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# Simultaneous Lightwave Information and Power Transfer in 6G Networks

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**Abstract**—The evolution of wireless networks towards the sixth generation (6G) and the inclusion of novel application-aware features characterized by sustainability requirements call for the use of energy-efficient communication technologies, where optical wireless communications can play an important role. In the quest for sustainability, battery recharging through energy harvesting (EH) has also attracted considerable attention. A promising approach consists in combining data transmission and EH into a single scheme, namely, simultaneous lightwave information and power transfer (SLIPT), which capitalizes on the technological maturity and efficiency of optical transceivers to ensure both functionalities. In this paper, we investigate SLIPT as a potential technology to help achieve the sustainability goals of 6G by discussing SLIPT transceiver architectures, optical beam propagation, and fundamental design trade-offs. We also categorize the applications of SLIPT with respect to range, from very short to long range considering indoor, underwater, and aerial scenarios and present its synergy with other popular technologies that are envisioned for use in 6G networks, e.g., artificial intelligence, reconfigurable intelligent surfaces, and quantum communications.

**Index Terms**—Simultaneous lightwave information and power transfer (SLIPT); 6G networks; Network sustainability; Energy harvesting; Optical wireless communications

## I. INTRODUCTION

The sixth generation (6G) of wireless networks is referred to as providing Internet of Intelligence, ensuring seamless and limitless connectivity, and full synchronization of the physical, biological, and digital worlds, paving the way for the development of novel applications, both indoors and outdoors [1]. Specifically, in the 6G ecosystem, an ever-increasing growth in the deployment of mobile nodes with global network coverage (requiring capabilities in the order of 10 Gbps/m<sup>3</sup>),

by integrating terrestrial, aerial, and underwater systems, and the use of native artificial intelligence (AI) are expected among others. Besides its technical aspect, 6G is envisioned to address related societal requirements, including improved energy efficiency, environmental consciousness, security, resilience, digital inclusion, and electromagnetic field radiation awareness. A key challenge towards serving a massive and continuously increasing number of intelligent nodes is the limited energy resources at the wireless devices. Although this is currently facilitated using hardware components, future deployments need to avoid frequent battery replacements to minimize the human intervention and material waste by exploiting energy harvesting (EH). To this end, 6G networks are expected to support wireless-powered devices.

The aforementioned goals can be achieved by integrating optical wireless communication (OWC) technology into the 6G wireless networks, both for communication and power transfer purposes [1], which can even be facilitated through hybrid networking between OWC and RF. The main reasoning for this is twofold: i) non-incremental advances to the current capabilities of wireless networks can only be achieved by using new frequency bands and OWC systems offer unique advantages compared with other alternatives, due to their low-cost implementation, high energy efficiency, and technological maturity of optical transceivers [2], ii) lightwave technology offers higher efficiency when used for energy transfer, without creating a burden to the already heavily saturated radio frequency (RF) spectrum [3].

Similarly to the RF wireless power transfer (WPT), lightwave power transfer (LPT) systems can be equipped with information transfer capabilities, leading to simultaneous lightwave information and power transfer (SLIPT) [3]. SLIPT has been proposed as a way to benefit from both the increased capacity offered by OWC systems and the ease of installation and efficiency of LPT. Depending on the transmitter radiation pattern, SLIPT can either be directive or non-directive. Non-directive SLIPT can be used indoors [3], while directive SLIPT can be applied on ground, in the air, and underwater [4], [5]. Although SLIPT has been investigated both theoretically and experimentally, by focusing on either the optimal design or the performance analysis, as shown in Table I, its capabilities and potential use cases have not been fully explored yet.

To this end, this work focuses on the integration of SLIPT with existing OWC technologies, such as visible light communications (VLC) and free-space optics (FSO), in the context of 6G, by discussing transceiver architecture, optical beam propagation, and fundamental design trade-offs. Moreover, emerging applications of SLIPT are presented, including the

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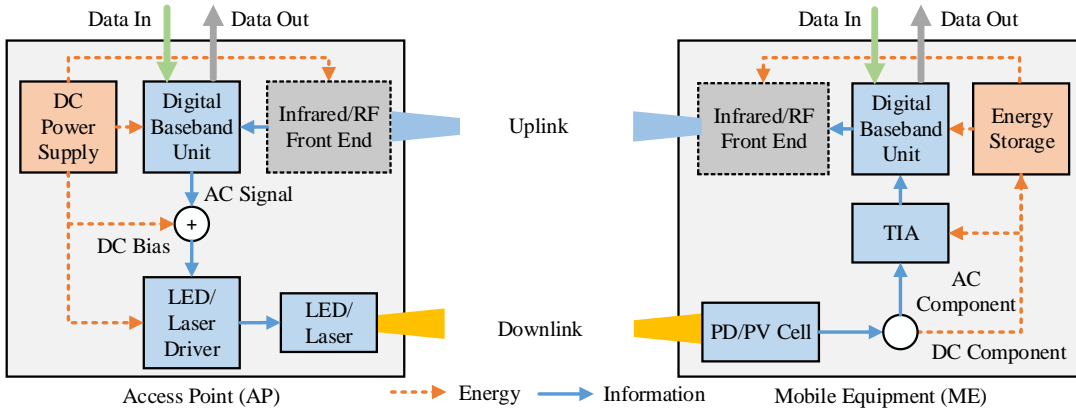


Fig. 1: SLIPT transceiver architecture. For the downlink, the SLIPT signal is prepared at the AP with an AC data-bearing signal and a DC bias to be used for EH. At the mobile equipment, the AC component of the received signal is transferred to the digital baseband unit for decoding, while the DC component is utilized to charge the energy storage. The uplink can be implemented either with an optical or RF link. TIA stands for trans-impedance amplifier.

facilitation of the deployment of ultra massive machine-type communications (umMTC) and solutions for “connecting the unconnected” in urban, rural, and remote areas. This is done through powering intelligent IoT devices, as well as the involved terrestrial, underwater, and aerial nodes such as high altitude platforms (HAPs), unmanned aerial vehicles (UAVs) and miniaturized satellites, in a cost-, energy-efficient, and environmental-friendly manner. Finally, we discuss potential challenges and future research directions, including how SLIPT can be combined with other 6G-related technologies, such as AI, reconfigurable intelligent surfaces (RISs), and quantum communications, in order to achieve high energy efficiency and to support more challenging use cases.

TABLE I: Channel Types and References

Channel	Transceiver	Distance	Power	Reference
Indoor	Non-directive	< 5m	1W	[3], [6]–[10]
Indoor	Beam-steered	< 5m	0.1-10W	[11]
Terrestrial	Directive	0.1-10km	0.1-10W	[4]
Underwater	Directive	1-100m	0.1-10W	[12], [13]
Aerial	Directive	50-1000m	0.1-10W	[5]
Satellite	Directive	50-300km	1kW	[14], [15]

## II. TRANSCIEVER ARCHITECTURE, OPTICAL BEAM PROPAGATION, AND DESIGN TRADE-OFFS

### A. Transceiver Architecture

Different transceiver architectures can be used for SLIPT, depending on the directive or non-directive nature of light signals and the beam-steering capability. A general SLIPT architecture is shown in Fig. 1.

1) *Directive SLIPT*: Directivity of the light beams can be exploited to efficiently transfer lightwave information and power between two nodes [4], since geometric spreading losses can be minimized. This is especially promising for applications where efficient long-distance point-to-point communication and power transfer is needed such as in underwater and aerial scenarios. In this architecture, resonant lasers or narrow-beam light-emitting diodes (LEDs) are used as transmitters. Highly directive light signals are obtained by

limiting the half-power angle of the transmitter in the range of mrad. While in FSO, to efficiently collect the optical signal, without interference from ambient light-induced shot noise, the field-of-view (FoV) at the receiver is narrowed, SLIPT architectures with a larger FoV could utilize the ambient light to increase the harvested energy. At the receiver, photodiodes (PDs) or photovoltaic (PV) cells can be used. Directive SLIPT architectures often require precise beam alignment systems, which can be disturbed by wind forces, building sway, etc. In PD-based receivers, liquid convex lenses, which can change their curvature, can be used to focus the received light on the active area of the PD, which can be of positive-intrinsic-negative (PIN) or avalanche PD (APD) type. APDs provide a high internal gain required for applications such as underwater SLIPT [12], with the drawback of inducing relatively high shot-noise, whereas PIN PDs are interesting in applications that require low-complexity designs and where a high gain is not required. On the other hand, PV cells can be used for joint detection and EH. It is shown that with wavelength optimization GaAs based PV cells can achieve an EH efficiency of 66% [14]. However, due to high transient time of PV cells, the data rates can be reduced. In directive SLIPT, eye safety is a very important factor to consider, expressed as the optical energy density. Eye safety limitation depends on the wavelength used and it is stricter for collimated spatially coherent laser beams. For example, a light intensity of  $1 \text{ mW/cm}^2$  can be regarded as the eye safety margin for wavelengths around 850 nm for an exposure time less than 10 ms. Obviously, for space link applications, this constraint can be neglected.

2) *Non-Directive SLIPT*: Non-directive SLIPT is useful in cases such as indoor multi-user VLC systems with user mobility where transmitter and receiver alignment is not always realizable [6]. To accommodate this, wide-beam LEDs are typically used to transmit light signals onto a large area. Due to the non-directive nature of this architecture, irradiance can be low at the receiver, thus necessitating high-power LEDs. Recently, energy-efficient organic LEDs have been used for SLIPT systems to improve LPT efficiency [7]. Moreover, densely packed multi-element transmitter structures are de-

veloped using micro-LEDs ( $\mu$ LEDs) and they are used to provide evenly distributed lightwave power inside a room. As the received optical power in this architecture is low compared to directive SLIPT, PV cells are used to harvest energy due to their large effective area. Moreover, organic and perovskite PV cells, and especially carbon-based printable perovskite PV cells, have recently emerged to be used as SLIPT receivers due to their ability to harvest energy at low light conditions indoors and their printability in different shapes [7]. However, PV cells have transient time which limits the bandwidth and causes nonlinear effects. For this reason, a hybrid architecture, in which a PD is used to receive information, while a PV cell receiver is used for EH, could be desirable if it would fit on the mobile devices. **In any case, pre-distortion techniques to mitigate these phenomena and effectively enlarge the available bandwidth can also be utilized.**

3) *Beam-Steered SLIPT*: Under beam blockage conditions, neither directive nor non-directive SLIPT architectures are effective, thus beam-steered SLIPT transceivers should be used, including multi-element-based, beam rotation-based, and RIS-based architectures. In multi-element SLIPT setups, multiple LEDs are used at the transmitter and multiple PDs or PV cells at the receiver. To achieve wide coverage, these elements are placed on a 3D shape such as a sphere, hemisphere, pyramid, or cone to offer angle diversity. By selecting LEDs at the transmitter, the light beam can be steered toward users and a PD or PV cell can be selected at the receiver to vary the direction of incident light. Beam-steering is useful to achieve a better performance at different locations, especially under high mobility conditions. Apart from that, the use of retroreflectors has enabled a new SLIPT architecture with inherent beam-steering capabilities, termed *resonant beam SLIPT*, where the transmitter and the receiver, along with the air between them, constitute a laser resonant cavity [11]. Moreover, multi-element architecture can be combined with distributed access points (APs) to provide better coverage and robust solutions under blockages. In underwater setups, beam-steering is useful to mitigate the misalignment effects due to the swaying of nodes under oceanic currents. In addition to multi-element deployment, transmitters and receivers can be rotated toward the desired direction using gimbal mechanisms, optical phased arrays (OPAs), microelectronic mirrors (MEMs), liquid crystals (LCs), etc., while RISs can also be used to steer the light beams, achieving better performance in SLIPT systems. The combination of the above techniques can provide robust solutions for a wide range of 6G application scenarios.

### B. Optical Beam Propagation

Optical wireless transmission has been extensively investigated in recent years, mainly to support terrestrial networks, through FSO links, and indoor connectivity by VLC. Since 6G networks aim at 3D interconnection with aerial, satellite, and underwater nodes, further studies are required on the effect of the propagation medium. In fact, for indoor links, SLIPT can be performed rather efficiently in the case of an existing strong line-of-sight (LoS), which can be lost depending on the movement and rotation of the receiver. While propagating in the atmosphere, a laser beam suffers from various factors

whose composition is a function of both space and time, which introduce randomness to the optical properties of the atmospheric channel, giving rise to a phenomenon known as turbulence. Moreover, particles, such as water droplets and dust, cause scattering, which is more significant in lower altitudes. Another problem is the optical beam divergence caused by diffraction, especially when using low quality lasers. In case of high-power laser power beaming, an optical effect known as “thermal blooming”, which is the local increase in temperature around the laser beam, changes the optical properties of the medium causing further divergence. Finally, random vibrations cause misalignment errors, also known as beam jitter, which requires novel methods for beam-tracking to sustain a SLIPT link, particularly between terrestrial and aerial platforms or even satellites. These factors should be considered for the interconnection of satellite constellations with SLIPT, which has attracted increasing attention as part of the 6G networks to provide ubiquitous coverage with high-bandwidth connectivity, especially in remote areas. On the other hand, underwater optical channel modeling has also been investigated, where beam absorption and scattering, as well as link misalignment and oceanic turbulence can be among the most important channel impairments [13].

### C. Fundamental Design Trade-offs

Like most wireless technologies, SLIPT’s ability to offer simultaneously two distinct services relies on some design trade-offs, the most fundamental being the one between the harvested energy and the communication performance, as shown in Fig. 2. This trade-off calls for the appropriate selection of the DC bias, the receiver’s FoV, and the time that is allocated solely to EH, in the case of using time-switching. From a practical implementation point of view, the DC level of the transmitted signal should not exceed the linear operation range of the transmitter opto-electronic components. Obviously, the percentage of the power dedicated to information transfer should be large enough to accommodate high enough SNR at the receiver for signal detection. Usually, the operating voltage of the receiver is chosen to be the maximum power point (MPP). However, due to the parasitic capacitances in the receiver, the maximum available bandwidth of the receiver may not occur at the MPP, adding an extra degree of freedom in SLIPT systems, as a different operation voltage could end up supporting higher data rates, despite the loss in SNR. The aforementioned trade-off is present even if MPP tracking is not possible due to fixed electronic parts, or in the presence of ambient light affecting the operation voltage.

From a different perspective, when dealing with mobile platforms, particularly in aerial links, high precision beam-steering or complex retroreflector setups are required to improve and maintain the directivity of the SLIPT system, since such links are prone to pointing errors. Gimbal-based systems can accommodate a wide range of positions but at low angular steering speed and low pointing resolution. Higher precision systems based on mirrors, LCs, and adaptive optics are more suited for fine tuning but do not offer a wide array of motions. In any case, a feedback link, which may also be facilitated via RF, can help control the beam-steering elements. Nevertheless,

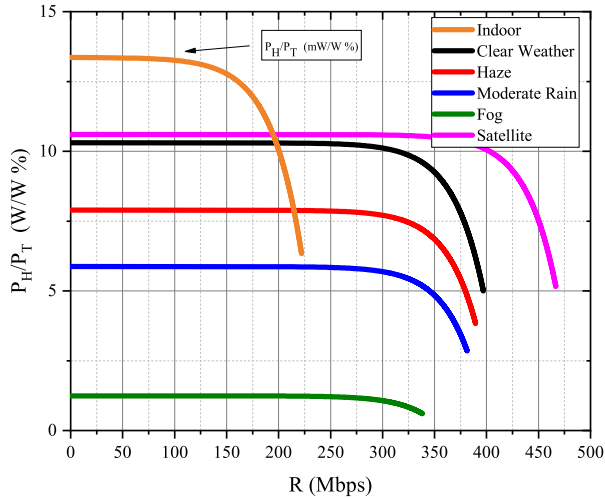


Fig. 2: Indicative rate-power regions in various SLIPT systems. The used parameters are indicative from various papers referenced below, such as [3]. The maximum power is also dictated by each application.

in some cases, it is possible to use a larger receiver area or a concentrator to limit the geometric and misalignment losses. However, this may create other issues, such as the UAV consuming more energy to hover when using a heavy solar panel, as well as decreased receiver bandwidth for data detection due to larger parasitic capacitances of the PDs. On the other hand, directive links take issue with receiver mobility, which is often the case indoors, and tracking techniques can increase the system complexity and the cost. As such, instead of narrow-beam laser diodes, wide angle LED-based transmitters can effectively deal with this issue at the cost of lower received power at the receiver plane.

### III. EMERGING APPLICATIONS

In this section, the emerging applications of SLIPT are presented, which are also illustrated in Fig. 3. SLIPT can be efficiently used in a large range of applications such as UAV communication, satellite communication, IoT sensor networks, in-body communication, smart grids, smart cities, vehicular communication systems, and underwater sensor networks.

#### A. SLIPT for Very Short Range Applications

In wireless sensor networks (WSNs), energy efficiency is critical to enable long-term operation of devices, particularly when they are placed in a difficult-to-reach location, making it difficult to replace their batteries [2]. An example is the medical implants like pacemakers, where battery replacement is complicated or impossible, as in pacemakers. Here, OWCs can be utilized as a safe alternative avoiding RF interference for communicating control messages with the implants. In fact, optical wavelengths in 700-1100nm can penetrate the skin and reach an in-body wireless node without posing any danger. On top of this, the lifetime of the batteries can be remarkably extended using transdermal SLIPT, which can charge critically-placed implants to extend their lifetime.

#### B. SLIPT for Short Range Applications

Dense deployment of Internet-of-Things (IoT) networks is restricted by the limited capacity of battery-operated devices.

SLIPT can be utilized to transfer power and information to IoT sensors [3], forming a network of zero-energy devices (ZEDs), which are passive low-power devices operating in a self-sustainable manner, eliminating the need for power supply. Utilizing ZEDs is of paramount importance in the context of IoT and for mMTC, where energy neutrality should be achieved to provide scalability. The use of ZEDs in 6G networks has the potential to significantly reduce the network cost, environmental impact, and power consumption. Furthermore, with the development of printable and organic LEDs, PDs, and PV cells, SLIPT transmitters and receivers can be mounted on any object. Smart home appliances, smart security systems, wearable devices, and in-flight services are some applications for short range SLIPT. Moreover, SLIPT's high-rate and low-latency data information and adequate power transfer can enable a range of modern concepts such as swarm robotics, where large number of simpler robots are coordinated to perform complex tasks, considering that in environments where no human presence is required, directive SLIPT can be used to transfer large amounts of power. Moreover, in dense indoor environments, SLIPT can assist in extended reality (XR) and metaverse immersion, which require a 6G-level quality of service. This results in the Internet of Senses, which is based on full immersive sensing by touch responses to vibration, sensitive to changes over one millisecond.

#### C. SLIPT for Medium Range Applications

1) *SLIPT for Access Points*: To increase the capacity of future generation networks, network densification has been identified as a prominent solution through the development of high capacity fronthaul and backhaul links. The use of small cell base stations (BSs) has become attractive due to the ability of supporting low latency applications, required in 6G networks. To provide wireless backhauling to small cell BSs with the advantage of requiring no extra infrastructure [4], either directive mmWave or FSO links can be used. The latter can offer comparable capacity in an energy efficient manner, without needing a costly fiber network or suffering from attenuation loss in rain and humid weather, in contrast to mmWave. On top of this, alternative power sources for the BSs are needed to decrease the operational costs of the BSs. WPT can be implemented, especially in the optical domain, i.e., LPT, which has been demonstrated to have the capability to power small cell BSs, thus opening new frontiers in network design, without adding extra interference to the already burdened RF domain. As such, the connected APs can utilize SLIPT, which is especially prominent in situations where the power network cannot reach the BSs such as remote areas.

2) *SLIPT for Aerial Platforms*: The advances in communications, computing, and energy storage have led to the use of aerial platforms. Whereas 5G networks have focused on massive connectivity through network densification and improved spectral efficiency, the paradigm shift of 6G networks is to offer complete 3D coverage, in land and air. Utilized as APs, aerial platforms can offer access to remote areas without coverage or enhance the network capacity in densely populated



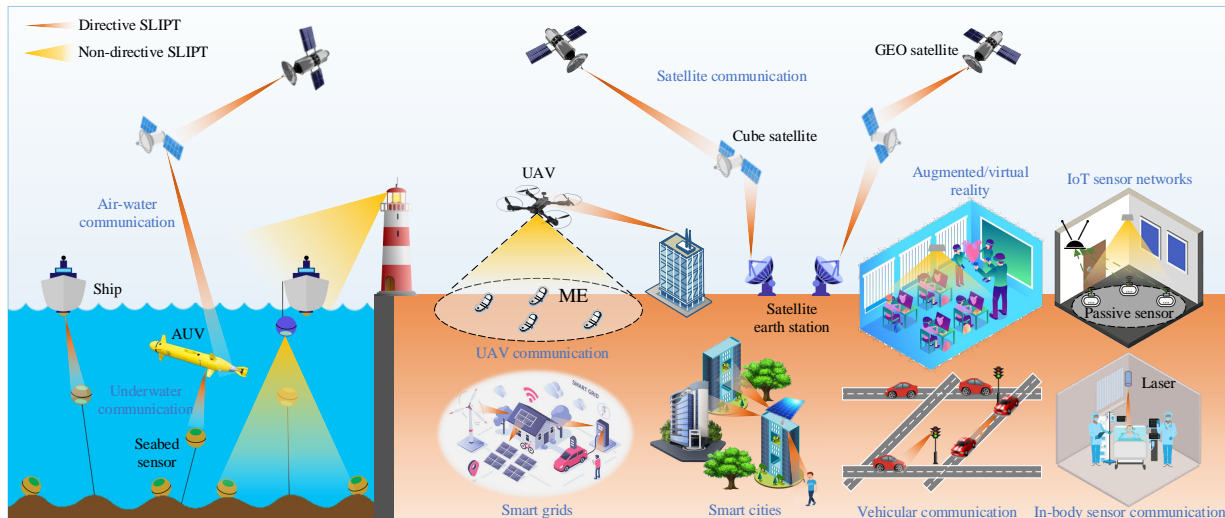


Fig. 3: Family of potential applications of SLIPT, including indoor, terrestrial, aerial, satellite, and underwater networks to accommodate 6G KPIs, such as energy sustainability and ubiquitous coverage.

urban environments, when it is required. Obviously, a ground-to-air fronthaul communication link is necessary to establish high-capacity wireless access to the aerial platform, e.g., a UAV or a HAP. This link is required to have a high capacity, which can be achieved through an FSO link. On the other hand, UAVs suffer from issues such as limited energy which reduce their hovering time. Laser power beaming (LPB) is a technique introduced to transfer power in the order of kW and MWs wirelessly through optical links [5]. Combining these two techniques into a SLIPT system provides a highly effective solution.

3) *SLIPT for Underwater Applications*: Remote sensing, ocean monitoring, and other emerging maritime-related applications require the use of autonomous underwater vehicles (AUVs) and the development of underwater sensor networks (USNs). The pursuit of complete 3D coverage of 6G networks can be expanded in underwater environments, where communications usually take place using acoustic waves that can reach very long distances at the expense of very low achievable data rates, while underwater optical fiber-based links are characterized by prohibitive cost and limited maneuverability. On the other hand, underwater OWCs have been regarded as a promising technology, offering high-capacity and improved energy efficiency [13]. In the context of Internet of Underwater Things, SLIPT can power up seabed USNs and AUVs, allowing their long-term operation, and it has been examined and experimentally validated as a promising way to charge underwater devices simultaneously with information transmission.

#### D. SLIPT for Long Range Applications

Low attenuation in free space propagation and the ability to produce narrow beams that focus on desired directions make lasers suitable for long range SLIPT. In this direction, high intensity LPB systems are capable of propagating through hundreds of kilometers [14], making them suitable for inter-satellite communications, planetary and lunar surface applications, and deep space exploration. Considering that the main source of power of satellites, rovers, and other exploratory

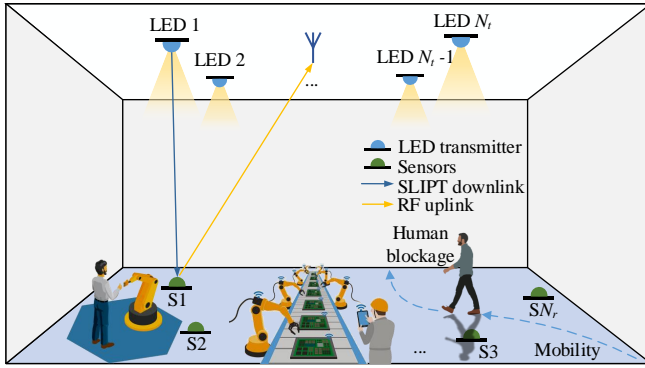
equipment is solar energy, in areas such as permanently shadowed lunar regions, the lack of constant solar illumination poses challenges for operating them. To this end, LPB coupled with steering and targeting systems becomes a promising enabler, where deep-space relays can be deployed to expand the coverage in such high range applications, given the reliance of SLIPT on LoS propagation.

## IV. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

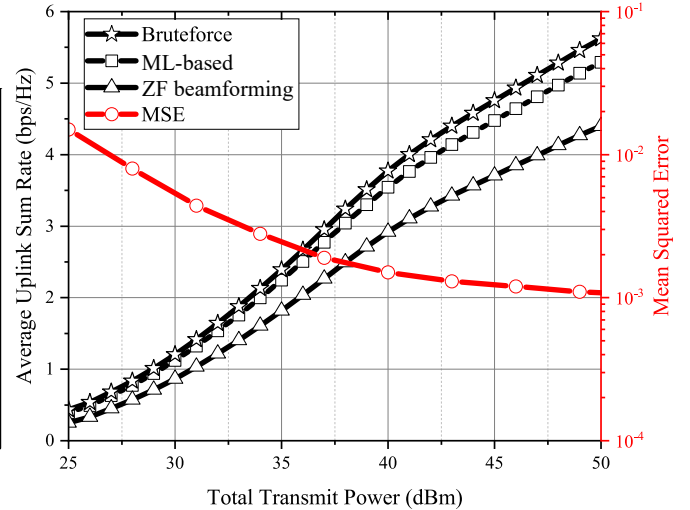
### A. Challenges

SLIPT systems face numerous challenges that delay wide implementation and integration with other networking solutions. One of the inherent challenges is the efficiency of solar cell receivers. It is possible to develop receivers with a conversion efficiency of over 40%, but these are usually costly and heavy, making them impractical for most mobile applications and a huge capital expenditure that hinders wide SLIPT adoption. Although this issue can be salvaged by extremely thin and lightweight film solar cells with an efficiency of around 20%, the limited bandwidth of such receivers, which restricts the achievable data rates, remains an issue. Due to this, it was proposed to equip devices with both a high-speed photodetector and a solar cell so that both work in conjunction to improve both aspects of the SLIPT system. However, this creates a different set of problems, such as physical space allocation on the receiver.

Besides receivers, bandwidth issues trouble the transmitter side, since LEDs, especially off-the-shelf, are limited to offering 20-100 MHz bandwidth, despite the original claim that VLC utilize a THz-wide spectrum. Fronthauling remains an issue in indoor SLIPT, as structural changes are required to enable networking for the illumination infrastructure. Also, multi-cell architectures emerged to enhance coverage, but require coordination to avoid interference between users, challenging the optimal deployment of SLIPT. On the other hand, choosing the optimal beam-tracking mechanisms for directive SLIPT systems can be challenging given the various



(a)



(b)

Fig. 4: Indoor use case of SLIPT in 6G: (a) Multi-cell SLIPT system that serves sensors and robots accounting for changes in the environment such as blockages. Uplink is facilitated through RF and over-the-air computing is performed. (b) Uplink sum rate and MSE versus total transmit power obtained using brute-force, ML-based approach, and ZF beamforming.

advantages and disadvantages of each method. Finally, as high-power optical beams are utilized in SLIPT, cooling systems for each component is required and eye safety concerns need to be taken into account. Especially, for the latter, the eye safety margin varies with the wavelength used and can impose strict constraints on the amount of transferred power in a SLIPT system in practice.

## B. Future Research Directions

1) *SLIPT and AI*: The optimal resource management of SLIPT can often become computationally infeasible with conventional methods, as complex transceiver architectures and equalization and compensation techniques for non-linear effects are considered. Training machine learning (ML) architectures to extract the optimal resource allocation parameters can alleviate some of the computational burden [8]. The issues with existing ML solutions, such as their computational complexity introducing latency and incomplete training due to limited training data, can be tackled with prediction-based “lightweight” ML architectures using recurrent neural networks. Deep learning, reinforcement learning, and transfer learning can be applied to obtain more accurate results for highly dynamic, hard to predict, and less informative applications. Large networks can be utilized with the use of federated learning (FL), which is a decentralized approach to locally train ML models and coordinate to optimize parameters. Additionally, SLIPT-assisted ML models can also be implemented, as efficient data processing at mobile devices can revolutionize the capabilities of distributed AI. Such an example is the use of LPT for FL-based wireless networks that has been proposed in [9], which is proved to be very efficient, since it reduces the amount of information that needs to be transferred by the mobile devices to the AP by using the RF spectrum. FL paradigm involves training statistical models and SLIPT can be used to deliver power to local devices, and multiple access schemes can be used to upload data to the central server, by prudently selecting a

time allocation parameter. The main principles of the concept can be used to many different applications, e.g., UAVs and mobile edge computing. Especially, in the context of FL, the combination of SLIPT with over-the-air computing can be examined, which is illustrated as a preliminary result in Fig. 4b. In more detail, in Fig. 4b, the average uplink sum rate and the mean squared error (MSE), in the case of over-the-air computing, are illustrated with respect to the transmit optical power. To derive this figure, a system consisting of  $N_t$  LEDs to transmit the information and lightwave power to  $N_r$  sensors is considered as shown in Fig. 4a. Here, the blockage due to user mobility is considered, while sensors harvest energy and use it for uplink using RF. To maximize the uplink sum rate, user mobility is predicted and the optimal beamforming matrix, and average powers at each LED are calculated using brute force, ML-based, and zero-forcing (ZF) beamforming approaches. A blockwise artificial neural network (ANN) consisting of an initial block to predict dynamic blockages caused due to human movement and average optical power at the sensors as inputs can be used. Next, several ANN blocks can be used to obtain the optimal beamforming matrix, time allocation parameter, and average transmit power levels.

2) *RIS-assisted SLIPT*: The reliance of most OWC links and SLIPT on the LoS availability can be a severe limiting factor in practice. Inspired by their utilization in RF systems, RISs have been investigated for lightwave systems to improve coverage and link availability, especially for mobile users. In OWC systems, RISs can be categorized into metasurfaces and mirror-based RISs and they can be adjusted on walls or integrated into the transceiver structure to steer the incoming light to the PD’s surface [10]. For instance, RISs can enhance the connectivity with a moving aerial platform, e.g., a UAV. Furthermore, RISs can be deployed on aerial platforms, thus serving a large number of devices, while providing flexible positioning. To fully utilize the capabilities offered by RISs, the exact position of the device is of critical importance to guarantee proper beam-steering, thus localization methods

should be integrated in these systems.

3) *SLIPT for Quantum Communications*: Quantum communications have been recognized as a potential solution for enhancing the security through quantum cryptography, quantum key distribution (QKD) protocols, and superdense coding. Recently, experimental validations of optical wireless quantum communication links have been realized both for terrestrial and satellite communications [15]. Considering that optical transceivers are usually required to transfer quantum information, SLIPT systems can be combined with quantum information transfer to realize the idea of a self-powered quantum internet. However, the high-power transmission of SLIPT does not usually coincide with the quantum information transfer requirements and different SLIPT protocols need to be designed. Time-switching between LPT and QKD can be a potential solution or the quantum information signal can be multiplexed to the classical SLIPT signal in a different wavelength to better utilize the available resources. In this case, advanced noise reduction techniques are needed to protect the quantum information signal.

## V. CONCLUSIONS

The recent interest in simultaneously providing information transfer and EH capabilities to fulfill the energy-efficiency requirements of future 6G networks has given rise to SLIPT. Although its use is rather limited, SLIPT can enable a plethora of applications as paving the way towards next generation networking. In this article, the different SLIPT architectures were listed alongside with fundamental design trade-offs, as well as some practical challenges and key future applications that are expected to emerge in the up-coming years.

## REFERENCES

- [1] L. Bariah, L. Mohjazi, S. Muhaidat, P. C. Sofotasios, G. K. Kurt, H. Yanikomeroglu, and O. A. Dobre, "A prospective look: Key enabling technologies, applications and open research topics in 6G networks," *IEEE Access*, vol. 8, pp. 174 792–174 820, Aug. 2020.
- [2] Z. Ghassemlooy, S. Arnon, M. Uysal, Z. Xu, and J. Cheng, "Emerging Optical Wireless Communications—Advances and Challenges," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1738–1749, Sep. 2015.
- [3] P. D. Diamantoulakis, G. K. Karagiannidis, and Z. Ding, "Simultaneous lightwave information and power transfer (SLIPT)," *IEEE Trans. Green Commun. and Netw.*, pp. 1–1, Sep. 2018.
- [4] J. Fakidis, S. Videv, S. Kucera, H. Clausen, and H. Haas, "On the Design of Optical Energy Harvesting and Storage Systems for Outdoor Small Cells," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Montreal, Canada, 2021, pp. 1–6.
- [5] M. S. Bashir and M.-S. Alouini, "Energy optimization of a laser-powered hovering-UAV relay in optical wireless backhaul," *IEEE Trans. Wireless Commun.*, vol. 22, no. 5, pp. 3216–3230, May 2023.
- [6] S. Ma, F. Zhang, H. Li, F. Zhou, Y. Wang, and S. Li, "Simultaneous lightwave information and power transfer in visible light communication systems," *IEEE Trans. Wireless Commun.*, vol. 18, no. 12, pp. 5818–5830, Dec. 2019.
- [7] D. H. Nguyen, T. Matsushima, C. Qin, and C. Adachi, "Toward thing-to-thing optical wireless power transfer: Metal halide perovskite transceiver as an enabler," *Frontiers in Energy Research*, vol. 9, p. 679125, Jun. 2021.
- [8] T.-D. Le, G. Kaddoum, H.-V. Tran, and C. Abou-Rjeily, "Evolution Strategies for Lightwave Power Transfer Networks," *IEEE Wireless Commun. Lett.*, vol. 10, no. 11, pp. 2572–2576, Nov. 2021.
- [9] H.-V. Tran, G. Kaddoum, H. Elgala, C. Abou-Rjeily, and H. Kaushal, "Lightwave Power Transfer for Federated Learning-Based Wireless Networks," *IEEE Commun. Lett.*, vol. 24, no. 7, pp. 1472–1476, Jul. 2020.

- [10] 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 Veh. Technol. Mag.*, vol. 17, no. 1, pp. 37–46, Mar. 2022.
- [11] M. Liu, S. Xia, M. Xiong, M. Xu, Q. Liu, and H. Deng, "NLOS Transmission Analysis for Mobile SLIPT Using Resonant Beam," *IEEE Trans. Wireless Commun.*, pp. 1–1, May 2023.
- [12] K. W. S. Palitharathna, H. A. Suraweera, R. I. Godaliyadda, V. R. Herath, and Z. Ding, "Lightwave Power Transfer in Full-Duplex NOMA Underwater Optical Wireless Communication Systems," *IEEE Commun. Lett.*, vol. 26, no. 3, pp. 622–626, Mar. 2022.
- [13] I. C. Ijeh, M. A. Khalighi, M. Elamassie, S. Hranilovic, and M. Uysal, "Outage probability analysis of a vertical underwater wireless optical link subject to oceanic turbulence and pointing errors," *J. Opt. Commun. Netw.*, vol. 14, no. 6, pp. 439–453, Jun. 2022.
- [14] 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," *IEEE Internet Things Mag.*, vol. 5, no. 3, pp. 180–185, Sep. 2022.
- [15] M. Grillo, A. A. Dowhuszko, M.-A. Khalighi, and J. Hämäläinen, "Resource allocation in a quantum key distribution network with LEO and GEO trusted-repeaters," in *Proc. 17th Int. Symp. Wireless Commun. Syst. (ISWCS)*, Berlin, Germany, 2021, pp. 1–6.

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