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Simultaneous Lightwave Information and Power Transfer: Policies, Techniques and Future Directions

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ABSTRACT Harvesting energy from the surrounding environment is an important and practical solution to prolong the life of energy-constrained internet-of-things (IoT) devices, e.g., wireless sensors, etc. Visible light communications (VLC) has been proved able to provide high-speed data links, while meeting the illumination requirement. Thereby, the energy of VLC signals may be harvested by the energy-constrained IoT terminals, such as indoor sensors and portable/wearable devices. This paper presents the concept of *simultaneous lightwave information and power transfer (SLIPT)* with a particular focus on the design of the receiver and the practical methods to realize SLIPT in the domains of time, signal components, and photoelectric converters. Furthermore, this work also introduces the applications of SLIPT to various network topologies and communication technologies, e.g., multiple-input multiple-output, hybrid VLC-radio frequency, and secure communications. Finally, a detailed discussion of future research directions and challenges for the design of SLIPT systems is also presented.

INDEX TERMS Cooperative communications, Energy Harvesting, secure communications, simultaneous lightwave information and power transfer, visible light communication

I. INTRODUCTION

Nowadays, harvesting energy from the surrounding environment has been regarded as a promising and practical way to prolong the lifetime of power-constrained systems, e.g., wireless sensor networks (WSNs), wireless personal and Blacktooth networks, which operate under extremely low duty cycles. Among the sources that can be used to harvest energy, radio frequency (RF) signals have gained special attention in the recent years, due to their capability to controllably deliver energy to the intended terminals at long distances [1], [2].

However, there is a safety problem, which cannot be avoided in practical applications with wireless RF power transmission. To this end, the transmit power of RF signals cannot be too high, because in this case there are electromagnetic effects on human health. For instance, the general population exposure limits (power density) for electromagnetic fields from 1500 $\sim$ 100,000 MHz presented by Federal Communications Commission (FCC) are 1 mW/cm^2 within 30 minutes, and from 300 MHz to 1500 MHz are $f/1500$ mW/cm^2 (where f is the frequency in MHz), respectively [3]. However, it should be mentioned here that RF wireless power transfer is subject to stringent transmit power constraintsčň due to safety regulations, e.g., the maximal transmit power regulated by the FCC limits. Because of this, ambient RF sources, e.g., base stations, radio and television broadcasting,

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global positioning systems (GPS) and Wireless Fidelity (Wi-Fi), etc., usually operate far below the FCC limits. Moreover, using extra RF sources for wireless power transfer or increasing the power of existing sources to facilitate energy harvesting will lead to strong electromagnetic interference, which in turn negatively affects the electronic equipment precision and the performance of wireless communication systems.

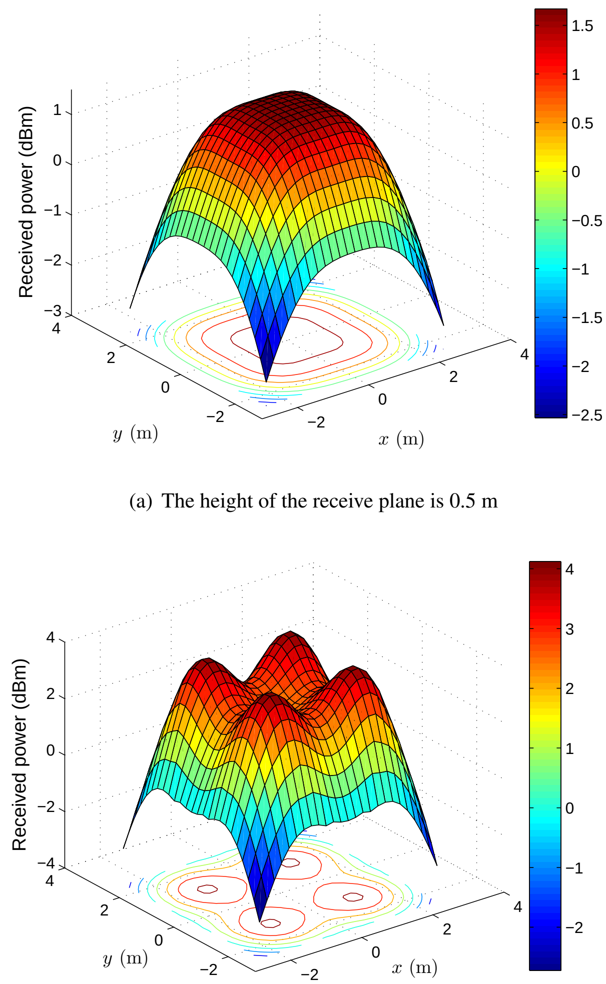
In order to overcome the aforementioned problems, energy harvesting (EH) through visible light communications (VLC) systems has been proposed as an alternative solution for energy constrained systems [4]–[14]. This is motivated by the fact that VLC systems can support high data-rate transmission without producing any electromagnetic pollution, compared with the traditional RF [15]. In LED-based VLC systems, LEDs are adopted as the optical sources to convert the non-negative electrical signal to the modulated optical signal, while photoelectric converters (PECs) are used as the detector at the receiver to convert the optical power back into electrical current for signal processing. It is highlighted that lightwave wireless power transfer is fundamentally different to RF, due to divergent channels characteristics, transmission/reception equipment, and EH model, among others.

As an effective complementary technology to conventional RF communications, VLC can offer a potential of very high data rate. Benefiting from the ever-increasing popularity of solid-state lighting, compared with other artificial light sources, such as the incandescent light bulbs, LEDs exhibit several merits, such as longer lifetime, higher brightness, no health hazards, and lower power consumption. As a unique advantage, LEDs also provide a dual functionality of supporting lighting and data communication by using the same high-brightness LEDs. Also, the level of indoor lighting has been proved to be enough to power electronic devices [16], [17], with respect to the eye safety regulations [18]. Consequently, VLC is an eco-friendly and sustainable technology. These advantages lead to a whole range of interesting and important applications of VLC in the era of internet-of-things (IoT), including but not limited to indoor networks, like high-speed data transmissions via lighting infrastructures in offices, aeroplane cabins, trains and hospitals, and outdoor networks, e.g., car-to-car communication and access point-to-train communication.

In this paper, we investigate the concept of $simultaneous\ lightwave\ information\ and\ power\ transfer$ $(SLIPT)$ for VLC systems, in order to extend the lifetime of energy-constrained terminals and hence alleviate the bottleneck of energy-sensitive networks, while avoiding safety problems imposed by traditional wireless RF power transfer systems. Specifically, compared with the existing works on SLIPT [4], [10], the main contributions of this work are listed in the following:

1) We provide a comprehensive review for works on SLIPT for first time in the literature;

2) The basic theory is established for several novel different architectures for SPLIT receivers;



(a) The height of the receive plane is 0.5 m

(b) The height of the receive plane is 1 m

FIGURE 1: Indoor optical energy distribution with the room size of 5 m × 5 m × 3 m.

3) Several different techniques and designs have been presented in this work to enable SPLIT.

The reminder of this work is organized as follows: in Section II, the indoor optical power distribution of LED lights is introduced. In Section III, first, solar panel and photodiode (PD) based light EH models are discussed. Next, in the same section, various types of SLIPT receiver architectures are introduced, evaluated and compared. In section IV, V and VI, we discuss the applications of SLIPT in multiple-input multiple-output (MIMO) systems, hybrid VLC-RF systems, and secure communication systems, respectively. Section VII provides some interesting future directions, including hardware design, fundamental limitations, resource allocation, and imperfections, and, finally, section VIII concludes the paper.

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II. ENERGY DISTRIBUTION IN INDOOR SLIPT SCENARIOS

In a SLIPT system, LED lamps are adopted as energy sources and large-area photodetectors are used as receivers to collect as much energy as possible. The transmission range for indoor VLC is relatively short, because of the pathloss attenuation. According to [19], [20], the line-of-sight (LOS) propagation model of VLC clearly reveals that the transmission gain over the VLC channel is inversely proportional to the square of the distance between the LED lamp and the receiver. Therefore, the received optical energy is also inversely proportional to the square of the distance between the LED lamp and the receiver.

Fig. 1 illustrates the optical energy distribution in indoor scenarios with two different heights of the receive plane, 0.5 m and 1 m, in which the locations of 4 LED arrays are (1.25, 1.25, 3), (1.25, -1.25, 3), (-1.25, -1.25, 3) and (-1.25, 1.25, 3), semiangle at half power is 70 degrees, the transmit power per LED is 20 mW, the number of the LEDs in each array is 60 $\times$ 60, and the active area of the receiver PEC is 1 cm^2. It is obvious that the received optical power ranges from -2.5 dBm to 1.75 dBm, and -2.7 dBm to 4.1 dBm for heights 0.5 m and 1 m, respectively. Another important feature of the energy distribution is that there will be four peak areas for the received optical power, when the height of the receive plane is 1 m. Also, the worst received optical energy appears in the four corners of the room. Moreover, regarding Fig. 1, it can be seen that the received optical power is on the order of mW. By considering the power conversion efficiency for LED light (13.5%, 19.4% and 21% for silicon, GaAs, $Al_{0.2}Ga_{0.8}As$ photovoltaic cells, respectively) [21], then, the achieved charging power is on 0.1 mW order. So, it is enough to charge low power nodes for their regular operations. For example, Fig. 8 of [22] reveals that the total average power consumption is 0.274 mW for the strain sensor and 1.73 mW for the accelerometer, which are used for monitoring buildings to assess earthquake damage. Therefore, VLC is capable of providing sufficient power to realize wireless energy harvesting.

III. BASIC SLIPT RECEIVER DESIGNS

A. PD VS SOLAR PANEL BASED EH

There are two potential architectures to realize lightwave EH, i.e., solar panel and PD based [16], [17], which correspond to *photovoltaic* (zero-bias) and *photoconductive* (reverse bias) PEC working modes, respectively. More information about these two modes are provided below.

1) Photovoltaic mode

In the photovoltaic mode, the PEC is zero biased to exploit the photovoltaic effect, which is the basis for the solar cells. The utilization of this mode for EH is quite simple and energy efficient, since no external power or other components are needed. Also, this mode can be effectively used for information decoding (ID), when precision and reliability are more important than high data rates, since it suffers less from noise than photoconductive mode, at the expense of higher capacitance.

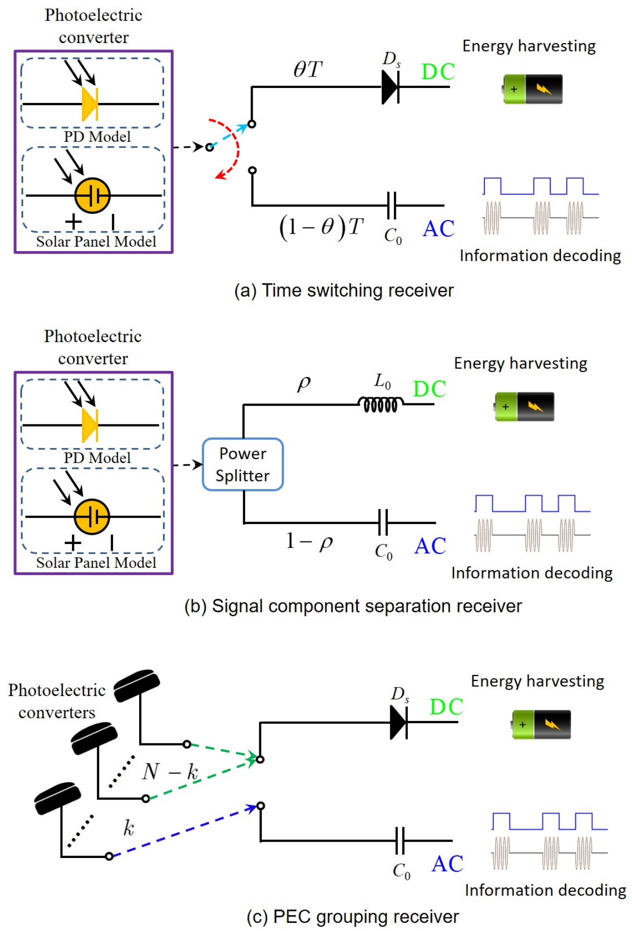


FIGURE 2: SLIPT receiver architectures.

2) Photoconductive mode

In the photoconductive mode, an external reverse bias is needed to generate the photocurrent, which is linearly proportional to the illumination intensity. The voltage across the PD lowers its capacitance, which enables faster amplification. This characteristic motivates the utilization of this mode for high speed information detection. It needs to be mentioned that it is quite challenging to use common PDs (e.g., positive-intrinsic-negative, PIN) for EH. Except of decreasing the energy efficiency due to the requirement of external power for operation, the hardware complexity is also increased. This is because a Schottky diode needs to be employed in the EH branch as rectifier to convert alternating current (AC) components to direct current (DC) ones for EH [16].

B. SLIPT RECEIVER DESIGN

In the following, three efficient SLIPT receiver architectures are proposed to realize separation of the signals used for EH and ID in three different domains: time, power, and PEC.

1) Time Switching Receiver

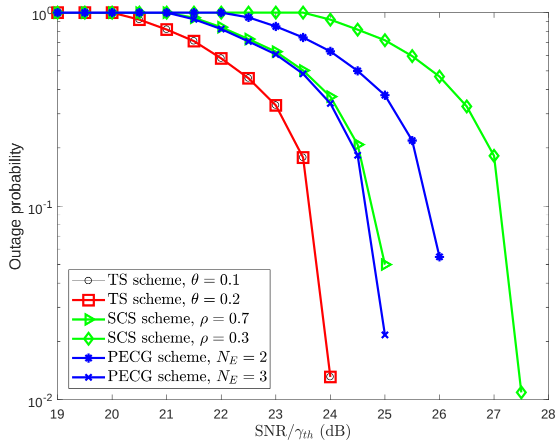
SLIPT can be easily realized by using two disjoint circuits, each of which has different functionality, i.e., either EH or ID. When a time switching (TS) scheme is employed, the receiver switches in time between the energy harvester and information decoder (Fig. 2a). That is to say, the signals are split in the time domain and the received signal is processed either for EH or for ID at each PEC, for fractions of time θ and $1-\theta$, respectively. Thus, TS creates an interesting trade-off between the harvested energy and communication performance, which calls for conscious regulation of θ.

2) Signal Component Separation Receiver

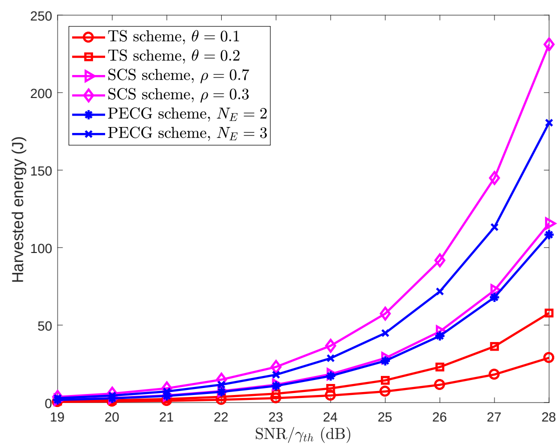
This scheme relies on a unified EH and ID receiver. Under the signal components separation (SCS) scheme the received photocurrent is split into two streams: DC for EH, and AC (which carries the information) for ID, as shown in Fig. 2b, where the inductor L_0 in the EH branch is used as the RF choke. The inductor L_0 is adopted to attenuate the AC signal, thus removing ripples from the DC signal and improving the gain for ID process [6], while capacitor C_0 is used to block the DC component of the signal. The performance of the SCS can be adjusted by tuning the fraction ρ of the maximum input bias current, I_{H}, that is occupied by the DC bias added to the electrical signal during the modulation of the optical intensity of the LED. As ρ increases, the harvested energy also increases. However, as ρ deviates from the value $\frac{1}{2}(I_{\mathrm{H}}+I_{\mathrm{L}})/I_{\mathrm{H}}$, with I_{L} being the minimum input bias current, then the communication performance is negatively affected. This is because the communication performance depends on the peak amplitude of the modulated electrical signal, which is constrained by both I_{H} and I_{L}. Considering the above, it becomes evident that the mechanism for the adjustment of ρ, which is performed at the transmitter, is fundamentally different to the regulation of θ under TS scheme, since the latter is performed at the receiver. Also, it should be noted that SCS scheme can achieve higher EH efficiency compared to TS scheme, since it realizes EH and ID at the same time, without wasting the DC component for the sake of ID. However, this comes at the expense of a more sophisticated receiver design.

3) PEC Grouping Receiver

When there are multiple PECs employed at the receiver, EH and ID can be simultaneously realized by using a subset of PECs for EH and the remaining PECs for ID (Fig. 2c). Differing from SCS and TS schemes, under the PEC grouping (PECG), stringent time synchronization and hardware perfection are not needed at the receiver. SLIPT with multiple PECs is especially important since it enables the utilization of different PEC working modes, giving the capability to increase both the ID and EH rate. Moreover, the receiver can control the subset of PECs, which are used for EH and ID, by using a switching key.



(a) Outage probability



(b) The harvested energy

FIGURE 3: Performance comparison among the proposed three receivers.

C. PERFORMANCE OF THE PROPOSED RECEIVERS

The performance of the proposed SLIPT receivers is presented and compared in Fig. 3, where the height of LED lamps is 3 m, semiangle at half power is 70, the noise power is 0 dBm, the number of the LEDs is 60×60, the active area of the receiver PD is 1 cm^2, the time duration is 3.6 $\times 10^4$ s, ρ denotes the power splitting factor, N_E denotes the number of the PCs adopted for EH under PCS scheme. In the considered system setup, a group of LED lamps located at the center of the ceiling of the room and a receiver with multiple PECs is uniformly distributed in a disc with radius 3 m on the floor. The receiver employs the proposed SLIPT schemes (namely, TS, SCS and PECG) to harvest energy and decode the information. We only consider LOS propagation and omit reflections from surrounding surfaces for simplification. The performance metric is the outage probability and an outage event occurs when the received signal-to-noise ratio (SNR) is below a predefined threshold (γ_{th}). We also assume that

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the receiver is equipped with a battery with infinite energy storage size.

The comparison shows that the outage performance of the TS scheme with $\theta = 0.1$ and 0.2 outperforms the others, where the harvested energy under the TS scheme with $\theta = 0.1$ is the lowest one among the ones under the three proposed schemes. The harvested energy of the SCS scheme for $\rho = 0.5$ and $\rho = 0.7$ is larger than that of the PECG scheme with $N_E = 2$ and $N_E = 3$, respectively. On the contrary, the outage probability (OP) of the PECG scheme with $N_E = 2$ and $N_E = 3$ outperforms that of the SCS scheme for $\rho = 0.7$ and $\rho = 0.5$, respectively.

IV. MIMO SLIPT

Normally, a group of LED lamps are placed to close to each other on the ceiling of a room to provide illumination, which facilitates their employment as multiple sources during the process of data communications. Therefore, MIMO VLC can be employed to achieve diversity gain, especially for the case where the receiver is located in poor-connection zones, e.g., in the corners of the room (see Fig. 1).

However, the aforementioned benefit provided by the MIMO VLC systems comes at the cost of increased hardware complexity of the systems. Fortunately, advanced transceiver designs, originally developed in traditional RF communication systems, can be applied to MIMO SLIPT VLC systems to reach a suitable tradeoff between EH, data transmission, and cost. When SLIPT is adopted in MIMO VLC systems, the design of the receiver will be much more complex and difficult, compared with that with a single PEC, so that multiple copies of the received signals are effectively utilized. For example, one or more multiple LED lamps can be selected to transmit the data information, while other LED lamps are used only for illumination. Then, the complexity of the signal processing at the source will be significantly reduced, as well as that of the received signal processing at the terminal. Another example is the selecting combining scheme, which can also be adopted at the terminal in MIMO SLIPT VLC systems. Under this case, the optimal signal with the maximum optical power is chosen for ID and the others are used for EH.

Moreover, MIMO SLIPT VLC systems also exhibit a multidimensional pool of resources, e.g., signal-spaces, light transmit powers, time slots, sub-carriers, codes, and users, which can be exploited by signal processing techniques to enhance the system performance. Therefore, efficient resource allocation schemes can be designed to deal with the tradeoff between optimality and feasibility and to realize a balance between information transmission and lightwave energy transmission. In more detail, there are mainly three aspects that need to be considered by a resource policy for MIMO SLIPT VLC systems: 1) transmission rate and light transmit power control, that provide quality of service (QoS) of information delivery, light EH, and inter-user interference guarantee; 2) multiple access techniques to schedule resource components among various types of users, while satisfying the individual QoS requirements on ID/EH; 3) a signaling policy to allow simultaneous information and light wave energy transmission of independent data or/and light wave energy streams to the scheduled users. Normally, some QoS metrics, e.g., transmission rate, outage probability, fairness, energy efficiency, and EH efficiency, can be considered to assess the system performance of MIMO SLIPT VLC systems.

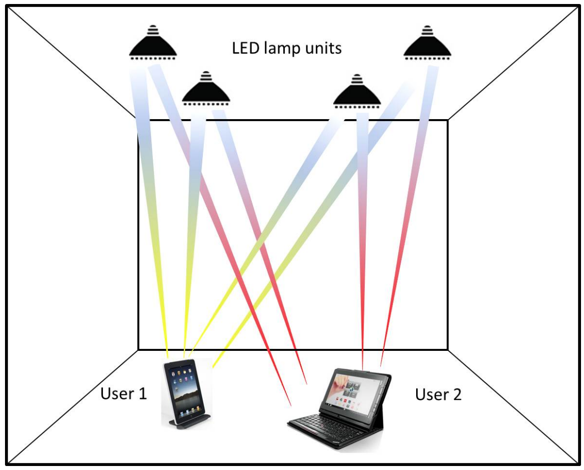

FIGURE 4: Optical beamforming in MIMO VLC.

Particularly, when multiple LED lamps and multiple PECs are respectively adopted at the transmitter and the receiver, precoding and beamforming techniques can be employed to realize spatial steering of independent signals and to coordinate interference mitigation, as shown in Fig. 4. In other words, precoding and beamforming schemes aim to manipulating these independent signals' amplitude and phases and adding them up constructively in desired directions and destructively in the undesired ones, which lead to the coexistence of various data/light wave energy streams conveyed to the concurrent receivers. Furthermore, the design of precoding and beamforming schemes rely on some system factors to fully exploit the spatial domain, e.g., the amount of channel state information (CSI) available at the LED lamp, the network scenario (like single-LED-cell or multi-LED-cell) and the LED lamp settings. Thus, CSI acquisition, control signaling, and coordinated scheduling are challenging tasks for MIMO SLIPT VLC systems to implement precoding and beamforming schemes.

V. HYBRID VLC-RF SLIPT

VLC aims at providing broadcast communications and serving as an alternative for the existing RF systems, like Wi-Fi. However, there are some inherent disadvantages of the VLC technology, which limit its application in practical scenarios [23]:

1) It is a challenge for VLC to realize bidirectional communications, as VLC over the backward link (uplink) may produce glare, which can be a safety or discomfort issue to human.

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2) LOS propagation is crucial to VLC and hence non-LOS communications is challenging, e.g., sending signals across obstacles.

So far, traditional RF transmission, e.g., Wi-Fi and millimeter wave communications, is considered as a suitable alternative for the backward link (uplink) of VLC systems [24] and it can also be adopted as cooperative links to extend the coverage of the system [9]. So, hybrid VLC-RF systems have been suggested and designed to exploit the advantages of both RF and VLC technologies, while avoiding the weaknesses [4]. Unfortunately, it is normally impractical and challenged for power-hungry terminals, e.g., portable devices and sensors, to implement bidirectional communications and to increase the coverage by using RF technologies only. Therefore, hybrid VLC-RF SLIPT is an alternative and promising solution to overcome the aforementioned energy bottleneck problem. In the following, cooperative hybrid VLC-RF systems with SLIPT will be discussed.

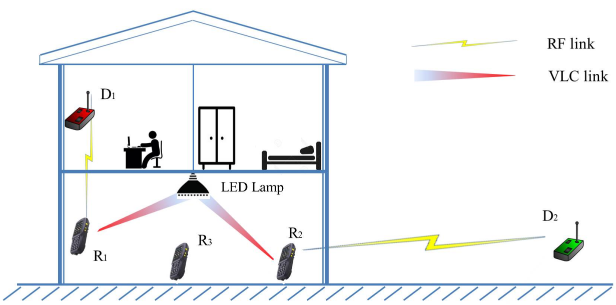

FIGURE 5: Hybrid VLC-RF system in cooperative scenarios

In traditional RF communication systems, cooperative communication was introduced to expand the coverage of wireless networks, by using spatial diversity. Inspired by this, cooperative communication can also be adopted in hybrid VLC-RF systems to overcome the inherent limitations of VLC, e.g., the light cannot penetrate walls, which results in a short transmission range, compared with Wi-Fi and other RF technologies. It can also be used to extend the data transmission range of the indoor VLC systems to outdoor, e.g., vehicular networks.

As depicted in Fig. 5, in a cooperative SLIPT VLC system, each relay is equipped with a PEC and an RF antenna. Especially, by using SLIPT at the relays, the information delivery over the link between the jth ($j = 1, 2, 3$) relay and the destination (R_j-D_i ($i = 1, 2$) link) can be carried out by making the use of the harvested energy from the light signal over LED-R_j link. Then, the terminals which are out of the coverage of the LED lamp, such as D_1 and D_2, can also communicate with the LED. Moreover, one should notice that RF communication technologies should be adopted over R_j-LED link to avoid the glare produced by using VLC, when D sends back data to the LED via the relays. In multiple-relay scenarios, as shown in Fig. 5, relay selection should be considered to achieve the tradeoff between system performance and consumed system resources. Moreover, it is also easy to observe that the amount of the harvested energy depends on the optical transmission distance, namely, the length of LED-R_j link, while the channel gain of the link between the jth relay and D_i (R_j-D_i link) relies on the distance between R_j and D_i. So the locations of the relays play an important role in the cooperative hybrid SLIPT VLC system, as shown in Fig. 5. In this case, the deployment of the relays should be optimized in order to exploit the benefits of SLIPT. Another interesting issue is that, for certain positions of the relays, the optimizations of the SLIPT can also be implemented at each relay, to deal with the tradeoff between EH and ID.

VI. SECURE SLIPT

Because of the inherent broadcast nature of VLC channels, the information transmission may be eavesdropped by unauthorized terminals in the coverage of the LEDs in spite of LOS propagation and better signal confinement, since light signals are transmitted without optical fibers or any sort of wave-guiding [25]. In SLIPT VLC systems, the transmitted signals consist of both information bits and light wave energy, which may increase the eavesdropping probability of the transmitted information. This is because there may exist two modes of terminals in SLIPT VLC systems, one for light EH only and the other for information detection, then, compared with traditional VLC systems, the information security problems are more prominent in SLIPT VLC systems, because some of the EH terminals might become malicious nodes and overhear the data transmission between the source and legitimate receiver.

Recently, physical-layer (PHY) security has been recognized as a promising way to protect the information-theoretic security from eavesdropping, which makes use of the characteristics of transmission channels [26]. Thus, PHY security approaches can be applied in SLIPT VLC systems to improve the secrecy performance, by exploiting the intrinsic randomness of the VLC channels and reaping the benefits offered by SLIPT. Next, two examples on secure SLIPT VLC are given:

1) Cooperative jamming, which was proposed to improve the secrecy performance of RF systems, can also be employed in SLIPT VLC/VLC-RF systems. More specifically, in SLIPT VLC systems the cooperative LED lamps that are close to the eavesdropper can send jamming light signals to degrade the received SNR at the eavesdropper.

2) Transmit beamforming techniques can be employed to enhance the secure communication for the SLIPT VLC systems with multiple LED lamps. Specially, the transmit beamformer can be designed and optimized to maximize the received SNR at the legitimate receiver, subjected to maximum SNR constraints imposed by the eavesdropper.

VII. FUTURE RESEARCH DIRECTIONS

There are several open problems for SLIPT VLC systems, as information and energy are both transmitted through the VLC channel at the same time. In the following we discuss some of the research directions:

Hardware design: The unique features of SLIPT receivers require novel designs for practical applications, compared to common PD receivers or solar panels, which aim at realizing a single purpose: information communication or EH. To this end, the utilization of i) separate receivers, ii) lenses at the receiver to adjust the field-of-view, and iii) new generation PECs (e.g., organic) should be investigated. Among others, SLIPT transceivers should be capable of adjusting the DC and AC components in the optical signals to simultaneously satisfy the demands of both EH and information communication. Also, there is a trade-off between the size of the mobile devices versus the receiver's light collecting area. Moreover, the efficiency of SLIPT can be further improved by the exploitation of new bulbs, which utilize both visible and infrared light. Especially, the design should also utilize the popular process technologies, like complementary metal oxide semiconductor (CMOS), for cost cutting and marketing.

Fundamental Limits: It is particularly challenging to characterize the fundamental limits of SLIPT, since the VLC channel is totally different from the traditional RF ones. Stochastic geometry can be applied to deal with the performance, while taking the randomness of the terminals' positions into account [27]. Moreover, the overall system performance should be carefully defined and characterized, due to the complexity of the hybrid systems.

Resource Allocation: As ID and EH performance should be jointly considered in SLIPT VLC systems, how to effectively allocate the system resources to achieve the optimal system performance is a meaningful, but difficult task. In the hybrid SLIPT VLC-RF systems, there are system resources, such as light power, relays, LEDs, PECs, injection angle, and so on, which can be adjusted and allocated during the performance optimization process. For example, optimal PEC/antenna selection, optimal SLIPT relay selection, and optimal deployment of SLIPT relays can be designed for cooperative hybrid VLC-RF systems.

Imperfect CSI: Most existing works on VLC/VLC-RF relied on the assumption of perfect CSI, however, it is difficult to achieve perfect CSI in practical scenarios. Therefore, it is important to study the impact of imperfect CSI on SLIPT VLC/VLC-RF systems. For example, strong CSI assumption plays an important role during performance modeling, analysis, optimization, and system design for SLIPT systems.

Emerging Applications: SLIPT is a promising technology to implement in order to alleviate the bottleneck of energy constrained wireless networks. Potential applications include building/human health monitoring, indoor environmental monitoring, network coverage expansion, etc.

So far, several manufacturers have deployed EH products for commercial use; however, large-scale production of these devices has not been yet attained. The most popular source of indoor ambient energy is the light. Consequently, harvesting energy from the light is a self-sustaining and cost-effective solution for low-power autonomous devices in indoor scenarios, such as remote sensors and embedded devices. Thus, as a promising concept, SLIPT pertains to different layers of applications such as smart housing, smart manufacture/industry 4.0, healthcare, automotive, medical, and aerospace, where each of these diverse domains are assumed to be equally critical in EH.

VIII. CONCLUSION

In this paper, the basic concepts of the SLIPT in VLC systems have been presented. Particularly, various receiver architectures have been introduced and demonstrated. Also, the applications of SLIPT in MIMO and cooperative networks have been discussed. Moreover, PHY security issues have also been investigated and the potential security improving methods have been provided. Finally, future research challenges and directions for SLIPT VLC systems have been discussed and outlined.

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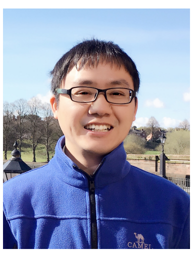

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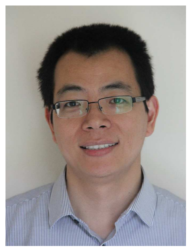

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