Distributed Laser Charging for Mobile Wireless Power Transfer - Will it Work?

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***Abstract*—Increasing the battery-recharge period of smart phones is becoming a challenge, since their power consumption is increased due to their enhanced functions requiring sophisticated multimedia signal processing. An attractive solution is constituted by wireless charging, which is capable of replenishing the battery over the ether. Given this motivation, we present the fundamental physics and the related system structure of a promising wireless charging technique, namely of distributed laser charging (DLC). Relying on DLC's unique features, we may be capable of transmitting say 2 Watt power up to a distance of say 10 meters. Following the comparison of the other three major wireless charging techniques, namely inductive coupling, magnetic resonance coupling and microwave radiation, we will demonstrate the benefits of DLC in the context of mobile applications. We will then propose a pair of wireless charging network architectures, namely a DLC-aided infrastructure based network and a DLC-based ad-hoc network. These network architectures illustrate the potential of DLC in realizing the "fully-charged" utopia for any device, anywhere, anytime.**

I. Introduction

The increasing power-consumption of smart phones is tangibly demonstrated by the fact that the second-generation (2G) phones' 20-MFlop complexity was increased to above 100-MFlops for their third-generation (3G) counterpart, which was further increased by the fourth-generation (4G) phones. Sub-1Volt nanotechnology is capable of mitigating the power-consumption, however it is vulnerable to electromagnetic interference. On the other hand, charging mobile devices like smart-phones, tablets, laptops, and wearable-devices imposes the daily nuisance of having to carry a power cord and finding a power source. Therefore the "charging of any-device, anywhere, anytime" paradigm has drawn substantial research attention.

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More than a century ago, Nikola Tesla entered science history for his ground-breaking invention of alternating current (AC) electricity and for his Wardenclyffe Tower project aiming for transferring electrical energy without cords through the ionosphere [1]. His pioneering adventures have motivated scientists and engineers to conceive more practical wireless power transmission techniques. Wireless power transmission, or wireless charging, is the technology of transmitting electrical power from a power source to electronic devices or batteries without using wires. The benefits of wireless charging have been summarized in [2] in terms of user convenience, product durability, usage flexibility and its on-demand availability. At the time of writing the three major techniques of wireless charging are magnetic inductive coupling, magnetic resonance coupling and microwave radiation, which have been surveyed in [2] in terms of their advantages, disadvantages, effective charging distances and applications. The wireless charging standards of Qi and Alliance for Wireless Power (A4WP), have also been reviewed in [2].

Following the transfiguration of the desk-phone to cell-phones, of desktop computers to laptops/tablets and of fixed electronic devices to wearable devices, mobility has become a key feature of most electronic devices, However, the above-mentioned wireless charging techniques still face critical challenges, as pointed out in [2]. For example, inductive coupling is not suitable for certain applications due to the associated short charging distances ranging from a few millimeters to a few centimeters. The family of magnetic resonance coupling techniques also has its own impediments, since it is a challenge to reduce the coil size to be implemented in portable devices and also hard to tune the resonator, where the operational distance ranges from a few centimeters to a few meters. By contrast, microwave radiation is capable of transmitting power up to several kilometers. However, it is difficult to collimate to the target device and unsafe when the radio-frequency (RF) density exposure is high. Although beamforming and energy-harvesting based on microwave radiation have indeed been proposed, but their reliability and availability is limited by administrative regulations, such as the Federal Communications Commission (FCC) due to the associated safety and health considerations. Thus, the RF power transfer remains in the milli/micro-Watt-range, which is not practical for charging typical smart-phones, laptops, etc. [3, 4]. Apart from these three techniques, distributed laser charging (DLC) is one of the new ideas for wireless power transmission, which is especially suitable for safe mobile applications. The

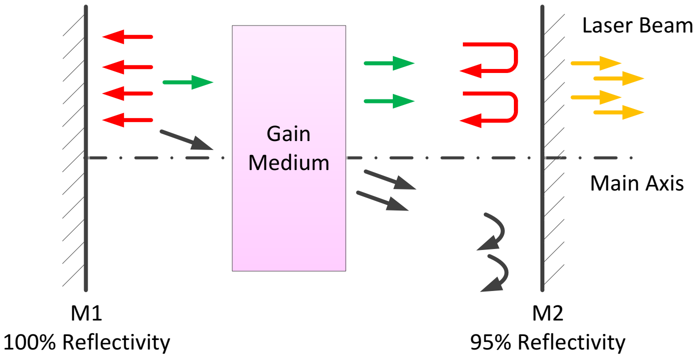


Fig. 1: Laser Fundamentals

practical DLC systems, providing 2-Watt power up to a 10-meter distance are under development at the time of writing by Wi-Charge, etc. for typical mobile devices [5].

In this article, we first introduce the fundamental physics behind the DLC technique and describe its system structure. Then we summarize and compare its features with the other three wireless charging techniques. Furthermore, we propose a pair of wireless powered network architectures, which illustrate the DLC's benefits in different scenarios. Finally, we discuss some open issues and future research topics.

II. Distributed Laser Charging

In this section, we commence by providing a rudimentary introduction to the laser mechanism. Then, we describe the distributed resonating laser regime, which the DLC technique relies upon.

A. Laser Fundamentals

The acronym "LASER" refers to "Light Amplification by Stimulated Emission of Radiation" [6], which is widely used in our daily lives in laser pointers, laser printers, barcode scanners, disk burner and players, just to mention a few.

Based on [5], Fig.1 illustrates the pair of parallel mirrors M1 and M2 in conjunction with a gain medium made of gallium arsenide (GaAs) for example, which is used for emitting the photons (small, energy-carrying light particles) excited (or pumped) by an external power source. The gain medium puts the atoms or molecules into an upper excited state by elevating them from a lower state. These excited atoms or molecules will transit from the upper state to the lower state spontaneously, which leads to photon emissions.

A photon is indicated by a single arrow in Fig. 1. A photon originating from mirror M1 enters the gain medium and in response a pair of photons are emitted, as illustrated by the thick green arrows. Naturally, this is a somewhat simplistic way of describing the amplification process by the gain medium invoked for conceptual simplicity. This pair of photons travels towards the mirror M2, where they are reflected back towards mirror M1, as represented by the pair of red u-shaped arrows next to M2. Then, these two photons pass through the gain medium again and stimulate four photons emitted towards M1, as indicated by the four red arrows pointing to M1. Thus, each photon passing through the gain medium increases the power of the recirculating light between M1 and M2. This process of positive feedback is termed as resonation, where the resonator consists of a pair of mirrors and a gain medium.

As in Fig. 1, the line perpendicular to the mirror-surfaces of M1 and M2 is referred to as the main axis. Only photons that travel exactly parallel to the main axis are amplified, while those that are even slightly skewed will be scattered and exit from the resonator, which are shown by the black arrows in Fig.1. Therefore, the resonating power is concentrated along the main axis only.

In general, the mirror M1 is perfectly reflective with 100% reflectivity, while M2 is semi-transparent associated with, say 95% reflectivity. This allows a small fraction of the light power to leave the resonator from M2 and creates a very sharp high-power light beam. This beam is known as the laser beam, which is depicted by the yellow arrows in Fig.1.

Increasing the pump power exciting the GaAs gain medium leads to an increased power loss, since the photons are increasingly scattering off the resonator. When the net gain (gain minus loss) attained reduces to unity, the gain medium is said to be saturated. This equilibrium determines the operating point of the laser [6].

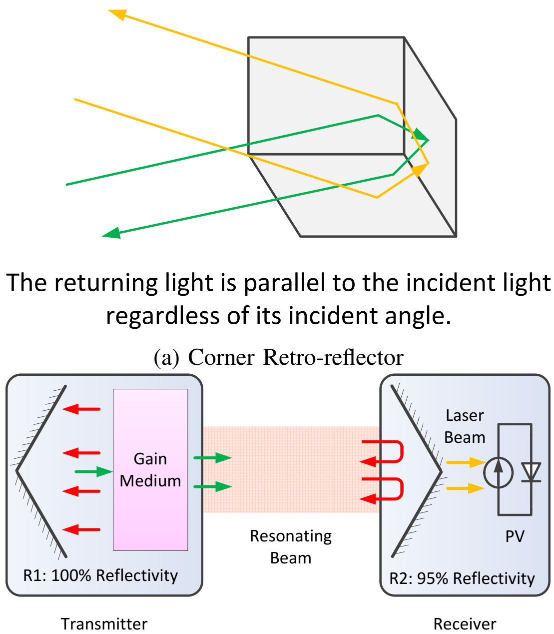
In summary, laser is generated by a resonator and it is characterized by a narrow, high-power collimated beam, which can be sent over long distances. Laser's key features include: 1) monochromaticity: a laser beam is concentrated in a narrow range of wavelengths; 2) coherence: all the emitted photons bear a constant phase relationship with each other; 3) directionality: a laser beam typically exhibits low divergence [6].

B. Distributed Resonating Laser

As detailed in [7], a retro-reflector is a device or surface reflecting light back to its source's direction, regardless of its angle of incidence. For example, as seen in Fig 2a, the structure of three mirrors arranged perpendicularly to each other in a corner forms such a retro-reflector. For the regular flat-panel mirror seen in Fig. 1, the reflected light is parallel to its incident light, if and only if the angle of incidence is vertical to the mirror. However, for a retro-reflector mirror, the reflected light is parallel to its incident counterpart, regardless of its angle of incidence. Retro-reflectors are commonly used in safety clothing, road signs, bicycle reflectors, etc.

Based on [5], Fig. 2b portrays a laser resonator consisting of a gain medium and the pair of retro-reflector mirrors R1 and R2. In this resonator, the photons that do not travel along the line connecting R1 and R2 fly away without being amplified, as detailed in Section II-A. Only the photons that travel along the line connecting R1 and R2 can reach a retro-reflector and are hence reflected back to the other. These photons are amplified while passing through the gain medium. This process generates a resonating beam, regardless of the specific angles of incidence, as long as R1 and R2 are in line-of-sight (LOS) of each other. This resonator differs from the regular laser resonator of Section II-A as follows:

1) R1 and R2 spontaneously form a resonator, regardless of the incident angle, as long as they are in line-of-sight of each other.



(a) Corner Retro-reflector

(b) Distributed Resonating Laser

Fig. 2: Distributed Laser Charging

2) A foreign object between R1 and R2 stops amplification immediately, because the photons cannot resonate through an obstacle.

Similarly, as detailed in Section II-A, a laser beam can be generated if R2 is semi-transparent. A photovoltaic (PV) cell can be installed behind R2 to convert laser light to electrical energy, similarly to a solar panel. We refer to the combination of R1 and the gain medium as a "transmitter", and to the combination of R2 and the PV cell as a "receiver". Whenever the receiver is within line-of-sight of the transmitter, a resonating beam may be formed, where power is delivered by the resonating beam from the transmitter to the receiver.

Typical laser systems integrate resonator components in a single device and the laser beam exits the device, which is referred to as "integrated resonating laser" in Section II-A. However, the laser system considered here distributes the resonator components to the transmitter and the receiver, respectively, where they are spatially separated. This laser may be termed as a "distributed resonating laser".

We refer to the wireless charging technique based on the distributed resonating laser as "distributed laser charging".

III. Distributed Laser Charging Features

Given the DLC mechanism discussed in Section II-B, let us now discuss its features.

Self-aligning: Mobile charging can be realized as long as the transmitter and the receiver are in line-of-sight view of each other. In this situation, the distributed resonator (consisting of the two retro-reflectors plus the gain medium) can generate a resonating beam, without the assistance of specific aiming or tracking. No user action of initiating the charging process in DLC leads to WiFi-like experience, which is in contrast to a wired charger or a typical wireless charging pad. We refer to

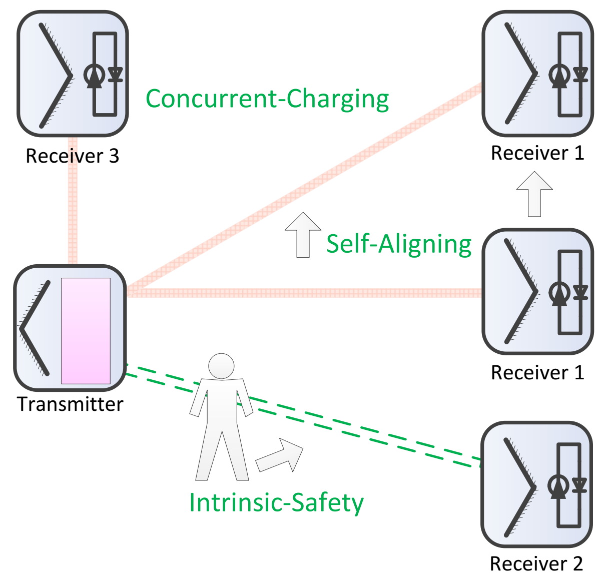


Fig. 3: DLC Features

this feature as self-aligning, which is portrayed in Fig. 3, where the resonating beam can be self-established, when Receiver 1 changes its position.

Intrinsically-safe: The DLC power level may reach tens of Watts, which is over most consumer electronics' owerneed [5]. At first instance this might raise safety concerns. However, DLC is different from integrated resonating lasers owing to its spatially distributed resonator structure. Upon encountering an obstruction along the resonating beam path, the resonation ceases at the speed of light, since the photons are blocked by the obstacle. Thus, the laser action is curtailed immediately without any software or decision-making circuitry involvement. The distributed resonator only delivers energy along an unobstructed line from the transmitter to the receiver. We denote this feature as intrinsically-safe, as shown in Fig. 3. In this example, a person is entering the resonating beam path spanning to Receiver 2, who instantly blocks the wireless power transmission to Receiver 2 by blocking the line-of-sight path between the Transmitter and Receiver 2.

Concurrently-charging: As discussed in Section II-B, when a receiver is placed in the LOS path of a transmitter, a DLC resonating beam can be generated between them. Thus, a single transmitter is capable of creating several resonating beams pointing to multiple receivers, which facilitates concurrent wireless charging from a single transmitter to multiple receivers [5]. We refer to this feature as concurrently-charging multiple receivers, as shown in Fig.3, where Receiver 1 and Receiver 3 are being charged simultaneously.

Hot-spot charging: The effective range of a distributed resonating laser is typically shorter than that of an integrated resonator laser, but nonetheless, distances of up to 100 meters may be achievable [5]. This range is substantially higher than that of typical inductive coupling and magnetic resonance coupling, given the same transmitter/receiver size and power level. Relying on its self-aligning feature, DLC is capable of providing a certain wireless charging coverage area, where the effective resonating beam can be generated between the transmitter and the receiver. For example, an indoor DLC transmitter placed on the ceiling is capable of covering a hot-spot area of about 50 square meters. Therefore, DLC may be deemed suitable for charging consumer electronics and providing WiFi-like hot-spot charging experience. Indeed, a prototype DLC system has been designed to deliver up to 2 Watt power by Wi-Charge [5], which is capable of simultaneously charging several laptops and smartphones.

Compact size: The DLC receiver can be designed to be compact, namely as small as a smartphone camera [5], where the resonating beam's diameter is about a millimeter, or so.

EMI-free: DLC does not leak any significant amount of power outside the resonating beam. In contrast to other wireless charging techniques, DLC imposes no radio-frequency radiation. Therefore, it inflicts no electromagnetic interference (EMI) upon the surrounding electronic devices.

Wavelength-agnostic: DLC may rely on the employment of both visible, as well as infrared and ultraviolet laser. Both the infrared and the ultraviolet resonating beams are invisible, which may hence be deemed eminently suitable for consumer electronics, since no visible light interference will be imposed. By contrast, other applications, such as charging of audio entertainment devices may prefer visible resonating beams, which create a conspicuous audio, mobile-phone, tablet, laptop and headphone charging hot-spot, just to name a few. DLC's visibility-agnostic characteristic enables system design flexibility in different applications.

SWIPT-ready: Simultaneous wireless information and power transfer (SWIPT) is possible, provided that the communication and the networking modules are integrated in the DLC transmitter and receiver. Visible or invisible light based communication techniques can be co-designed with the aid of DLC for realizing SWIPT [3, 8, 9]. Furthermore, both control signaling and wireless power transmission can be integrated in a single resonating beam without any reliance on classic radio communications such as WiFi, Bluetooth and so on.

LBS-ready: Location based services (LBS) functions can be integrated into a DLC system. A DLC-based positioning system can be realized by invoking a charge-coupled device (CCD) assisted image sensor in the transmitter. Therefore, the resonating beam can be mapped as a spot on a bird-eye camera-like image sensor, which estimates the angle of the receiver relative to the transmitter on a 2-dimensional surface. At the same time, the distance between the transmitter and the receiver can be readily obtained by measuring the round-trip-time of a laser pulse. Therefore, the 3-dimensional position of the receiver relative to the transmitter can be conveniently derived by combining the angle and distance estimates. Since the typical measurement accuracy of the laser angle and timing is usually better than that of classic radio-frequency based positioning techniques [10], the DLC-based positioning system can be used for accurate location based services.

LOS-dependent: DLC also has its limitations. Having a line-of-sight (LOS) path between the transmitter and the receiver is necessary for generating the resonating beam.

In summary, DLC is self-aligning, intrinsically-safe, capable of supporting concurrent multiple-receiver hot-spot charging, has a compact size, supports EMI-free operation, albeit it is inherently LOS-dependent. Furthermore, DLC can be wavelength-agnostic, SWIPT-ready as well as LBS-ready.

IV. Comparison of wireless charging techniques

In order to compare DLC to different wireless charging techniques, we refer to Table I of [2] and add the DLC features discussed in Section III to form Table I of this treatise. Based on our comparison of their advantages, disadvantages, effective charging distances as well as potential applications, the DLC philosophy may be deemed suitable for LOS-based mobile applications. For example, DLC may be capable of safely providing 2-Watt power, reaching up to a distance of 10-meter for mobile devices, such as smart-phones, laptops, wearable devices, home and office electronics, robots, etc. [5].

DLC has the same advantages as other laser power transmissions, which include:

1) Large distance: the associated collimated monochromatic wavefront propagation facilitates having a narrow beam cross-section area for transmission over large distances.

2) Compact size: solid state lasers can fit into compact consumer products.

3) EMI free: no radio-frequency interference is imposed on existing radio communications, such as WiFi and cell phones.

4) Access control: only receivers hit by the laser can receive power.

On the other hand, the concerns of laser power transmission as well as DLC include:

1) Conversion efficiency: conversion from electronic energy to light is inefficient. Typical photovoltaic cells can only achieve 40% to 50% efficiency with monochromatic light, although this is higher than that of solar panels.

2) Laser hazard: laser can blind or even kill humans by localized spot heating. However, DLC is intrinsic-safe, since any obstruction blocking the resonating beam will curtail power transmission at the speed of light.

3) Propagation attenuation: laser energy attenuation in clean air is very low, albeit it becomes significant due to atmospheric absorption and scattering by clouds, fog, rain, etc.

We will discuss these factors in Section VI as part of the open issues and future research ideas before concluding this treatise.

V. DLC-Powered Networks

A. DLC Infrastructural Network

Deploying DLC transmitters to charge DLC-receiver aided devices will lead to improved convenience in people's daily life.

Wi-Charge Inc. demonstrated the feasibility of the DLC transmitter and receiver seen in Fig. 4 [5]. As seen in Fig.5, a DLC transmitter can be combined with a light-emitting diode (LED) array to become a DLC-equipped lightbulb. Therefore, this DLC-equipped lightbulb can be conveniently installed to provide both an illumination and a power charging capability. The DLC transmitter's size would not substantially increase the regular LED-array size. The DLC receiver size can be at the centimeter level and may be readily embedded in mobile devices, such as smart-phones, laptops, tablets, and so on. The

TABLE I: Comparison of different wireless charging techniques

Wireless charging technique	Advantage	Disadvantage	Effective charging distance	Applications
Inductive coupling	Safe for humans, simple implementation	Short charging distance, heating effect Not suitable for mobile applications, needs tight alignment of the charger and charged devices	From a few millimeters to a few centimeters	Mobile electronics (e.g, smart phones and tablets), toothbrushes, RFID tags, contactless smart cards
Magnetic resonance coupling	Loose alignment between chargers and charged devices, charging multiple devices simultaneously at different power High charging efficiency, non-line-of-sight charging	Not suitable for mobile applications Limited charging distance Complex implementation	From a few centimeters to a few meters	Mobile electronics, home appliances (e.g., TV and desktop), electric vehicle charging
Microwave radiation	Long effective charging distance Suitable for mobile applications	Not safe when the RF density exposure is high Low charging efficiency	Typically from tens of meters, up to several kilometers	RFID cards, wireless sensors, implanted body devices, LEDs
Distributed laser charging	self-aligning, safe, multiple-RX charging, high-power, compact size, EMI-free, visibility -agnostic, SWIPT-ready, LBS-ready; Suitable for mobile applications	Line-of-sight required, Low charging efficiency	Up to 10 meters	Mobile devices (e.g., cellphone, laptop, tablet, wearable devices, drone), consumer electronics (e.g., projector, speaker, toothbrush), sensors, LEDs

Fig. 4: Demo DLC Transmitter and Receiver

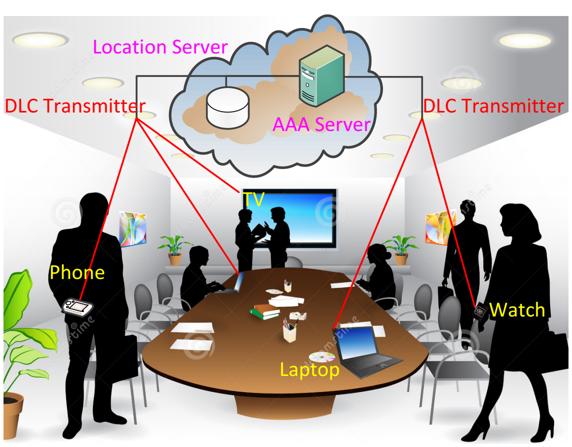


Fig. 5: DLC Infrastructural Network

DLC-equipped LED-array should have a power charing coverage similar to its illuminating coverage, providing wireless power charging reminiscent of WiFi communications. Due to its LOS limitation, ceiling installation of the DLC transmitter is preferred.

Apart from wireless charging, as discussed in Section III, the DLC networks are also capable of supporting other applications, such as LBS, security surveillance, etc. For example, security camera installations usually involve wiring calamities due to the lack of power supply availability. By contrast, a DLC-receiver equipped camera facilitates convenient installation and flexibility. Similar problems may occur for other electronic devices, such as projectors, active speakers, TV sets, etc.

Ubiquitous DLC services can be provided, similar to cellular communications or public illumination. However, this requires considerable financial investments. The DLC infrastructure may be commercialized for wireless power charging services at a reasonable cost. The pioneering research on the architecture and protocol of wireless charger networks has been presented by Lu, *et al.* [2]. Referring to the proposal in [2], a promising business proposition may be created to operate the DLC infrastructure at high-user-density locations, such as airports, train stations, restaurants, hotels and other public venues. DLC supports concurrent charging for providing wireless power to multiple devices. However, the implementation of network management systems including resource allocation, authentication, authorization, and accounting (AAA) in DLC networks requires further research. For example, a mobile device equipped with a DLC receiver may be authenticated - via WiFi or Long Term Evolution (LTE) - with the aid of the authentication server of the DLC network. Once the service request has been authorized, the AAA server may inform the DLC transmitter to initiate the DLC service for the mobile device. The user experience of wireless charging may be deemed reminiscent of WiFi/LTE in data communications.

B. Ad-hoc DLC Networks

In this section we provide an application example in the context of a drone aircraft to demonstrate DLC's beneficial features.

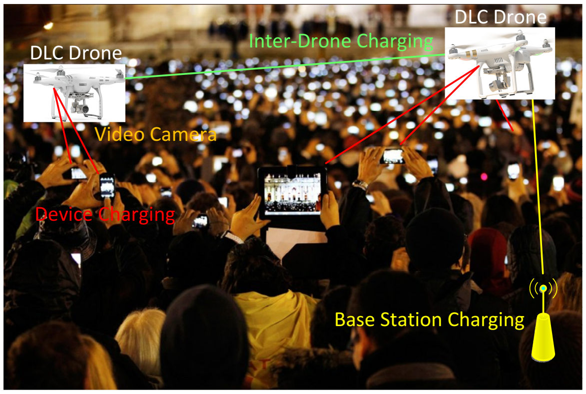


Fig. 6: DLC Ad-hoc Network

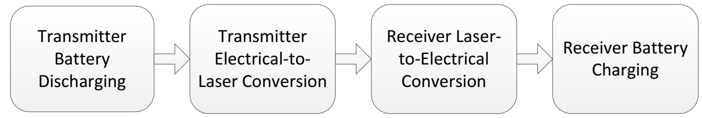
As seen in Fig. 6, a compact DLC receiver can be mounted on a battery-powered off-the-shelf drone for charging the drone's battery. A DLC transmitter (termed as a power base station) on the ground can provide laser-based power supply for the drone. Since the DLC is capable of self-alignment and LOS propagation is usually available, the drone can be charged as long as it is flying within the DLC's coverage range. Thus, this DLC-equipped drone can operate for a long time without landing until the maintenance is needed. As discussed in Section III, a DLC system providing a 2-Watt, 10-meter wireless power supply is capable to supporting such an application.

A DLC transmitter can also be combined with a DLC receiver in a single drone. In this case, the drone becomes capable of playing the role of a DLC relay. This DLC relay drone becomes hence capable of charging other DLC receivers within its coverage range. Therefore, an ad-hoc wirelessly powered network can be established by the DLC-equipped drones. Moreover, dynamic network organization can be adopted for attractive future applications by using intelligent cooperative algorithms. For example, multiple DLC transmitters can be used for charging a single device as well. Such a network may be readily established at a public event serving a large user-population at festive ceremonies, concerts, in a sport stadium and so on, where occasionally on-demand wireless power charging is necessitated. This may be achieved without building a permanent infrastructure. Beyond power transmission, this network can also be used for data communication, security surveillance, location tracking, etc. Nonetheless, the power charging efficiency and the battery life of such a DLC-aided ad-hoc network has to be further studied, which will be discussed next.

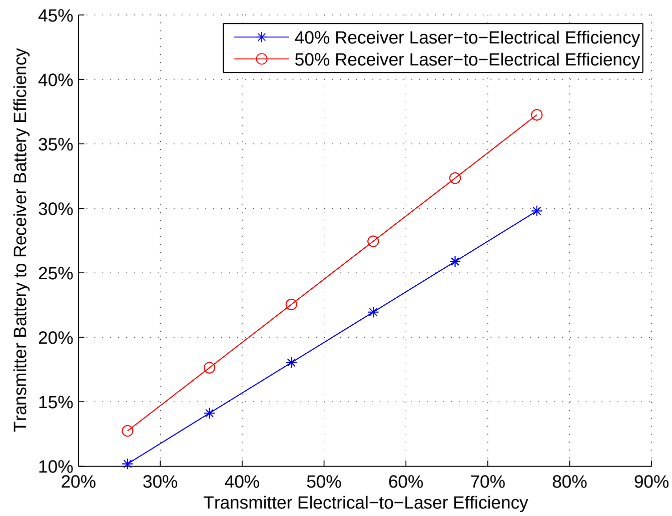
VI. Open Issues and Future Research

Let us now continue by discussing several open issues and research directions for the DLC techniques considered.

1) The maximum achievable power conversion efficiency is one of the major concerns for DLC systems. Again, photovoltaic cells are capable of achieving a 40% to 50% efficiency with the aid of monochromatic light, such as laser light [11]. The attainable efficiency is higher than that of normal solar panels, whose efficiency typically ranges from 10% to 20% [12]. By contrast, the Lithium-ion battery charging and discharging efficiency can be as high as 99% [13]. The electrical-to-laser conversion efficiency varies from 25% to 76% [14]. As exemplified by the inter-drone DLC power transmission scenario of Section V-B, the associated power conversion stages are illustrated in Fig. 7a, which include: a) the transmitter battery discharging having a 99% efficiency; b) the transmitter's electrical-to-laser conversion efficiency of 25% to 76%; c) the receiver's laser-to-electrical conversion efficiency of 40% to 50%; d) the receiver's battery charging with a 99% efficiency. The overall conversion efficiency between the transmitter's and receiver's battery is given by the product of these four factors, assuming that the resonating beam's propagation loss is negligible. Fig.7b shows the overall power conversion efficiency from the transmitter's battery to the receiver battery vs. the electrical-to-laser power conversion efficiency, given the laser-to-electrical PV efficiency of 40% and 50%, respectively. The overall conversion efficiency varies from 10% to 37%, which indicates that there is considerable space for improvement. Moreover, the thermal effects of DLC systems have not been widely investigated in the open literature. Furthermore, the choice of wavelengths achieving the best power transmission efficiency and the selection of appropriate performance metrics should also be studied.



(a) Transmitter to Receiver Conversion Stages



(b) Transmitter to Receiver Conversion Efficiency

Fig. 7: DLC Conversion Efficiency

2) In contrast to the integrated resonating laser, DLC is intrinsically safe, where laser power is transferred from the transmitter to the receiver only. DLC is physically incapable of delivering any power to foreign objects, including human tissues [5]. However, this cautious optimism should stimulate further safety-related studies of DLC, since this subject has not been investigated in many important specific situations,

as exemplified by absorption and scattering by glass, smoke, steam, etc. Furthermore, the safety concerns of the photons scattering off the R1-R2 LOS direction in Fig. 2b should also be further investigated. Hence safety investigations constitute the pivotal research direction of this promising DLC technique.

3) The laser propagation loss in outdoor applications is significantly affected by the weather, especially by rain, fog, snow, etc., which has been investigated in [15]. However, there is a paucity of literature on the DLC's propagation-induced resonating beam power loss. These path-loss aspects impose significant constraints on the effective DLC transmission distance, which requires further research.

4) Requiring LOS in DLC power transmission limits the convenience of charging mobile devices. Reducing the blind angle to increase the availability of a LOS path may lead to innovative DLC system designs and architectures. For example, the shape of the retro-flecting DLC receiver may be designed to have a spherical surface in order to maximize the useful angle of reception. Furthermore, innovative cooperative techniques may be conceived for avoiding obstacles in the LOS path. Therefore, creative ideas are needed for improving the DLC quality-of-service (QoS). A possible solution is to build a wireless charging relay, which assist the DLC receiver with the aid of other non-line-of-sight (NLOS) wireless charging transmitters, such as a magnetic resonating transmitter. Although this may lead to other concerns, such a hybrid charger may be capable of supporting NLOS mobile wireless transmission.

5) The DLC network architecture has been briefly discussed in Section V, but the related protocols conceived for power charging, data communications, LBSs, etc. have to be further developed.

6) The DLC and wireless communication schemes exhibit some similarity. For example, they aim for efficiently transmitting energy and information, respectively. Additionally, their transmitter/receiver structures are similar as well. Hence carefully adapting the well-developed science and technology of wireless communications for DLC research and development constitutes a compelling research proposition.

7) Another concern is the capability of tracking a mobile receiver in DLC systems. Intuitively, achieving this ambitious goal is more challenging than the employment of other wireless power transfer techniques, primarily due to the significantly shorter wavelength of the laser beam. However, given the paucity of literature on DLC receiver tracking, this remains an open challenge at the time of writing, hence motivating future research.

In a nutshell, both academic research and practical DLC developments are in their infancy, hence many technical aspects have remained hitherto unanswered.

VII. Conclusions

Wireless charging technologies are still in their infancy, but they no longer may be viewed as "science fiction" – they require wider investigations in the context of realistic mobile devices and consumer electronics. In this article, we have presented the rudimentary physics of DLC conceived for wireless power transmission. Then, we summarized and compared its features to those of the other three major wireless charging techniques. We found that DLC is especially suitable for safe mobile applications in order to provide a charging-experience reminiscent of the convenience of WiFi data communications. To demonstrate its usage, we proposed two wireless powered network architectures: the fixed DLC infrastructure and the ad-hoc DLC network. Finally, we discussed a range of open issues and future research aspects.

Indeed, DLC constitutes a promising technique, which is capable of facilitating imaginative applications, such as "tireless" robots in land-based, air-based and marine scenarios - a truly fertile ground for scientific innovation.

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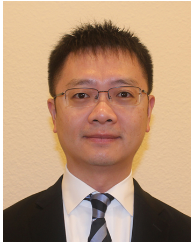

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