighting conditions [124], [125].

E. Resonant Beam Charging (RBC)

The sixth generation (6G) mobile communication systems are expected to integrate free-space optical communication (FSO) and WPT to meet future connectivity demands [126]. However, challenges such as mobility and safety in laser-based wireless power and data transfer persist [127]–[129]. An RBC system addresses these challenges by employing retroreflectors at both the transmitter and receiver to enable mobility and self-alignment [130]. RBC systems inherently prioritize safety, as any obstruction in the direct LOS disrupts resonance and halts power transfer, allowing for immediate detection of interruptions. This also ensures that individuals outside the resonant cavity are shielded from beam radiation. Furthermore, RBC can simultaneously charge multiple devices wirelessly, with transmitters installed on base stations to power devices within range. Equipped with an RBC transceiver, a device can act as a relay to distribute power to nearby IoT devices [58]. In biomedical applications, RBC facilitates WPT to wearable devices while taking into account safety constraints. Additionally, the resonant beam supports SWIPT through imperceptible information modulation, enabling efficient and secure communication [130].

The architecture of the RBC system is illustrated in Figure 9. The transmitter comprises a high-reflectivity mirror (M1), a pump source that energizes the gain medium, and a partially transparent mirror (M2), which together form an optical resonant cavity. To achieve cavity stability, M1 and M2 must have high reflectivity. This configuration generates an intracavity resonant beam, part of which escapes through M2 as an external beam. The emitted beam contains discrete optical frequencies, determined by the EM-field variations within the cavity and the receiver incorporates a PV panel. The energy transfer process in RBC occurs in three phases: (1) converting input power into stored energy, (2) transmitting the stored energy as beam power, and (3) converting beam power into electrical output [58].

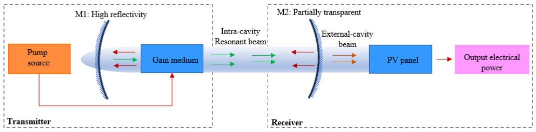


Fig. 9: Architecture of the RBC system [58].

The original RB design, introduced in [131]–[133], provides a secure wireless power supply of multiple watts over meter-scale distances for IoT devices, quickly gaining widespread attention. [132] detailed the operational principles, developed a numerical model, and analyzed RB system performance. [58] validated the RB system experimentally, achieving 2 W of power transfer over 2.6 m transmission distance. [134] further advanced the technology with a long-distributed-cavity laser utilizing a cat-eye retroreflector for alignment, a telescope to expand and focus the laser beam, and an aspheric lens to correct intracavity spherical aberration. Additionally, [58] presented an analytical energy transmission model for the RBC system, validated using MATLAB Simulink.

A recent study in [133] introduced a self-aligned RBC system for long-distance power transfer in mobile applications, inspired by optical resonators and retroreflectors. This system employs a spatially separated laser resonator (SSLR) with a double-retroreflector design, removing the need for complex tracking controls, and incorporates focal telecentric cat's eye retroreflectors. Experimental results demonstrate OWPT exceeding 5 W (yielding over 0.6 W electrical power) with minimal diffraction loss to a receiver of a few centimeters in size. The system supports receiver mobility within a 2 m vertical range, a 6° FOV, and a horizontal range of ±18 cm from the transmitter. Detailed analysis, setup, and verification are provided in [133] and illustrated in Figure 10.

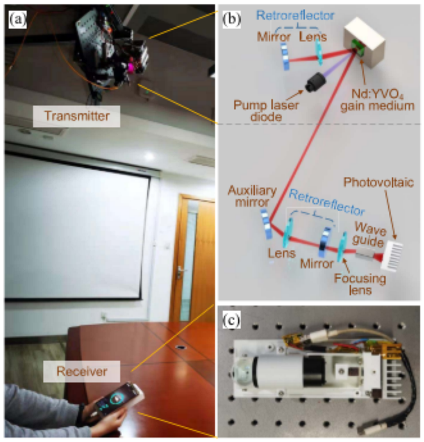


Fig. 10: Experimental setup of charging a smartphone with RBC (a) Application scenario (b) Components (c) Receiver with the size of 16.7 cm × 6.0 cm × 3.6 cm (Picture adopted from [133], with permission).

Resonant beams generated through SSLR offer advantages such as high power, self-aligned mobility, and inherent safety that can address significant challenges of beam steering and receiver positioning or tracking in SLIPT. In [135], an asymmetric SSLR-based mobile SLIPT system is proposed, with a detailed optimization process addressing the trade-off between power and data transfer. Numerical results show that the optimized asymmetric system achieves substantially higher power and communication rates compared to the symmetric design from a prior study [136].

1) *Adaptive Resonant Beam Charging (ARBC)*

The single-user ARBC system described in [92] employs feedback control to improve PTE, akin to link adaptation. Multiuser power control methods introduced in [137] include (1) alternative charging, where users are charged sequentially, reducing efficiency, and (2) a more robust TDMA-PWM approach that combines time division multiple access (TDMA) and pulse-width modulation (PWM) for concurrent charging with individual power control. This method supports more users with greater simplicity and reliability.

While a single transmitter can serve multiple receivers, tracking individual power needs simultaneously presents challenges. Alternative scheduling divides time into frames, charging one receiver per frame, while another method sequentially charges receivers at specified rates, bypassing fully charged devices [92], [137]. However, frequent power switching within frames can strain the gain medium and require complex transmitter designs, and single-receiver power allocation limits flexibility and capacity. Optimizing these approaches is crucial for enhancing ARBC system performance.

Achieving adaptive resonant beam WPT over a broad dynamic range, including varying distances and FOV, remains challenging without alignment-free lasers. In [138], the researchers address dynamic range requirements and optical aberrations as key limitations. Their alignment-free laser demonstrates multi-watt optical output power over 1-5 meters with a receiver FOV of ±30° and a transmitter FOV of ±4.6°. Using an InGaAs PV cell, the system achieves an electrical output power exceeding 1.3 W. The study suggests further design improvements could yield output powers of 100 W or more, expanding the potential of resonant beam charging for IoT applications.

2) *RB-SWIPT and RB-Communication*

The RB-SWIPT system, first proposed in [139], addresses key challenges in high-data-rate, high-power, long-range, and human-safe SWIPT [87], [140]–[142]. Early designs, however, faced issues with transmission loss, beam interference, and system performance [143].

In [114], a long-range RB-SWIPT system was developed, demonstrating near-zero diffraction loss over 20 m. It achieved up to 9 W power transfer and a maximum spectral efficiency of 20 bit/s/Hz. To improve energy concentration, [144] introduced an RB system with double aspherical cat's-eye retroreflectors. This design reduced spherical aberration by modulating beam phase distribution, achieving an axial range of 7 m—double that of a spherical resonator—with up to twice the power at 1 m and a 3° FOV. Maximum output power and spectral efficiency reached 4 W and 12 b/s/Hz, respectively.

An improved RB-SWIPT system is proposed in [143], as shown in Figure 11. The system extends transmission distance and minimizes interference using reflectors (M1-M4), lenses (L1-L3), a gain medium, a pump source, a telescope internal modulator (TIM), an electro-optical modulator (EOM), and a second harmonic generator (SHG) at the transmitter. The receiver includes a beam splitter, a PV cell, and an avalanche photodiode (APD). The TIM reduces beam losses, while the SHG generates frequency-doubled beams (532 nm) to prevent interference. M1 and M2 manage 1064 nm energy transfer, while M2, M3, and M4 handle data transfer. Numerical results showed 8 W power transfer and 18 bit/s/Hz spectral efficiency over a 100 m transmission distance, with SHG ensuring unidirectional signals and reduced interference.

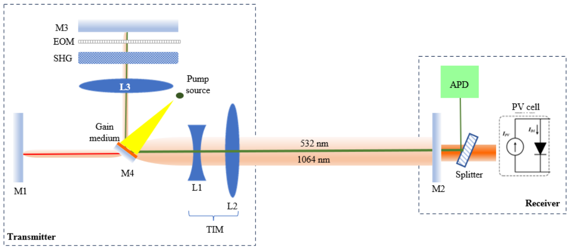


Fig. 11: System structure of improved RB-SWIPT : (Green lines: 532 nm resonant beam; Orange lines: 1064 nm resonant beam; Red line: 1064 nm external beam) [143].

Figure 12 illustrates the Resonant Beam Communication (RBCom) system block diagram, which integrates a modulator, a current regulator, and a communication and energy harvesting (CEH) circuit. The modulated current allows the output laser to carry power and data simultaneously. The CEH module separates the communication signal from the PV panel's output and directs the remaining energy to a DC-DC converter for battery charging [130]. RBCom was introduced as a viable wireless communication system in [130]. To address echo interference during data transfer, [145] proposed a second-harmonic RBCom design. In [142], an RBCom system demonstrated SLIPT via free-space optical communication, achieving over 40 mW of charging power and a 1.6 Gbit/s channel capacity. Further advancements in [146] presented an RB-SLIPT system for mobile receivers, delivering 4 W charging power and 3 Gbit/s data transfer within a 20° FOV over 3 m, ensuring self-alignment without tracking.

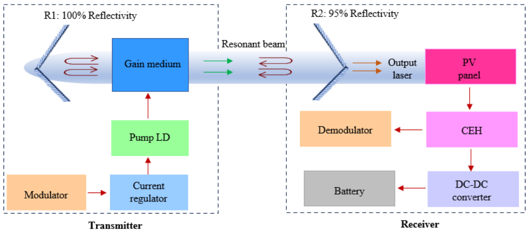


Fig. 12: Block diagram of an RBCom system [130].

3) Self-protection RBS

High-power WPT systems require safety mechanisms when power levels exceed safety thresholds. The Auto-Protection concept employs auxiliary retroreflectors on the transmitter and a beam splitter on the receiver to generate low-energy protective beams (PBs) around the main high-power beam. These PBs reflect back to the transmitter, constructively interfering with the main beam to increase receiver reflectance and reduce the pump power needed for resonance. If a PB is blocked, the main beam halts, ensuring only the harmless PB briefly interacts with the object. However, maintaining constructive interference depends on precise phase alignment, which can fail if PBs are out of phase, reducing reflectance. To address this limitation, [108] proposed using a half-wavelength phase retarder to ensure consistent constructive interference, enhancing system portability and functionality by allowing receivers to operate in varying locations.

The self-protection RBS system introduced in [147] as illustrated in Figure 13, addresses similar safety challenges. This system surrounds the main resonant beam with low-power PBs, which halt transmission if intersected by an external object, thereby stopping the resonant beam due to the excitation threshold limit. The authors detailed the self-protection mechanism based on EM-field propagation, self-mixing interference, and an output power model. Numerical results demonstrate safe power transmission of approximately 4.6 W with a spectral efficiency of 12.8 b/s/Hz over a 2 m transmission distance. This self-protection mechanism provides a secure, non-mechanical solution for SLIPT applications.

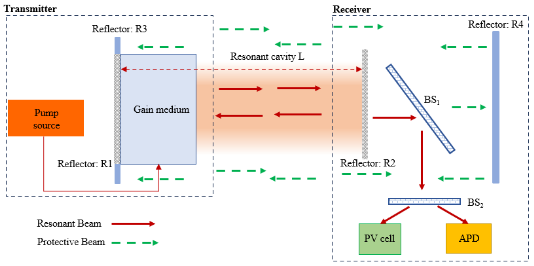


Fig. 13: Schematic of a self-protection RBS system [147].

SLIPT systems face challenges in achieving narrow beam transmission with mobile receivers. To address this, [146] proposed the Simultaneous Mobile Information and Power Transfer (SMIPT) system, which utilizes an energy-concentrated resonant beam for self-alignment with mobile receivers through geometric and analytical models. Figure 14 illustrates the mobility mechanism of SMIPT. Numerical results show the system can deliver 5 W electrical power with a spectral efficiency of 9.5 b/s/Hz over a 40° FOV and a 3 m distance. The study also examines the rebuild-up time of the transmission channel after receiver movement, providing insights into the effects of moving speed. Future research directions suggested in [146] include: (1) sustaining SMIPT stability under varying speeds, (2) designing systems for long-distance transfers (hundreds of meters) and multi-receiver setups, and (3) addressing NLoS scenarios through technologies like IRS.

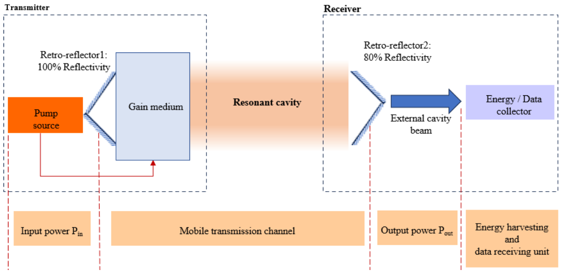


Fig. 14: SMIPT structure and energy flow [146].

Choosing a laser for OWPT system implementation has to follow many critical safety constraints that are related to the application and MPE [148], [149]. Currently, most of the works on OWPT are being carried out with laser-based schemes. The reasons for this choice is due to the natural advantages of lasers: high power density, great directionality, low divergence, narrow spectrum, and long transmission distance. However, lasers have significant disadvantages that need to be taken into consideration. Generally speaking, there are strict safety regulations surrounding laser products since they possess a number of risks involving eye, skin and tissue damage as well as environmental hazards, heating up, etc. [3]. The Japanese safety regulations controlling the use of laser products regulate that, considering a series of factors related to power level, emission duration, and wavelength, lasers shall be divided into different groups [150]. Furthermore, detailed guidelines about installing, securing, maintaining, and servicing lasers within optical communication systems have been presented by the American National Standard for Safe Use of Lasers (ANSI Z136. 1-2022) [151]–[154].

III. OWPT USING LEDs

LED-OWPT systems provide important safety advantages over laser-based OWPT systems particularly suitable for environments where living tissue exposure is a concern or include public or residential areas in IoT applications [155]–[157]. Reduced temperature sensitivity [158] and high emission efficiency [159] make LEDs stand out. They also offer cost-effectiveness and a long lifespan. These systems efficiently transfer energy and minimize risks from customary power sources so they are ideal for powering remote and mobile devices. Lens-collimated LED arrays can achieve high PTE reaching up to 70% [160]. Output powers of 532 mW at a 1 m transmission distance have been shown by recent improvements using optimized LED arrays and the energy demands of small IoT devices are met without requiring batteries or wide-ranging wiring [161].

A recent design achieves 0.8 W output power and has a small form factor compared to the previous designs, which makes it ideal for mobile IoT applications. Portability and reliability in communication are improved by the modular nature of these designs while safety is guaranteed [160]. Despite their advantages, key challenges for optimizing performance in real-world scenarios remain, including alignment precision and transmission distance limitations.

Research focusing on the properties of LEDs, including their incoherent light emission, began in 2012 and serves as the foundation for LED-OWPT systems [162]–[164]. These characteristics increase safety under MPE regulations [165] and they guarantee compatibility with portable devices because of their lightweight designs. To increase LED light intensity, engineers often enlarge the chip size or integrate multiple chips into a single module, which increases the emission area and irradiation size [166]. Although achieving complete collimation (light travels in parallel beams with minimal propagation spread) over long distances proves impractical because of the spatial incoherence of LEDs [167], [168], researchers have found that approximate collimation can be effectively achieved for short distances [3] and this provides a viable solution for applications that require shorter range alignment.

A. Using Lens Configurations in LED-OWPT Systems

This subsection focuses on the role of lens systems in enhancing the performance and efficiency of LED-OWPT systems. It discusses various lens configurations, including single and multi-lens setups, collimation techniques, and innovations such as adaptive beamforming and imaging lenses, which address challenges related to beam alignment, power attenuation, compact system design, and scalability. By reviewing state-of-the-art advancements, the objective is to highlight how these optical components enable precise energy delivery, improve PTE, and adapt to the demands of dynamic and real-world OWPT for IoT applications.

In LED-OWPT, diffraction requires a lens system—either single or multi-lens—to adjust transmission distance while maintaining the target's illumination spot size [80]. Achieving high directional precision using a single lens is difficult, leading to beam leakage and reducing PTE. A multi-lens setup with aspheric condenser and Fresnel lenses achieves the desired divergence angle. The aspheric condenser lens minimizes the Fresnel lens aperture to reduce optical energy leakage, while the Fresnel lens, though not superior to a convex lens in imaging, provides a large aperture in a compact form, ideal for IoT-based OWPT applications [3]. In [166], the researchers first addressed an initial single-LED OWPT system consisting of an LED transmitter coupled with an aspheric condenser lens and a Fresnel lens, which work together to focus the emitted light onto a GaAs solar cell as depicted schematically in Figure 15. As the transmission distance increases, the divergence of the beam also increases, which can lead to a decrease in power transfer efficiency. This setup highlights the importance of lens systems in collimating the light and optimizing the power delivery to the receiver, especially in applications where efficiency and transmission distance are critical.

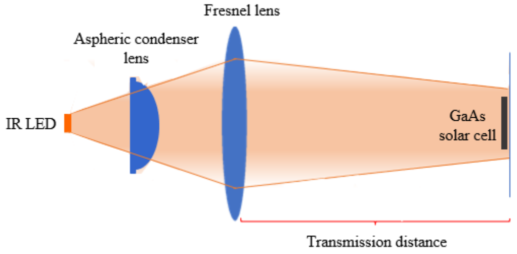


Fig. 15: Schematic of a single-LED OWPT system [166].

A portable LED-OWPT system using a GaAs PV cell and an 810 nm IR LED was developed in [169] for IoT terminals. Figure 16 (a) shows the lens system includes an aspheric condenser lens and a large-aperture, lightweight Fresnel lens concentrating light on a small area, and (b) presents the implemented prototype. Additional details about the lens system are available in [169].

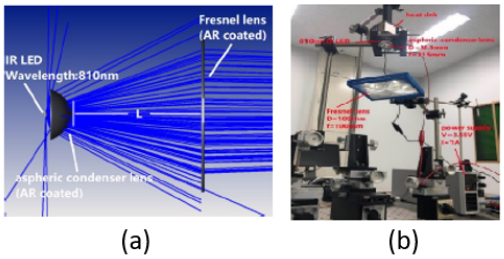


Fig. 16: A portable LED-OWPT system: (a) lens system, (b) implemented prototype (Picture adopted from [169], with permission).

This system configuration generates 251.8 mW electrical output power from the PV cell at 1 m transmission distance. The IR LED has a ±40° divergence angle and produces approximately 1 W power. To reduce system size, [169] suggests the use of mirrors that optimize space because a single mirror at a 30° tilt works well for lens distances (L) under 100 mm and a two-mirror setup is better for L over 100 mm to keep the correct distance. This mirrored configuration which is shown in Figure 17 not only maintains performance but also reduces the system's horizontal length by about 30% [169].

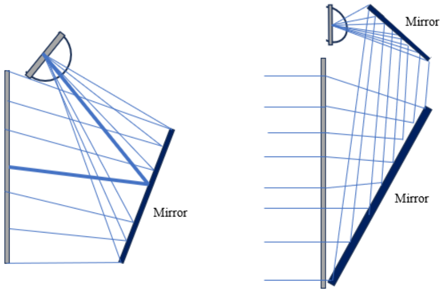


Fig. 17: Mirrored configuration proposed in [169].

Figure 18 shows a setup in which an LED chip is positioned at the focal point on the collimation lens's anterior surface. An imaging lens then focuses the collimated beam onto a distant light receiver. The illumination point's position is crucial, especially when using collimation optics with a short focal length [80].

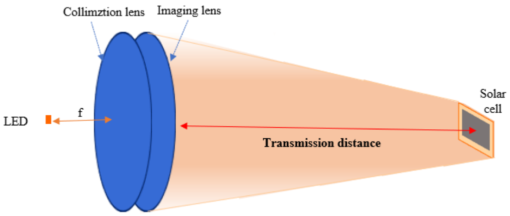


Fig. 18: Collimation method presented in [80] for a single-LED off-axis wavefront-projection device.

to concentrate the LED light and a Fresnel lens for further focusing, providing a compact and cost-effective solution for short-to-medium range applications. Both setups emphasize the importance of lens systems in optimizing PTE and maintaining precise alignment in LED-OWPT systems.

Figure 18 and Figure 15 illustrate different configurations of lenses for a single-LED transmitter in LED-OWPT. The first configuration, uses a collimation lens to focus the LED light, followed by an imaging lens that will ensure the accurate directionality of it, hence reducing beam divergence over longer transmission distances. The second one uses an aspheric condenser lens and a Fresnel lens for further focusing, providing a compact and cost-effective solution for short-to-medium range applications. Both setups emphasize the importance of lens systems in optimizing PTE and maintaining precise alignment in LED-OWPT systems.

Expanding the peripheral range of a collimation lens can increase beam leakage if the lens aperture remains constant, while a shorter focal length may widen the irradiation point, leading to power loss. Thus, there is a trade-off between irradiance and focus range in collimation optics. Research in [80] shows that using an objective lens with a constant focal length accommodates some variation in target distances with minimal efficiency loss. Alternatively, adjusting the imaging lens's focal length for different distances can help; however, as the communication range increases, the irradiation point may exceed the solar cell's surface, reducing efficiency. A zoom lens can adjust focal length flexibly. Also for LPT a liquid lens can modulate transmission distance without changing position by altering beam strength.

In [30], a perovskite-based OWPT system is presented, where a perovskite device with a light source comprising a pulse-operated LED is applied. Regarding misalignment, experimental results are presented. This paper theoretically and experimentally investigates the functionality of an OWPT setup without and with a collimating lens, showing that it is possible to increase the PTE by about one order of magnitude. This led to the development of a new predictive data-driven model. The study illustrates the potential of perovskite materials for flexible OWPT in dynamic applications, while it also points out ongoing challenges related to alignment adaptability and device durability.

In [170], a portable LED-array OWPT system is demonstrated, capable of remotely delivering around 400 mW of electrical power at 1 m transmission distance for small IoT devices. This study focuses on enhancing output power on the receiver side. Using multiple LEDs with a lens system effectively boosts the output power without substantially increasing the irradiation size. Collimated rays enable precise focusing, even with a Fresnel lens positioned close to the collimation lens, which significantly shortens the system's horizontal length. However, OWPT collimation lenses generally have a large back focal length, resulting in notable geometrical loss from light that misses the lens.

To improve lens system efficiency in LED-array OWPT, [170] proposes an alternative setup shown in Figure 19 with two sequential lens sets for collimation. This design positions the light source close to the first collimation lens set and adjusts the spacing between the lenses, reducing geometrical loss and boosting system efficiency. However, the additional lens set increases the transversal magnification, resulting in a slight enlargement of the irradiation size at the target distance.

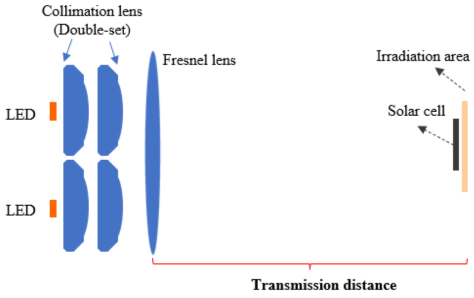
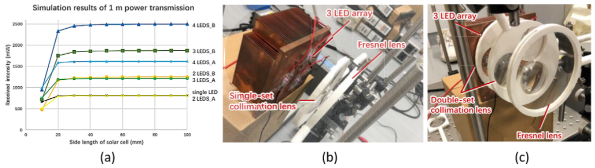


Fig. 19: LED-array OWPT system incorporating double-set collimation lens configuration [170].

In [170], simulations and experiments were conducted using multiple numbers of LEDs and solar cell sizes while maintaining a 1 m transmission distance. The study examined both single and double-lens configurations by using OSRAM SFH-4703AS LEDs that provide 1040 mW of output power and have a ±40° divergence angle. The two-LED array system achieved a final electrical output power of 268 mW from the solar cell, reported as one of the highest records in portable LED-OWPT to date. The three-LED system with a double-lens configuration achieved a maximum power of about 1800 mW while the single-lens configuration reached around 1400 mW, which shows the effectiveness of the double-lens setup. Figure 20 (a) shows the simulation results using Zemax simulation software and different numbers of LEDs with single-set configuration and double-set configuration. The experimental setups of a three-LED system with a single-set collimation lens and a double-set collimation lens are shown in Figure 20 (b) and (c), respectively.



(a) (b) (c)

Fig. 20: Three-LED OWPT system with a single-set and a double-set collimation lens: (a) simulation results using Zemax, experimental setup using (b) single-set collimation lens, (c) double-set collimation lens (Picture adopted from [170], with permission).

Experimental findings show that the double-lens configuration provides higher output power than the single-lens setup with a small number of LEDs, though this difference decreases or reverses as LED count increases. Additionally, the double-lens configuration, with its larger beam size, maintains a smoother beam size transition over distance, allowing greater tolerance for transmission range variations. While the single-lens setup maintains over 50% intensity from 450 mm to 1420 mm, the double-lens configuration achieves this from 250 mm to 1450 mm [170].

The use of LED arrays with a collimation approach to improve output efficiency is investigated in [28]. The optical projection test setup shown in Figure 21 includes an LED array featuring three near-infrared (NIR) LEDs arranged in a triangular configuration which effectively improves the quality of the projections. The communication range is matched by the imaging lens's constant focal length and the irradiation spots from different LEDs are overlapped by the collimation technique to create a consistent spot size and increase irradiation energy based on the number of LEDs.

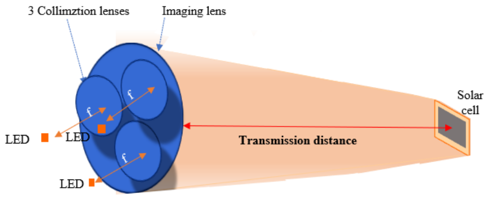


Fig. 21: LED array collimation technique from [28].

Addressing the challenge of efficient power transmission over long distances, [171] proposed LED-based OWPT system optimized for IoT applications. The system includes two high-power IR LEDs, plano-convex collimation, and Fresnel lenses to concentrate light onto GaAs solar cells at the receiver side. A custom-designed three-layer lens system, integrated with a depth camera and a liquid lens, achieves real-time auto-focus, significantly reducing power attenuation by optimizing the irradiation spot size. This approach increases effective surface irradiation by eightfold at a 3 m transmission distance, while maintaining a high lens efficiency of 74.5%. Additionally, simulations adjust the transmission distance and spot size, ensuring concentrated light delivery for improved power conversion efficiency. By leveraging commercially available components, the system adheres to lenient regulatory standards and highlights significant advancements in compact, efficient LED-OWPT systems for IoT applications.

An enhanced PTE and minimized OWPT system size utilizing an LED array is proposed in [160]. The study demonstrates a four-LED array collimation scheme featuring a collimation lens paired with an imaging lens, achieving up to 70% lens system efficiency. A simulated setup using Zemax simulation software, shown in Figure 22, places the LED module at the collimation lens's front focal point, generating parallel beams that are focused on the optical receiver through an imaging lens. This setup yields 0.8 W of electrical output power from a GaAs solar cell at a 1 m transmission distance. [160] also provides a detailed analysis of the module's thermal performance and surface irradiance at the receiver end.

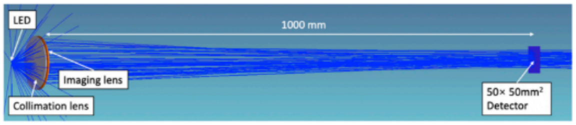


Fig. 22: LED collimation scheme simulated configuration (Picture adapted from [160], with permission).

[160] also proposed a four LED array collimation strategy to improve PTE while simplifying the design, which is shown in Figure 23. Although adding LEDs in an optimal layout can increase output power, this improvement requires a more complex arrangement with additional components.

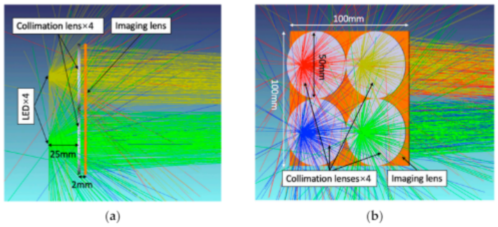


Fig. 23: Efficient LED-OWPT design proposed in [160]: (a) side view and (b) view from LED's side (Picture adopted from [149], with permission).

Figure 24 shows an experimental setup of an LED-OWPT system using only fluorescent lighting, following the simulation design in Figure 23, where all lenses have anti-reflection coatings for NIR light. A 5-series GaAs solar cell, angled at 54 degrees and positioned 1 m from the imaging lens, receives 2.69 W power over a 50 mm × 50 mm area, with room light output deemed negligible. The lens system efficiency is calculated at 72.06%, a 1.8-fold improvement over the previous system's 39.71% efficiency [158]. In [160], the emitting side, including heat sink, LEDs, and lenses, is integrated into a portable 120 mm × 114 mm × 61 mm module weighing 407.1 g. This compact, lightweight design enables easy transport by humans or robots for temporary power supply. Further setup details are provided in [160].

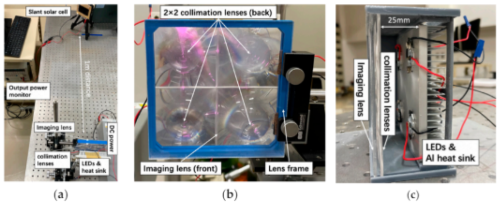


Fig. 24: LED-OWPT system proposed in [160]: (a) experimental setup; (b) front view of the lens system; (c) internal view of the portable source module (Picture adopted from [160], with permission).

B. Integrating Communication and Power via LED-OWPT for LIoT

One approach to addressing communication and sustainability challenges with visible light communication technology is the Light-based IoT (LIoT), which uses existing lighting infrastructure to provide both wireless connectivity and power to nodes [172]. By using the same optical transmitters for VLC and OWPT, LIoT eliminates the need for separate circuitry [173]. As shown in [174], LIoT can achieve communication and energy autonomy through indoor energy harvesting from visible light via PV cells. Designed to be battery-free, LIoT nodes theoretically offer unlimited lifetimes without regular maintenance [175]. A new LIoT-based data and energy networking model, depicted in Figure 25 (a), is proposed in [175] for mesh-type sensor networks, such as wireless personal-area networks (WPANs), with proof-of-concept results. Figure 25 (b) shows a typical LIoT node block diagram, emphasizing optimized photovoltaic energy generation to enhance overall network efficiency [175].

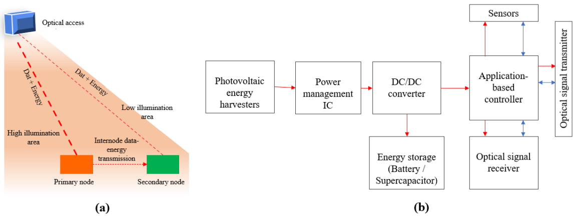


Fig. 25: Data - Energy networking structure: (a) concept, (b) typical block diagram [175].

Techniques such as maximum power point tracking (MPPT) improve the efficiency of energy generation in power management circuits within energy harvesters that are composed of either PV cells or optical rectennae and a DC-DC (boost) converter. One LIoT node could also use a combination of broad and narrow optical transmitters using small LED technology to cover the region around the node [175].

A conceptual framework for LIoT nodes interconnected for data transmission and energy distribution is illustrated in Figure 26. Here, Nodes 2 and 4 receive energy directly from optical access points (APs) and can share surplus energy with other nodes in need. For instance, Node 3, which may lack direct access due to shadows or obstructions, can receive energy from Nodes 2 and 4. The framework also demonstrates the use of an optical reconfigurable intelligent surface (RIS) [176], [177]; in this example, Node 5 obtains energy from an optical AP via a wall-mounted RIS [175].

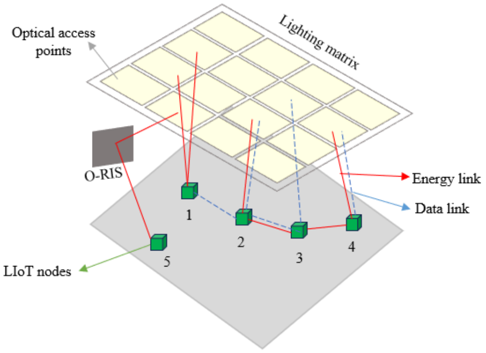


Fig. 26: Networking of data and energy via light [175].

If individuals are present in the environment, using some light sources may cause discomfort or disruption. Possible solutions include reducing light intensity or using IR light, though both may lower data or energy transmission. Alternatively, an optical AP could detect human presence, enabling the system to balance PTE with eye comfort. Additionally, scheduling node-to-node connections during periods of low human presence is recommended [175]. In [178], an IR and VLC bi-directional communication system uses identical transmission and reception circuitry and data encoding protocols. The LIoT nodes demonstrated average power consumption of 0.06 mW in sleep mode, 16.6 mW during data transmission, and 42.6 mW during energy transmission [175].

The integration of printed electronics technology is a promising step toward realizing LIoT. A study in [173] compared the performance of Organic Light-Emitting Diodes (OLEDs) and traditional LEDs for communication and power transfer in the uplink direction. Experimental results indicate that printed OLEDs are effective for low-data rate VLC applications and can support OWPT for LIoT. However, with precise transmitter-receiver alignment, conventional LEDs outperform OLEDs in energy harvesting and data rates.

C. Advancements in LED-OWPT for Dynamic Environments

This subsection focuses on recent developments in LED-OWPT, addressing critical challenges posed by dynamic environments. The focus is on innovations such as real-time tracking and alignment systems, adaptive safety mechanisms, and interference cancellation techniques caused by mobility for high practicality and efficiency of LED-OWPT for reliable power delivery and communication in real-world scenarios with target movements and physical obstacles, as well as environmental changes.

Real-time tracking of photovoltaic cells using differential absorption imaging was proposed in [179] to enhance the efficiency of the OWPT system by maintaining accurate position and orientation estimation of the PV target. This technique addresses a critical challenge in beam alignment, improving precision for higher PTE. It leverages the differential absorption of light to detect and track PV targets, accounting for factors like background light changes due to weather or diurnal variations and misrecognition from surrounding objects. Three tracking algorithms were evaluated, with an autoregressive model combined with thresholds outperforming Kalman filter-based methods in position accuracy. Experimental results showed position estimation errors under 17 mm and attitude estimation errors within 10 degrees, significantly improving alignment accuracy. This work supports dynamic target tracking and beam alignment, advancing OWPT implementation in dynamic environments.

Using LED-OWPT, achieving strong and efficient power delivery in dynamic real-world environments is still regarded as difficult due to interference and physical obstacles as well as device mobility. Ambient light from sunlight and artificial sources can also lower the signal-to-noise ratio for data communication [180], [181]. Minor obstacles can obstruct and scatter the optical beam between the transmitter and receiver and disrupt power flow resulting in OWPT performance reduction. Light pathways can be dynamically adjusted to overcome these interruptions by recent improvements such as adaptive beamforming and multi-beam strategies [182]. Furthermore, receiver mobility adds further variability to received power levels, therefore mobile receivers require precise alignment between LEDs and photodetectors which drives the development of real-time tracking and alignment systems that change beam direction according to the receiver's position. These advanced methods can improve the robustness of OWPT systems [183], [184]. Also incorporating IR-LEDs for moving devices helps to counteract motion and ecological effects. Innovations in VLC and light fidelity (Li-Fi) [185]–[189] and free-space optical communication continuously expand the capabilities of OWPT and actively address the limitations of conventional approaches.

Laser-based OWPT systems currently offer higher PTE, but LED-based systems are promising. Practical implementations of LED-OWPT systems maintain high PTE over transmission distances greater than 1 meter, retain 93% efficiency at 2 meters and 65% at 3 meters [190]. One study achieved 532 mW at a 1 m transmission distance—another improved PTE and PDL by reporting 223.9 mW at the same transmission distance with an important 77% optical efficiency [161], [166]. Recent innovations have further increased output power; a four-LED array system reaches 0.8 W with 70% lens efficiency at 1-meter transmission distance [160]. Additional reported studies on LED-OWPT are presented in Table I.

Based on the studies reviewed in this section, LED-OWPT can effectively power IoT devices and wearable electronics over long distances. Using high-power LEDs can also enhance PTE due to their higher directivity. Also, a three-layer lens system improves the irradiation spot for better performance over long distances for different applications [171]. Improvements in LED-OWPT efficiency and range strengthen its potential for future mobile and wearable technologies and IoT applications as continuing research aims to maximize transmission distance and power transfer capabilities.

IV. DISCUSSION

The aim of this review article is to provide a comprehensive exploration of Optical Wireless Power Transfer (OWPT) technologies for researchers interested in this field. Based on the optical transmitter used, the OWPT methods can be categorized into the two main groups of Laser Power Transfer (LPT) based and LED-based OWPT. Due to the low beam divergence and high-density power transfer capabilities, LPT systems demonstrate remarkable potential in high-power and long-distance applications. These capabilities make LPT a transformative solution for high-demand applications as space exploration and dynamic electric vehicle charging. We reviewed the development of different state-of-the-art laser-based techniques such as High-Intensity Laser Power Beaming (HILPB), Distributed Laser Charging (DLC), Adaptive Distributed Laser Charging (ADLC), Simultaneous Light wave Information and Power Transfer (SLIPT), and Resonant Beam Charging (RBC) in this paper. We also addressed practical challenges of LPT as the alignment sensitivity, the necessity of beam forming, safety concerns tied to the Maximum Permissible Exposure (MPE) for living tissue, and finally the environmental adaptability which hinder its widespread deployment, especially in densely populated or ecologically sensitive areas. To overcome these problems, the use of advanced safety protocols was suggested, including fail-safe systems that adjust power levels based on environmental feedback, to mitigate the safety concerns associated with the use of lasers in OWPT systems.

In comparison, LED-based OWPT systems offer a higher degree of safety, cost-effectiveness, and compatibility with compact devices, making them highly suitable for powering IoT, healthcare, personal electronics, and smart infrastructure. Furthermore, LED-OWPT can significantly enhance sustainability by integrating it with ambient lighting and creating self-powered, stationary, or mobile systems for indoor and outdoor applications. Despite these advantages, challenges persist in optimizing power transfer efficiency (PTE) and achieving consistent power delivery over long transmission distances or mobile applications for LED-based OWPT. Innovations such as single-lens and double-lens systems, collimation techniques, and multi-LED arrays have been developed to address these issues, improving PTE and enhancing their effectiveness in real-world applications. Table II provides an insight into the reviewed OWPT techniques with their key advantages and challenges, aiming to provide an applicable overview for the reader.

An important issue in OWPT, especially in dynamic environments with human activities, is the safety concern. In [195], a camera-based safety system is proposed, which can dynamically adjust the safety distance by using a depth camera and object recognition algorithms based on the velocity and proximity of the objects entering the OWPT transmission zone, as illustrated in Figure 27. It continuously monitors the proximity and speed of objects relative to the light beam and automatically adjusts or cuts off light output to stay within Maximum Permissible Exposure standards, reducing risk associated with laser or LED emissions. The scalability of the system, whereby it easily integrates multiple cameras, makes it especially fitting for large indoor spaces powered by IoT. These developments epitomize the key stride toward robust and adaptive safety mechanisms in OWPT for guaranteed reliable operation

TABLE I: Summary of Related Works for LED-OWPT.

Ref.	**Technique**	**Power Output**	**Distance**	**Key Observations**	**Key Limitations**
2020 - [164]	NIR-LED with Fresnel lens and crystalline silicon (C-Si) solar cells.	230 mW	3 m	• Compact, suitable for small IoT devices.	• Beam divergence reduces efficiency over distance. • Requires precise alignment.
2021 - [170]	Lens-collimated triple-LED array OWPT	380 mW	1 m	• Achieved highest recorded power for LED-OWPT. • Uses 17 cm² GaAs solar cell.	• Increased lens alignment sensitivity. • Higher irradiation size leads to power loss.
2022 [191]	Double-lens system for collimation and beam focusing.	532 mW	1 m	• Single LED configuration reduces the size by 46%. • LED-array system reduces size by 56% and increases output by 40%.	• Alignment errors cause beam displacement. • Efficiency challenges due to LEDs' wide-angle emission characteristics.
2022 - [158]	NIR-LED array incorporated. Analyzes factors affecting output saturation in LED-OWPT	over 1 W	1 m	• Compact design suitable for IoT applications. • Thermal features confirmed the practical application of the LED-OWPT system.	• Serious heat issues in compact system designs. • Increased number of LEDs causes misalignment errors in performance.
2023 - [160]	Four-LED array OWPT with collimation system.	0.8 W	1 m	• Modular design reduces size by 46%. • Compact and efficient for IoT. • Analyzes thermal performance and effective surface irradiance.	• Efficiency not optimal; 65% optical power lost during transmission. • Diminishing returns beyond four LEDs.
2023 - [192]	OWPT with robotic arm visual tracking. Addresses challenges in pose estimation for 3D tracking.	N.A.	20 cm	• Successful tracking of moving 2D objects was achieved. • Real-time 3D tracking feasibility. • Effective in a limited 80° range.	• Refraction affects transmission efficiency. • Galvano mirror limits tracking distance to 20cm. • Image detection becomes unstable beyond 80-degree range.
2024 - [193]	NIR-based OWPT for biological applications (IMDs).	N.A.	N.A.	• 95.7 kbps data rate. • Energy harvesting from NIR light can prolong battery life in IMDs. • Data transmission via Gaussian minimum shift keying (GMSK) modulation. • Results indicate feasibility for future clinical applications.	• Biological tissue absorption and scattering affect optical signal propagation. • Non-optimized PV cells reduce performance. • NIR light has low intensity, slowing energy harvesting.
2024 - [194]	OWPT for AE sensors with 808 nm laser and silicon-based PV cells.	800 mW	N.A.	• The OWPT system efficiently powers multiple Acoustic Emission (AE) sensors. • The system uses Bluetooth for data transfer and control	• Non-uniform illumination and PV heating limit performance. • Challenges with DC-DC switching efficiency.

with no compromise on efficiency in a moving-object environment.

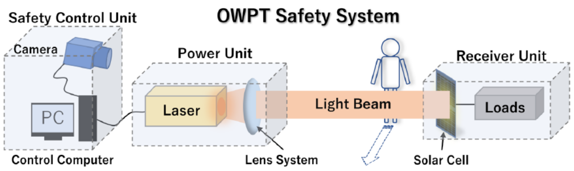


Fig. 27: OWPT safety system configuration. The powering unit consists of a laser with visible or invisible light (Picture adopted from [195], with permission).

The integration of OWPT into intelligent systems such as Low Power Wide Area Networks (LPWAN) enhances its scalability and efficiency. This capability facilitates seamless power delivery to IoT networks in healthcare, smart cities, and remote sensing, paving the way for resilient, low-maintenance systems.

While OWPT offers several advantages over other, more established, WPT techniques, there are still practical challenges that need to be addressed in future research since OWPT is still in its early stages. The impact of environmental factors, such as fog or rain, obstacles, and PV cell's partial shadings on the transmitted optical signals is challenging, leading to inconsistent and reduced power delivery. Researchers have highlighted the need for further research and technical improvements to address these challenges and improve the feasibility of OWPT system implementation in multiple applications. For LPT, optimizing laser wavelengths for specific environmental conditions and developing advanced photovoltaic materials such as perovskite solar cells could significantly enhance durability and efficiency. although temperature control, cooling, and incorporating huge heat sinks are crucial bottlenecks for developing portable LPT systems. Further exploration of dynamic beam alignment and auto-focus systems would improve transmission accuracy and extend application ranges, especially for IoT and marine environments.

It is good to mention that compared to LPT, LED-OWPT is in its developing stages, attracting great attention for incorporation into daily low-power applications. LED-based OWPT future research should focus on refining collimation and modular designs, particularly for wearable and compact IoT devices. Incorporating Intelligent reflecting surfaces (IRS) could address challenges in non-line-of-sight scenarios, improving power transfer efficiency. One attractive idea could be intelligent lighting using LED arrays in the implementation of an LED-OWPT system. Additionally, understanding environmental attenuations and shadings is crucial for ensuring reliable performance in indoor and outdoor applications, more specifically in trending low-power scenarios.

V. CONCLUSION

OWPT technologies have emerged as a transformative solution to address the increasing demand for efficient, long-range wireless power delivery in diverse applications, particularly in the context of IoT applications. This paper presents a systematic and integrated overview of both LPT and LED-OWPT, synthesizing state-of-the-art research and discussing their respective practical applications, system-level design considerations and safety challenges. Despite the discussed practical challenges, OWPT is poised to redefine wireless power delivery, offering solutions that balance efficiency and scalability with vast potential across the IoT domain. While issues like alignment precision, safety concerns, and environmental adaptability persist, continuous progress in beam alignment, safety protocols, and advanced material development suggests that these barriers are surmountable. Such advancements are paving the way for OWPT to achieve its full potential in diverse and impactful applications. As OWPT moves toward commercialization, successful deployments in dynamic environments, such as a scalable and energy-efficient IoT system for ecological monitoring in smart gardens, were enabled by OWPT.

Figure 28 provides a comparative overview of the various optical wireless power transfer methods evaluated in this paper, using the same set of criteria as has been used for Figure 2. These criteria include transmission distance, power transfer efficiency (PTE), safety, sensitivity to environmental conditions, receiver complexity, and adaptability to dynamic applications. The analyzed OWPT techniques—HIILPB, DLC, ADLC, SLIPT, ARBC, and LED-OWPT—each demonstrate distinct advantages and compromises.

Among these, LED-OWPT (highlighted in yellow) stands out with its significant strengths in safety and transmission distance, making it a promising candidate for dynamic scenarios requiring extended range and high-power delivery specifically in the IoT era. Conversely, ARBC and SLIPT excel in safety and robustness to misalignment, making them ideal for environments with fluctuating conditions. While no single technique surpasses all others across every criterion, the chart underscores that each method excels in specific areas, emphasizing the importance of tailoring OWPT solutions to the requirements of particular applications. This approach guides future innovations because it concentrates on applications that require safe, efficient, flexible, and long-range WPT solutions.

Overall, the chart illustrates the diversity of OWPT technologies and their varying performance levels based on different priorities, highlighting their potential to advance optical wireless power transfer systems.

TABLE II: Comparison chart of reviewed OWPT methods.

Method	Section	Key Advantages	Potential Challenges
HILPB	II. A	Can transmit power to any point in space; suitable for devices like UAVs and lunar habitats.	Practical and safety limitations reduce power conversion efficiency to 10%-20%; hindered commercial development.
DLC	II. B	Ideal for IoT with self-aligning capability; supports multiple receivers simultaneously.	Propagation attenuation, PCE concerns, and laser safety hazards; LOS dependence; IEC MPE restrictions.
ADLC	II. C	Improves battery performance with up to 50% power savings.	Susceptible to temperature fluctuations and resonating laser beam loss.
SLIPT	II. D	Facilitates wireless recharging; cost-efficient for remote sensors; balances data rate and energy harvesting.	Trade-offs between data rate, energy, and safety; challenges with transmission distance and mobile receiver support.
RBC	II. E	Self-aligning; safe; supports multiple devices; allows data transfer via resonant beam.	Internal losses reduce conversion efficiency.
ARBC	II. E. 1	Simple, robust transmitter design; accommodates more users.	Cannot monitor power needs of multiple receivers simultaneously; frequent power adjustments required.
RB-SWIPT	II. E. 2	Suitable for high-rate SLIPT.	Limited by transmission loss, beam interference; challenges in system design and performance evaluation.
Self-Protect RBS	II. E. 2	Ensures secure SLIPT without mechanical control.	Requires precise power threshold adjustments.
LED-OWPT	III	Cost-effective; safe under MPE regulations; compact and lightweight for portable devices.	Beam diffraction requires lens system; beam leakage reduces PTE over distance.

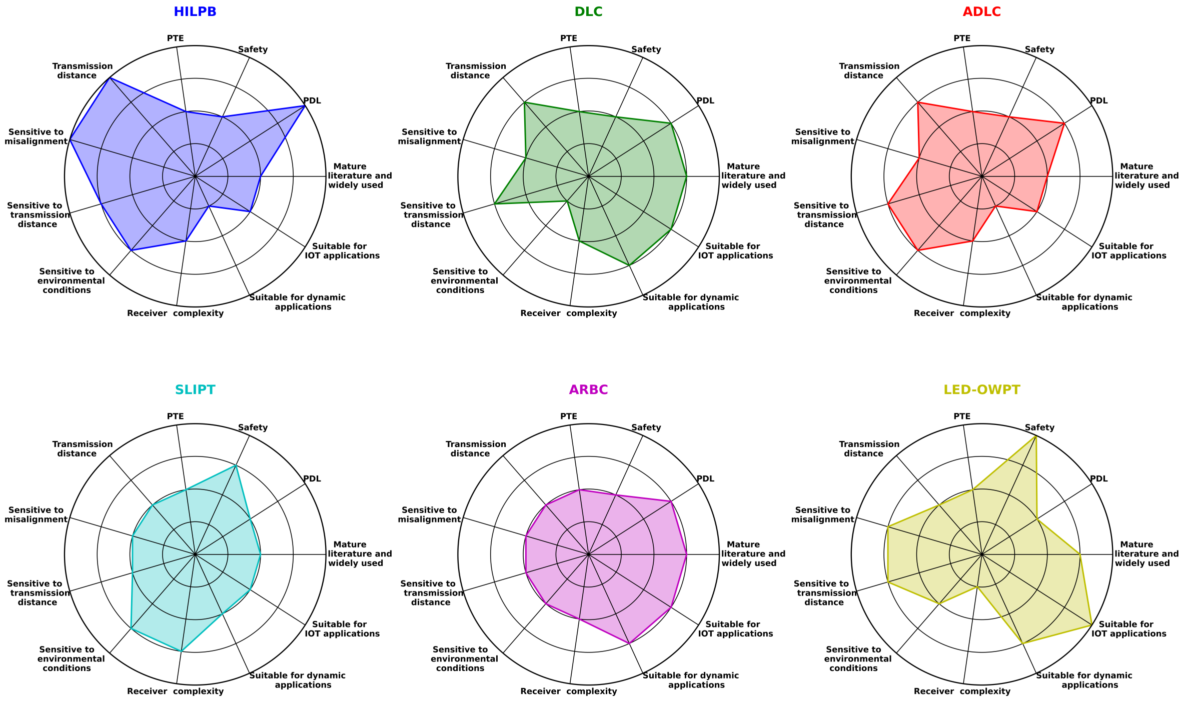


Fig. 28: Radar chart comparison of reviewed OWPT technologies.

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