Application scenarios for simultaneous optical power and data transfer

Richard Nacke[1,3], Carmine Pellegrino[1], David Lackner[1], Gerald Siefer[1], Behnaz Majlesein[2], Othman Younus[2], Isaac N. O. Osahon[2], Iman Tavakkolnia[2], Andreas W. Bett[1,3], Harald Haas[2], Henning Helmers[1]

[1] Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

[2] LiFi Research and Development Centre, Electrical Engineering Division, University of Cambridge, Cambridge, United Kingdom

[3] Albert Ludwigs University, Institute of Physics, Freiburg, Germany

ABSTRACT

Optical power transfer and optical data communication are versatile technologies with numerous applications, utilizing both fiber-coupled systems and free-space optical links. The integration of these technologies into a single link simplifies system design while combining the benefits of simultaneous power delivery and data communication for receiving systems. This study evaluates various applications by examining their power demands, data rate requirements, and external factors such as link medium and operational distance. A graphical representation is provided to facilitate application targeting for specific groups, dictating the needed system requirements. Three key application clusters are identified: A) Internet of Things connectivity (free-space, ~10 m, 0.2-10 W), B) network infrastructure (fiber/free-space/underwater, 10 m – 1 km, 10-100 W), and C) moving objects (free-space, 100 m – 500 km, 1-10 kW).

Keywords: optical wireless communication, optical power transfer, fiber optic communication, power over fiber, power beaming, simultaneous lightwave information and power transfer, applications

1. INTRODUCTION

The information and communications technology (ICT) sector is expected to consume 20% of global electricity by 2030 [1], introducing significant environmental challenges, including rising emissions. The ICT sector is anticipated to reach 3.5% of global annual emissions within the current decade and up to 14% by 2040 [2]. Energy-efficient, high-speed, low-latency, and secure connectivity is therefore increasingly critical. The use of optical links promises higher bandwidth and thereby lower energy consumption than conventional radio frequency (RF) [3], [4].

Fiber-optic communication forms the backbone of today's telecommunication infrastructure. More recently, this technology is extending into the "last mile" of telecommunication reaching the end-user's premises, this is also known as fiber-to-the-x [5]. At the same time, optical wireless communication (OWC) is being used in long-range free-space optical communication (FSOC) links in space, on Earth, and in between. OWC is also considered for short-range applications, known as Li-Fi in this context, providing an complementary technology for radio frequency (RF) based Wi-Fi [6] and cellular. Optical links have also been used to transmit power [7], [8], [9]. When an optical fiber is used to transmit power, this is known as power over fiber (PoF); for free-space links this is typically referred to as optical wireless power transfer (OWPT) or laser power beaming [10]. At the receiving end of an optical power link, a specialized photovoltaic (PV) cell referred to as photonic power converter (PPC), laser power converter (LPC) or optical power converter, is used to convert the received light into electricity [7], [11], [12], [13].

In this work, we consider combining these technologies, *i.e.*, amending an FSOC link with optical energy transfer functionality, or adding data transfer functionality to an optical power link. Haas et al. explored OWC with simultaneous energy harvesting using PV cell receivers starting in 2014 [14], [15]. In 2016, Helmers et al. proposed integrated optical power and data transfer links and discussed various device architectures [16]. This concept became also known as simultaneous lightwave information and power transfer (SLIPT), adapting the term simultaneous wireless information and power transfer (SWIPT) known from RF [17]. Simultaneous optical power and data transfer can be realized by replacing the reversed biased photodiodes used in OWC with forward biased PPCs, enabling power harvesting capabilities from the

Optical Power Delivery, edited by Bahram Jalali, Proc. of SPIE Vol. 13359, 133590L · © 2025 SPIE · 0277-786X · doi: 10.1117/12.3042965

optical beam. A schematic block diagram of a system with power and data transfer using a single optical channel is shown in Figure 1.

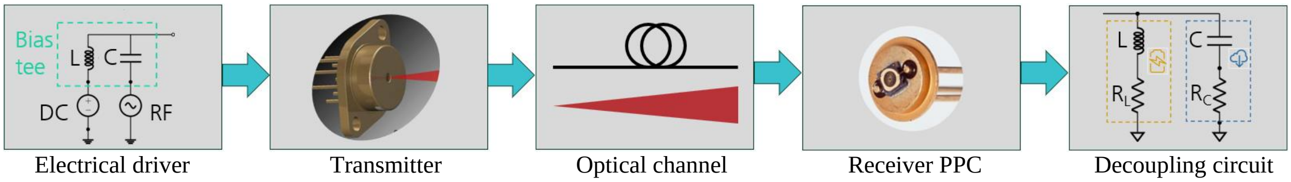

Figure 1: A possible simultaneous optical power and data transfer system. An AC and a DC signal are combined using a passive bias tee circuit. The combined signal drives the transmitter (typically a laser). The light is directed to the receiver over an optical channel, which can be either fiber-coupled or free-space. Note, beam divergence and optical losses in lenses used for beam guiding as well as absorption losses of the medium used must be considered. A PPC converts the optical to an electrical signal. A two branch receiver electronics is used to decouple the DC part for power harvesting by an inductor from the AC part containing the high data rate signal by a capacitor.

Regarding power transfer, the optical link features inherent galvanic isolation, which makes the link unaffected by electromagnetic fields from outside and prevents electromagnetic fields created by the power supply itself. Optical data transmission benefits from high data rates due to the high bandwidth of the optical spectrum [3]. Combining both functionalities into a single link can lower installation costs and resource demands, whilst enabling fast repositioning in a mobile scenario. Avoiding electrical cables systems can be advantageous due to weight savings. Additionally, the optical spectrum is license free, therefore operational costs significantly decrease for applications utilizing OWC in comparison with usage of most RF bands [18].

For the transmission, the optical attenuation in the transmission medium is important as low attenuation in the link provides best power transmission efficiency as well as best data signal reception. Optical telecommunication wavelengths in the O- (1260-1360 nm), C- (1530-1565 nm) and L-band (1565-1625 nm) [19] show low attenuation for atmospheric [20] and fiber-based [21] systems. Other wavelengths of low attenuation are around 800 nm, 980 nm and 1070 nm. For wireless underwater applications wavelengths of around 500 nm are favorable [22], [23], while wavelengths around 1070 nm are favorable for biomedical applications through tissue [24].

For free-space transmission, the diffraction of the beam, dictating the spot size at a given distance, is also a relevant metric due to its implication on the receiver size. Table 1 lists data on calculated spot sizes and proposed receiver sizes for different OWPT link distances from literature. The receiver is typically larger than the beam to account for additional losses due to tracking inaccuracy. Note that laser power beaming requires much smaller receivers than those needed in comparable technologies such as microwave wireless power transfer which requires the transmitter or receiver size to be in the order of kilometers for large distances [25]. For a specific system design, considerations on the beam quality, the tracking accuracy, eye safety requirements and options for array designs on emitter and receiver side may be relevant, but exceed the scope of this analysis.

Table 1: Overview of beam and receiver sizes as published in studies on OWPT in space. Note that the cited studies study somewhat different wavelengths (1060 nm [25], 800 nm [26], 1070 nm [27], 795 nm [28]).

	LEO / Lunar			GEO
Distance	400 km	1500 km	2200 km	36000 km
Ideal beam radius	0.05 m [26]	0.19 m [26]	0.25 m [26]	<5 m [25]
Proposed receiver radius	2.5 m [26]	0.75 m [27]	2.5 m [26]	10 m [28]

In the following, we identify applications which can benefit from a simultaneous optical power and data transfer link and discuss specific advantages. In addition, we indicate typical values for power and data rate demands and cluster them in groups of applications.

2. OPTICAL POWER AND DATA TRANSFER APPLICATIONS

In telecommunication networks, front- and backhaul systems can benefit from a simultaneous optical power and data transfer link providing an energy efficient solution, which reduces the power required for fiber and free-space nodes. This is achieved through energy efficient optical data transfer and reduced power consumption at the optical receiver, primarily by avoiding reverse biasing. Reverse biasing not only consumes energy in photodiodes, but also requires additional power for DC-DC conversion to sustain high reverse-bias voltages. This improvement enhances the overall efficiency of communication networks, making them more sustainable and cost-effective, particularly in scenarios where high data rates and energy efficiency are crucial. The decrease in power requirements for node systems can be further complemented by additional power harvested from the optical link. Thereby links integrated with OWPT offer the advantage of removing the need for a separate electric power supply at the receiver [2], [29], [30].

Figure 2 illustrates various application scenarios for telecommunication networks that integrate laser-based OWC and OWPT links, power over fiber (PoF) and fiber communication links alongside traditional RF-based systems.

OWPT offers a promising solution for remote charging or powering of drones and other unmanned aerial vehicles (UAV) using OWC. These devices could supplement wireless communications networks [31], [32] for events with temporarily demand for higher data rate (*e.g.* sports events and concerts), as a fast *ad hoc* replacement of existing/traditional communication networks in disaster control and emergency management (*e.g.* when existing network infrastructure is damaged), or to establish high-speed networks in remote locations with otherwise little infrastructure available. These complementary OWPT systems could consist of high-altitude platform stations (HAPS), large wing assisted drones, and small drones weighing up to several kilograms, or a combination of these.

Simultaneous optical power and data transfer links are also of interest for underwater vehicles and modular infrastructure, for inspection and surveillance purposes [33]. Commercial interest in underwater optical wireless communication (UOWC) is growing, with potential applications for underwater sensors, communication devices, and remote monitoring systems, where both power and data transmission need to be efficiently managed over long distances [34].

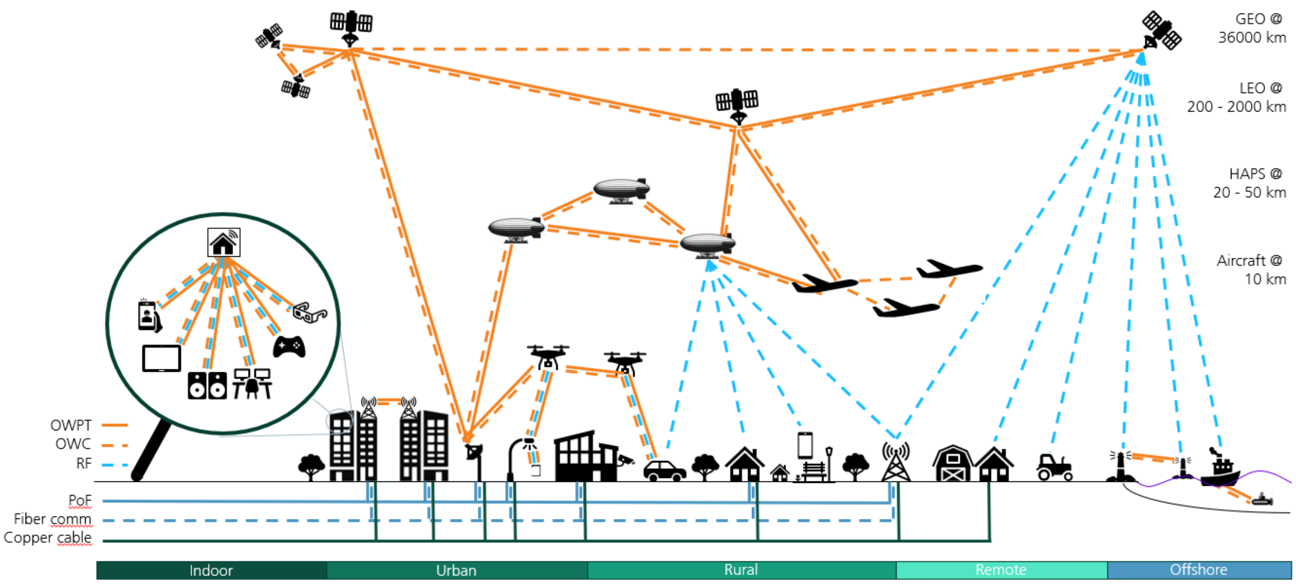

Figure 2: Overview of telecommunication networks. RF-based communication systems (dashed light blue) and copper power cables (continuous dark green) are supplemented by OWC (dashed orange), OWPT (continuous orange), PoF (continuous blue), and with fiber-optic communication (dashed blue).

OWC and OWPT are also of interest for satellite networks, enabling both power sharing and data exchange between individual satellites. Additionally, virtual satellites – composed groups of smaller, nearby satellites or CubeSats with selected functionalities – can utilize simultaneous optical power and data transfer to operate as a virtual larger entity with enhanced and comprehensive functionality [35].

Ground-to-satellite OWPT is already being explored and may benefit from additional OWC functionalities. Space-to-Earth OWPT is also being considered as a method to transfer solar energy harvested from space-based solar infrastructures to

Earth [36]. Ground-to-satellite OWPT links have been proposed to power space-based infrastructure [28]. In the future, such technologies could support extended lunar activities [37] and the exploration of planets and extraterrestrial moons.

Another prominent application area is the Internet of Things (IoT), where mobile receiver devices often require wireless data connections and power. As IoT devices can be frequently relocated and installed, simultaneous optical power and data transfer links are particularly advantageous. They reduce installation cost [38], lower maintenance cost by eliminating the need to replace batteries, minimize electrical connections or redundancy [39], and offer increased flexibility compared to cable and fiber driven devices [40]. The integration of simultaneous optical power and data transfer links in IoT use cases include powering and communication with sensors and microcontrollers for applications such as smart meters, digital shades, digital signage, smart locks, speakers. These technologies also extend to mobile devices including computer periphery, game controllers, headphones, and eventually smart phones, tablets as well as augmented reality (AR) and virtual reality (VR) goggles.

Simultaneous optical power and data transfer could revolutionize mobile devices such as smartphones, tablets, and smart glasses by transforming them into power-efficient screens with high-speed, low-latency connectivity. Computational tasks could be offloaded to energy-efficient cloud data centers, reducing local power consumption and enabling devices to act merely as lightweight input/output terminals at high data rates enabled by the optical connectivity. Masanet et al. showed that efficient cloud computing could reduce power consumption by up to 87% compared to local computation [41]. The resulting benefits include 1) drastically reduced battery requirements, allowing for mobile recharging and leading to thinner, lighter devices, 2) lower material consumption through reduced battery size, and 3) more energy- and cost-efficient processing through optimized duty cycles in cloud data centers. However, the limited efficiency of optical power transmission must be considered against these benefits. Initially, such applications may be confined to controlled environments, such as corporate buildings, which also offer improved security.

Industry 4.0 can similarly benefit from simultaneous optical power and data transfer links. Autonomous warehouse robots and small drones for monitoring or cargo delivery, which require both power and data, could use wireless optical links to achieve near-continuous operation with increased service-to-charge time ratio. Wireless charging during operation would maximize uptime and minimize downtime for recharging.

In the biomedical field, smart implants and medical wearables could significantly benefit from OWPT. Alternative technologies, such as plugs, inductive coils, or batteries, often have limitations, including the need to break the skin's protective barrier, size constraints, limited power availability, or the need for frequent battery replacements [42], [43]. OWPT offers a promising alternative, addressing these challenges while enabling high-bandwidth data transfer at Gb/s levels, which is especially important for demanding applications like brain-computer interfaces [44]. By integrating simultaneous optical power and data transfer links, biomedical devices could achieve galvanic isolation, higher data rates, wireless connectivity, and reduced receiver sizes as only a single channel is required.

In conclusion, the benefits of simultaneous optical power and data transfer links are diverse and highly dependent on the application scenario. The main advantages related to resource, cost and environmental benefits of combined optical data and power links are:

1) Enhanced energy efficiency through reduced power demand for OWC, with the ability to harvest power from optical beams and ambient light.

2) Reduced installation costs *e.g.* for network base stations by combining data link and power supply into a single optical link, whether wireless or fiber-coupled. This is particularly beneficial for temporary or dynamic setups.

3) Cost savings due to reduced need for maintenance (battery replacement) and potential for reduced resource and energy footprint due to minimized battery capacity requirements for remote or mobile applications.

3. DEMAND ASSESSMENT AND CLUSTERING

In Figure 3, we summarize the studied applications and categorize them based on approximate power and data demands. Real-world system designs inherently face a tradeoff between power and data rate [39], [40], [41]. As an example, higher powers necessitate large-area receivers, which increase capacitance and consequently limit bandwidth. As a result, applications towards the upper right corner of Figure 3 require more advanced and sophisticated solutions.

It should be noted that the plot spans more than six orders of magnitude in both power and data rate metrics, demonstrating the wide variability of application requirements. This highlights that there will be no "one size fits all" solution. However, clustering applications by power demand and operational distance provides a structured approach, as indicated by the orange circles in Figure 3. The three identified clusters are:

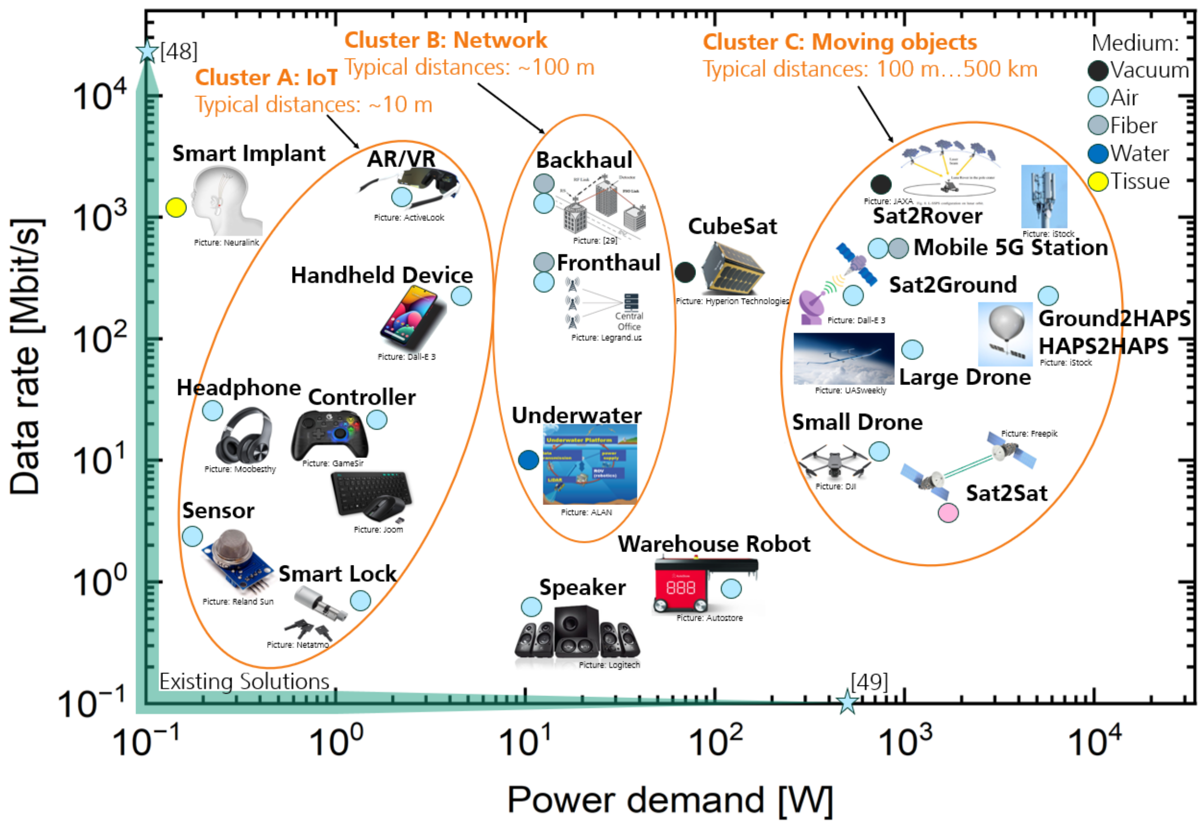

Figure 3: Overview of the studied application scenarios in terms of typical approximate expected required data rate and electrical power demand. Colors represent different transmission media. Star symbols shown on the two axes mark reported values for data only and power only optical links from [48], [49].

A) IoT Connectivity (free-space, ~10 m, 0.2-10 W): Cluster A includes applications with low power requirements, ranging from a few milliwatts to a few watts (up to tens of watts for some AR/VR devices). Operational distances are typically limited to a few meters, and most applications require data rates below 100 Mb/s. These requirements can be addressed with a single optical link. However, the mobile and dynamic nature of IoT devices necessitates advanced solutions for target localization, beam tracking, and steering to ensure reliable operation.

B) Network Infrastructure (fiber/free-space/underwater, 10 m-1 km, 10-100 W): Cluster B exhibits higher power requirements, ranging from tens of watts, with operational distances extending up to 1 km. To meet the necessary power densities, array-based solutions at both the transmitter and receiver are often required. Conversion efficiencies at both ends, transmitter and receiver, are critical to minimize heat loads and the associated thermal management requirements. For battery-powered applications, such as underwater robots or UAVs, power levels below those marked in Figure 3 would still be beneficial, as even small reductions in power demand can significantly extend operational lifetimes between recharges.

C) Moving Objects (free-space, 100 m-500 km, 1-10 kW): Cluster C represents applications with the highest power demands, reaching up to several kilowatts, and operational distances extending to hundreds of kilometers. In addition to arrayed transmitter and receiver solutions and advanced thermal management systems, these systems require high-quality laser sources and advanced optics to minimize beam divergence, which is crucial for maintaining efficiency over long distances. Additionally, real-time tracking and control systems capable of following moving objects with high precision are essential for successful operation.

For applications in Cluster C, particularly those involving high-power optical links through the atmosphere, laser safety regulations must be carefully considered [50]. To ensure safe operation, power density can be reduced by widening the beam diameter, adopting pulsed operation, or integrating external systems (*e.g.* light curtain [51] or camera based object detection [52]) that can detect beam penetration and trigger fast shutdown.

The priorities for each cluster vary depending on the specific application requirements. For Cluster A, the focus is on addressing the power and data needs of smart, mobile devices, where power delivery is often the primary limitation. In contrast, Cluster B emphasizes improving energy efficiency and versatility, particularly for network nodes in 6G and beyond, with high data rates being a key target. Cluster C encompasses a broader range of applications, where priorities can differ based on the use case. For instance, virtual satellites or satellite-to-rover links prioritize power supply efficiency, while other applications within this cluster may shift their focus between power and data rate requirements depending on operational demands or changing conditions over time.

4. CONCLUSION

The integration of optical power transfer and optical communication into a single optical link with simultaneous functionality offers significant potential across a variety of application domains. This approach simplifies system design, reduces resource demands by minimizing components, and enables easier and more economical installation. Additional advantages include galvanic isolation, as well as size and weight reductions, which further enhance system efficiency.

Three key application clusters were identified based on power and data demands: IoT connectivity applications (free-space, ~10 m, 0.2-10 W, 1-2000 Mbit/s) primarily involve mobile devices with low power requirements and relatively short operational distances. Advanced beam-tracking and localization solutions are required for reliable operation. Fixed network infrastructure applications (fiber/free-space/underwater, 10 m-1 km, 10-100 W, 10-2000 Mbit/s) focus on improving energy efficiency and achieving high data rates over medium distances. Thermal management and array-based transmitter and receiver systems may become critical for effective operation. Applications targeting moving objects (free-space, 100 m-500 km, 1-10 kW, 5-2000 Mbit/s) across long distances demand advanced optics, dense photovoltaic (PV) receiver arrays, and sophisticated tracking and beam-steering systems to maintain performance.

In summary, while no universal solution exists due to the diverse range of application requirements, clustering applications based on power and distance provides valuable insights into optimizing system design. Future advancements in optical technologies will further enhance the feasibility and efficiency of simultaneous optical power and data transfer across these application domains.

ACKNOWLEDGEMENTS

R. N. thanks Michael Schachtner for fruitful discussions. This work was supported by a Fraunhofer ICON grant and an Engineering and Physical Sciences Research Council (EPSRC) grant EP/X027511/1, “Green Optical Wireless Communications Facilitated by Photonic Power Harvesting (GreenCom)”. We acknowledge the use of OpenAI's GPT-4o for assisting with language refinement and summarization during the preparation of this manuscript. The authors take full responsibility for the content of this work.

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