INTELLIGENT REFLECTING SURFACE-AIDED VISIBLE LIGHT COMMUNICATIONS

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To satisfy the explosive growing traffic demands in wireless communications, visible light communication (VLC) performs as a promising technology due to its broad and license-free bandwidth. However, practical VLC systems usually confront challenges, such as blockage and high path loss. Different from traditional VLC techniques, intelligent reflecting surface (IRS)-aided VLC can achieve a remarkable performance gain.

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This article first expounds on system implementation from the view of the signal model and hardware architectures. Then, we categorize the advantages provided by IRS-aided VLC into three aspects and illustrate principles and potential usages elaborately, including the signal coverage expansion, illumination requirement relaxation, and signal power enhancement. For realizing intelligent VLC networks, we put forward an artificial intelligence (AI)-based IRS-aided VLC system in which the overall optimization can be accomplished by neural networks to meet the customized requirements. Furthermore, the open issues of IRS-aided VLC are discussed to direct future research.

The Prospect of IRSs in VLC

VLC has attracted increasing interest due to its license-free and broad bandwidth, lack of interference with radio-frequency (RF) communications, and ability for high-frequency reuse [1]. In general, VLC adopts the intensity modulation and direct detection (IM/DD) technique, and the ubiquitous light emitting diodes (LEDs) can be utilized directly as transmitters. Considering the thousandfold increase of data traffic volume, the almost 400 THz occupied by VLC implies a huge potential in meeting ultralarge-capacity demands in the future [1].

Though VLC is a promising candidate for next-generation communication technologies, some inherent characteristics of visible light limit its applications. Above all, severe blockages result from the nanoscale wavelength, causing dramatically attenuated signal power at the terminal. Then, the communication performance may degrade to satisfy the illumination requirements, which do not exist in RF. Moreover, the path loss in VLC is much higher than in other communications according to the Friis transmission equation, resulting in a limitation on the propagation distance.

The emerging IRS-based technologies offer an opportunity to improve the performance of wireless communication systems. Generally, IRS refers to a class of tunable surfaces that consist of massive artificial elements, which can inflict phase shift and/or amplitude modification separately on the electromagnetic (EM) waves. Through this surface, the propagation behavior of the wave can be manipulated at will, and consequently, the software-defined wireless environment is realized to facilitate communications.

By now, extensive research has been carried out on the utilization of IRSs in RF communications, including joint active and passive beam forming and physical layer security [2], [3]. Nevertheless, the investigation in the visible light range is far from adequate, and corresponding techniques in RF cannot be directly used in VLC due to unique constraints, such as the real and nonnegative amplitude, severe channel correlation, illumination requirements, and so on (Table 1). To explore the potential of VLC IRSs, the irradiance performance evaluations and channel model analyses of the reflected paths are provided in [4]–[6], and the use of IRSs is also considered as an approach to realizing beam steering in VLC [7]. To the best of our knowledge, the current research on VLC IRSs mainly focuses on the device layer and signal propagation model, and far too little attention has been paid to the overall framework of IRS-aided VLC.

Significantly, this article aims at presenting the cutting-edge achievements of IRS techniques in the lightwave range as well as summarizing the potential opportunities and challenges of the IRS-aided VLC system. To this end, the signal model of the reflected light is reviewed first, after which dominant hardware implementations are classified into three types, namely, mirror array-, metasurface-, and liquid crystal switch-based IRSs. Then, facing the fatal defects of VLC, we highlight three promising aspects with which IRSs can be helpful: the signal coverage expansion, illumination requirement

TABLE 1 ***A comparison between IRSs in the RF and VLC ranges.***

Characteristics		***RF***	***VLC***
Signal features	Wavelength	1 mm–10 m	370–520 nm
	Amplitude	Complex	Real-valued and nonnegative
	(De)modulation	Coherent (de)modulation	IM/DD technique
	Beamforming	Phase shift and/or amplitude scaling	Hard to implement
IRS devices	Physics	Metamaterials that enable exotic interactions with impinging EM waves	Snell's law of reflection/EM wave manipulation/liquid crystal arrangement in an electric field
	Hardware architectures	Metasurface that consists of numerous meta-atoms	Mirror array/metasurface/liquid crystal switch
	Adjustment mode	Phase shift and/or amplitude scaling	Reflector rotation/voltage control/switch on and off
Propagation model	Near field	Additive model	Additive model
	Far field	Multiplicative model	Can be ignored
Main functions	Coverage expansion	Useful in high-frequency ranges	Highly useful
	Illumination relaxation	N/A	Differentiated illumination
	Power enhancement	Can be used in near-/far-field scenarios	More significant near the IRS
Physical layer security		Signal cancellation by tuned reflected paths	Introduce unintended reflected signals as interferences

N/A: Not applicable.

relaxation, and signal power enhancement. More detailed discussions are provided:

- The reflected light can be manipulated by an IRS to propagate to the target photodetector (PD), and therefore, the communication services in the dead zones and junctional regions are supported by the reflected light from the IRS.
- For applications of in human-centric intelligent illumination and Internet of Things (IoT) device-oriented energy harvesting (EH), the emission power of LEDs can be decreased to a lower level than before, whereas the lacked power can be compensated for by the IRS.
- Exploiting IRSs to collect the energy of nonline-of-sight (NLoS) paths can enhance the received signal power at the terminal. The scenarios of single-input, single-output (SISO); multiple-input, multiple-output (MIMO); and the overall resource management can benefit from IRSs.

Moreover, an integrated IRS-aided VLC system is proposed in the "Future Applications and Open Issues of IRS-Aided VLC" section, where emerging technologies, such as AI and cloud/edge computing, are adopted to facilitate policy decisions. Finally, the "Conclusions" section summarizes the article.

System Implementation

This section gives an account of the system implementation of IRS-aided VLC. To this end, the signal model of the specular reflection path by an IRS is discussed for both near- and far-field scenarios, after which three different hardware architectures of VLC IRSs are described.

Signal Model

In VLC, NLoS components include the specularly reflected, diffuse, diffraction, and scattering paths, among which the specularly reflected one is of chief importance [4], [5]. As shown in Figure 1, this NLoS path is composed of three components, namely, the LED-to-IRS link, reflection on an IRS, and IRS-to-PD link. Generally, the constructions of the channel model can be divided into the near- and far-field scenarios according to the relationship between the wave propagation distance and wavelength, and a threshold distance is given by [8]

$$L = \frac{2D^2}{\lambda} \tag{1}$$

where D and λ represent the largest dimension of the antenna array and wavelength of the signal, respectively. In the RF range, this threshold distance is tens of meters, resulting in the "multiplicative" and "additive" models when the propagation distance is longer and shorter than L, respectively [2], [8]. Nevertheless, L in VLC will lead to a large threshold due to the nanoscale wavelength, and consequently, the far-field scenario can be ignored. Based on this discussion, the channel modeling of the IRS-aided VLC has been investigated in [4] and [5], and the approximation irradiance formula follows the "additive" model, indeed, under the point source assumption.

From a geometrical optical point of view, this additive model is consistent with the phenomenon of specular reflection, where the reflected light can be regarded as emitted from the imaging LED. In addition, the energy consumption on the media surface is modeled by a multiplicative attenuation factor [5]. In this way, even though beam forming is hard to implement in VLC, the reflection direction can be manipulated by adjusting the status of the reflector. Notably, each IRS unit has two degrees of freedom, namely, the reflection factor relying on the surface properties and reflection direction based on the configuration of the IRS unit.

Hardware Implementation

As shown in Figure 1, the hardware implementation of IRSs in the lightwave range can be divided into three main categories, namely, mirror array-, metasurface-, and liquid crystal switch-based IRSs. These IRS architectures can be

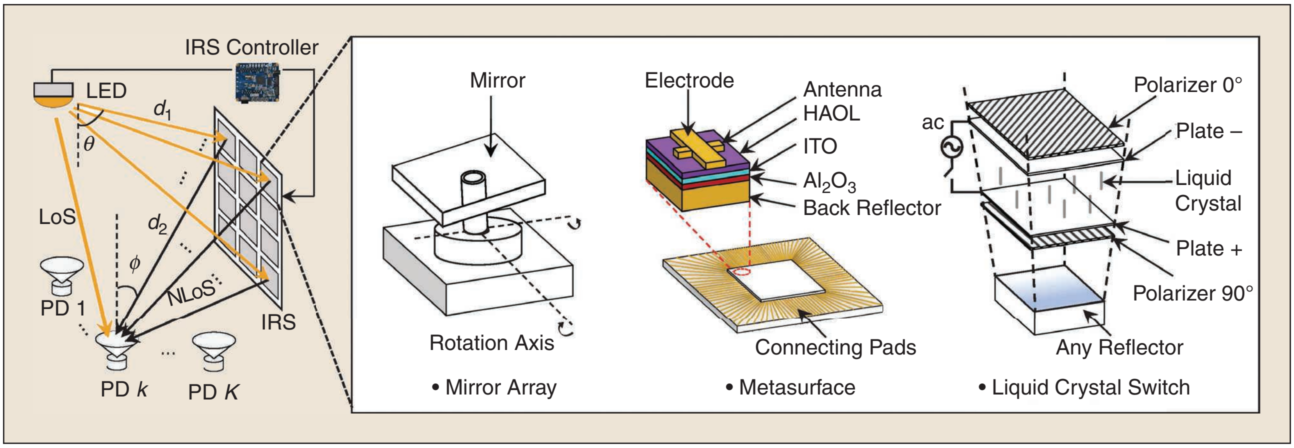

FIGURE 1 The hardware architectures of VLC IRS: the mirror array, metasurface, and liquid crystal switch. HAOL: hafnium oxide/aluminum oxide laminated; ITO: indium–tin-oxide.

configured electrically with a field-programmable gate array as the controller center. More detailed descriptions of the hardware implementation are provided:

- *Mirror array*: Based on Snell's law of reflection [5], the lightwave propagation can be manipulated by the rotations of planar mirrors. Specifically, each unit has two perpendicular rotation axes so that it can adjust the orientation in a similar way as the element in the microelectromechanical system. Therefore, the NLoS channel gain is determined by the rotation angles of the mirror array, which provides superior maneuverability. Though this implementation is mature in industrialization, the rotations of the mirror may disturb the users, and consequently, the mirror array approach is more suitable for user-free scenarios, such as an intelligent factory or automated container terminal.
- *Metasurface*: A metasurface is an artificial planar consisting of numerous meta-atoms, which will create the induction current and response fields when the EM wave impinges the surface [9]. When the surface is composed of a dynamic conductive pattern, it can interact with the impinging EM waves and design them in a controlled way. A feasible device in the near-infrared (NIR) range is shown in Figure 1 that can manipulate the direction of reflected light electrically [10]. So far, the technology of an electrically controlled metasurface in the visible light range remains in laboratories, and industrial manufacturing of the applied device is not yet mature.
- *Liquid crystal switch*: Covering a reflector with a liquid crystal switch is another IRS implementation, and the choices for the reflector are diverse. Then, the arrangement of liquid crystal molecules can be changed in the electric field, which determines whether the reflected light can continue to propagate or not. In this way, the specular NLoS paths can be controlled electrically, and the configuration of liquid crystal switch-based IRSs is simplified into a binary selection problem in mathematics.

Expanding the Signal Coverage

In general, IRSs favor current VLC systems in three aspects: a larger signal coverage area realized by reoriented reflected paths; more relaxed illumination constraints, where both human-centric illumination and luminous energy collection for IoT devices are considered; and a faster communication speed, including the cases of single and multiple transceivers. These characteristics are shown in Figure 2 at a glance, and then the contents are further elaborated in the following three sections. First, the coverage area limitation in VLC is discussed in this section, and IRSs are introduced to expand the signal coverage.

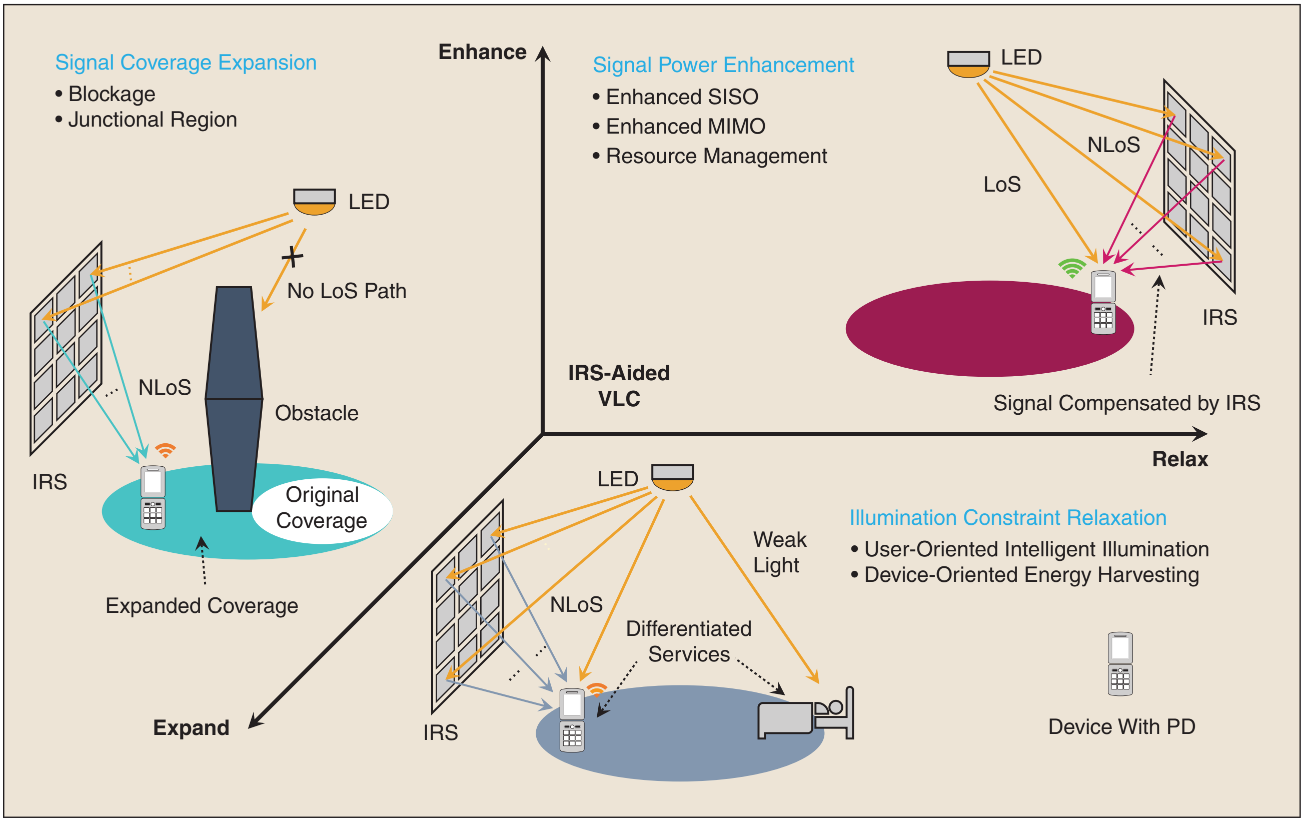

FIGURE 2 The three merits of IRS-aided VLC: signal coverage expansion, illumination constraint relaxation, and signal power enhancement. LoS: line-of-sight.

Blockage Problems

Though VLC is a promising communication technology in the data explosion era [1], the extremely high frequency of visible light leads to severe problems, among which blockage is of the highest priority. The path loss behavior and time dispersion analyses of VLC are carried out in [11], where the numerical results demonstrate that the locations and transceiver components have significant impacts on the VLC channel. Moreover, the penetration loss of the visible light can be larger than 35.5 dB, which is the loss of composite walls in millimeter-wave (mm-wave) communications [11]. Therefore, the VLC performance will be severely impaired if the line-of-sight (LoS) paths are blocked by obstacles. Deploying a wider range of LEDs in dead zones is a feasible solution, but this lacks flexibility and cannot cope with moving obstacles.

Fortunately, given their adaptability and passivity, IRSs provide a promising approach to overcome blockage problems. The signal model investigations in the "Signal Model" section demonstrate that the VLC channel reflected by the IRS depends on the locations as well as the geometric parameters of the transceivers and IRS units. With the acquisition of the information about locations and channel states, the propagation behavior of the reflected light can be controlled by designing the coefficients of the IRS.

It is worth noting that the nanoscale wavelength of the visible light offers a high spatial resolution, which indicates more accurate wave manipulations than those in the RF or mm-wave ranges. In this way, the blocked user can be served by the reflected light instead, and consequently, the signal coverage area has been expanded. An example is shown in the left part of Figure 2, where the PD-equipped device is blocked by an obstacle, and its communication services are provided by signals reflected from the IRS.

Junctional Region

The high path loss of the visible light leads to a small cell, and the quality of service (QoS) in junctional regions is generally poor. On the other hand, when the user switches from one cell to another, handover operations will account for overhead and degrade the performance further [1]. Nevertheless, the capability of an IRS to manipulate the reflected light exhibits great potential for improving the signal performance of the junctional region. More specifically, two types of reflection components, namely, the desired signals and interferences, are redirected to the target the PD and useless place, respectively.

This process is adjustable and varies from different transceiver locations and channel states, and the handover operation is supported due to the reconfigurability of the IRS. Because of this, multiple IRSs can be utilized to facilitate communications, an approach that has been widely applied in RF [2]. In the considered scenario, the management of adjacent LEDs and IRSs are jointly optimized, and the user can receive several clusters of reflected light simultaneously for performance improvement.

Relaxing Illumination Requirements

The second advantage of IRSs is the relaxation of the illumination requirements in VLC, and two specific applications are investigated in detail, namely, user-oriented communications under illumination requirements and IoT device-oriented EH.

Communication Under Illumination Constraints

The pursuit of numerous studies lies in higher spectrum efficiency and broader bandwidth, and the achievable rate of VLC has already exceeded gigabytes per second [1]. Nevertheless, illumination and communication are two coexisting functions in VLC, which is different from other communication technologies. Though VLC is deemed as a revolutionary solution to meet future high-speed communication requirements, illumination is still the primary task of an LED, and human eyes are important receivers as well. It is summarized in [12] that people need specific light intensity when doing different jobs, e.g., 30 lx is required in computer tasks, while 500 lx is recommended in writing. The complexity of situations requires human-centric and intensity-adaptive illumination networks. In the meantime, the literature also reveals that the emission power of an LED may be decreased to satisfy the luminous constraint [12], and the dimming control can degrade the color quality by the color shift.

To address this problem, dimming techniques in different dimensions are proposed, including intensity-domain, time-domain, frequency-domain, spatial-domain, and hybrid multidimensional dimming schemes [12]. These solutions aim to balance the average light intensity and communication performance. However, conflicts may happen among different requirements of users. Suppose an Internet surfer, for whom the light intensity is unimportant, needs to download large files at high speed, while there is another person reading who has the opposite requirement. The system must have high adaptability to meet all QoS and illumination demands for these two users.

As a reconfigurable surface, an IRS can improve the system flexibility to achieve user-oriented communications under illumination constraints. As shown in Figure 3, the requirements are sent to the system controller, which consists of an IRS configurator and LED modulator. Their mechanisms rely on the specific IRS implementation and determinations of dimming techniques and data modes, respectively. Note that these two modules in the control layer coexist and cooperate with each other, and a joint optimization is performed to pursue the global optimal status. Then, the IRS reconfiguration is carried out to modify the propagations of the reflected light, and consequently, the lacking luminous energy of the target user can be compensated for in a controlled manner.

EH for IoT Devices

With the advent of the IoT era, billions of devices will access the network, and a tremendous amount of energy will be consumed to support massive appliances. To prolong the service time of IoT devices, the wireless EH technology represented by power-splitting and time-switching schemes has long been valued [13], and MIMO and IRS techniques are used to overcome the path loss in wireless transmission [2].

As a promising technology, the simultaneous lightwave information and power transfer (SLIPT) in VLC is mainly realized by the solar panel-based receiver [13]. In contrast to the traditional EH schemes in RF, SLIPT can adopt a time-splitting (TS) scheme to support EH and data transmission simultaneously, allowing for continuous power collection since the intensity amplitude is positive. Moreover, the dc and ac component separation can be implemented easily and in parallel by inductors and capacitors, and therefore, the switching key is no longer needed in SLIPT [13]. Even so, the wireless EH in VLC is more intractable than that in RF due to a much higher path loss, and it is infeasible to place massive LEDs at the transmitter considering the emission power constraint. Consequently, IRSs can be exploited to facilitate SLIPT by manipulating the light propagation and gathering the specularly reflected energy, and this process consumes little energy due to the passivity of IRSs.

According to the numerical results and supplement prototypes, the harvested power level in SLIPT is on the order of milliwatts [13], which can hardly support portable devices. However, most IoT devices, such as sensors, have extremely low power consumption and data rates, and they are usually stationary. For these devices, IRS-aided SLIPT can not only extend the service time by wireless power transfer but also provide very low data rate transmission by the TS scheme.

Enhancing the Signal Power

The third advantage of IRS-aided VLC lies in the enhanced signal power, and promising techniques include IRS-aided SISO, IRS-aided MIMO, and overall resource management. The utilization of IRSs in this aspect is elaborated on in the following sections.

IRS-Aided SISO

A geometric optical model of the IRS-aided SISO system is introduced in [5], where the channel response is divided into the product of four factors, namely, the responsivity of PD, power loss in propagation, atmospheric turbulence, and geometric and misalignment losses. Then, two different channel models, that is, the conditional and statistical models, are investigated elaborately, after which numerical simulations are carried out to show the effect of the misalignments and transceiver components on the SISO channel gain.

Nevertheless, this model is suitable for a mirror array-based IRS, and an analytical framework is proposed in [4] around two cases of a mirror array and metasurface. Specifically, the power density acquired at the center of each PD is derived for both types of reflectors, and, then, closed-form upper bounds are approximately given under the point source assumption. Moreover, the influence of factors in the free space channel is taken into

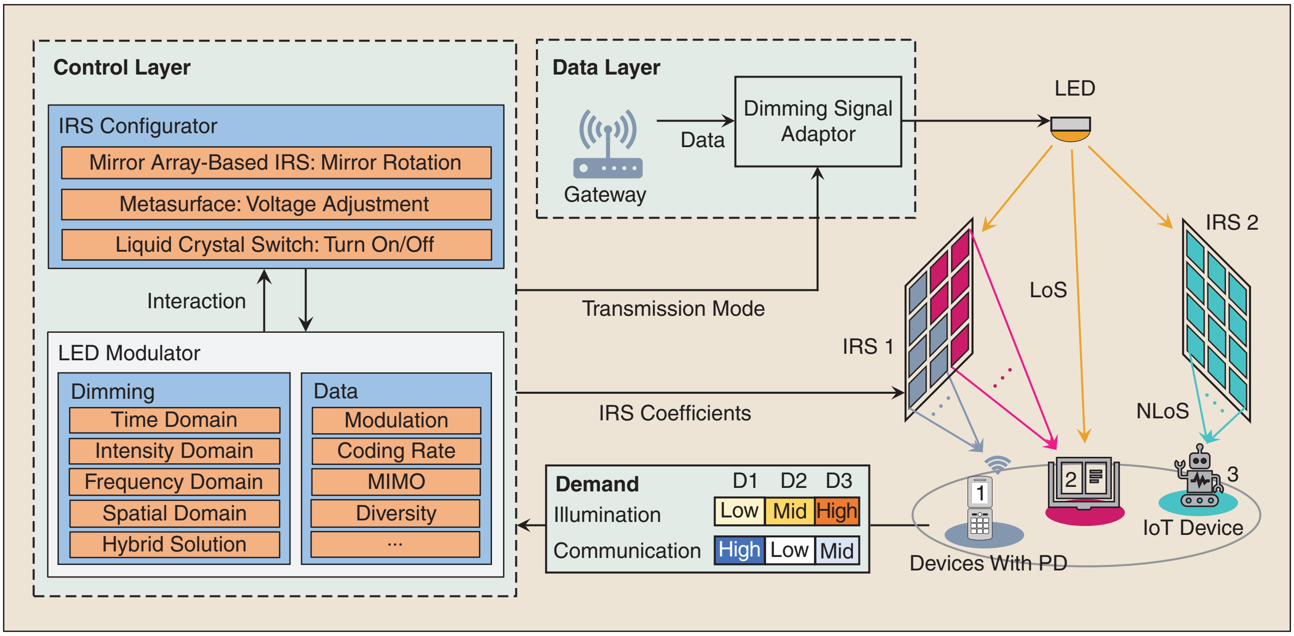

FIGURE 3 IRS-aided VLC can satisfy the pertinent illumination and communication needs of users under tighter constraints.

consideration [6], including the pointing error, probability of obstacles, jitter of the IRS surface, and so on. The results of this work demonstrate that IRSs can reduce the blockage probability within a reasonable number of NLoS channels.

To verify the improvement in the received signal power attributable to IRSs, the numerical results of the achievable sum rate versus average signal-to-noise ratio (SNR) and number of IRS units are shown in Figure 4(a) and (b), respectively. In the simulations, LEDs are fixed on the ceiling of a room with a size of 8 × 8 × 3 m, and PDs are randomly distributed on the plane 1 m above the floor. Then, the modulation bandwidth and emission power on each LED are set to 40 MHz and 5 W, respectively. To reflect the actual wireless environment, each PD has a 50% probability of being blocked by homogeneous media, which can be modeled by a multiplicative attenuation factor with a value of 0.2. Notably, the relaxing greedy algorithm is proposed [14] to realize the IRS configuration with low computational consumption, and different optimization policies are provided for comparison.

The result in Figure 4(a) highlights the effectiveness of a VLC IRS in the sum rate improvement, and nearly 10 Mb/s of gain can be achieved in the high-SNR regimes when the number of IRS units is 256. Moreover, the simulation in Figure 4(b) demonstrates that the sum rate increases almost linearly with the number of IRS units under the point source assumption, which offers instructive insights on the IRS configuration policy.

IRS-Aided MIMO

Although the frequency band of VLC is far from fully used, the low-pass characteristic of LED devices greatly limits the data rates. To tap the potential of spectral efficiency thoroughly, MIMO technology is of high availability in achieving the multiplexing and/or diversity gain, which makes massive MIMO a key technology of 5G and beyond. Nevertheless, a bottleneck of MIMO VLC is a severe correlation of the MIMO channel, leading to a much smaller number of data streams than the nominal one. Therefore, various decorrelation techniques are proposed to improve the performance of MIMO VLC, including cross-links blocking, power imbalance, image receivers, and joint optimization of the precoder and equalizer [15]. These schemes are totally based on the design of transceivers, but they can rarely achieve high-quality MIMO gain in practical applications.

IRS-aided MIMO communications have attracted much attention in RF, and the performance evaluations under both frequency-flat and -selective fading channels are carried out [3]. Particularly, by jointly optimizing the IRS coefficients and MIMO transmit covariance matrix, the MIMO channel capacity can be greatly improved, including the rank, condition number, and channel total power [2], [3]. As for MIMO VLC, considering their ability to manipulate the directions of specularly reflected paths, IRSs can potentially be exploited to modify the MIMO channel matrix. This process can be modeled as designing an NLoS increment on the ill-conditioned LoS channel matrix mathematically, and consequently, the aggregate MIMO channel can, possibly, be improved by proper IRS configuration. However, to the best of our knowledge, there is no specific channel model to describe the MIMO channel reflected by a VLC IRS until now, and the work of channel modeling and capacity optimization remains to be further investigated.

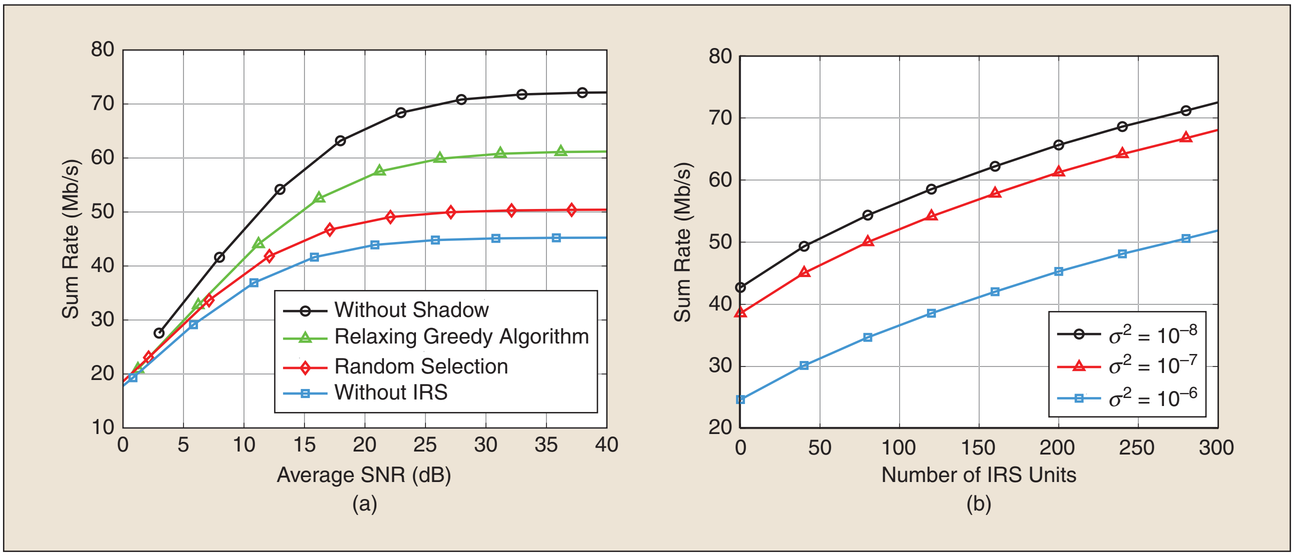

FIGURE 4 The achievable sum rate of IRS-aided SISO VLC versus the (a) average SNR and (b) number of IRS units when no shadow appears and the relaxing greedy algorithm is adopted.

Joint Resource Management

Based on the aforementioned discussions, the performances of both SISO and MIMO VLC benefit a lot from the IRS deployment. However, resource management in a real communication system often covers different resource types, including the power adjustment, IRS configuration, and so on. Optimizing the coefficients of IRS individually can rarely achieve the global optimal status, and therefore, joint optimizations are usually carried out in RF IRS-aided systems to maximize the achievable sum rate or energy efficiency [3].

The resource management can also be optimized jointly in IRS-aided VLC, where the optimization variables include the user association behavior, emission power on each LED, and configuration matrix of the IRS. Without loss of generality, the achievable sum rate can be chosen as the objective function, and the QoS and illumination requirements are constraints [14]. A general process is shown in Figure 5, where PD receives the incident light of the LoS and NLoS paths simultaneously and sends requests to the controller according to the individual rate gap. After synthesizing the information by the controller, several types of instructions are assigned to the corresponding control units:

- *LED clustering*: Cluster the transmitters so that one portion of them serves a specific PD.
- *Power allocation*: Set the emission power of the LEDs properly.
- *IRS configuration*: Adjust the reflection properties of the surface based on its hardware architecture.

In mathematics, these optimization problems are generally nonconvex [3], [14]. Therefore, the gradient descent algorithm or Newton method may cause convergence problems and/or a large dual gap. To solve this problem, nonconvex optimization techniques are better solutions, including the alternating optimization, majorization-minimization, and semidefinite relaxation algorithms, among others.

Future Applications and Open Issues of IRS-Aided VLC

In reality, the illumination and communication requirements of VLC are difficult to meet simultaneously. Take the illumination demand as an example: the light intensity for different types of work varies from 30 to 500 lx [12], and it may also change based on the time of day. On the other hand, the communication demands are also complicated. Low latency is extremely important in mobile communication scenarios, while a high data rate is needed in data-hungry applications, such as ultra-high-definition video play. To further seize the opportunities and explore the potentials of IRS-aided VLC, the following challenges need to be investigated extensively in the future:

- *Material layer*: The development of the metamaterial field has a profound impact on the applications of VLC IRSs. Researchers are devoted to designing tunable surfaces that can be controlled electrically, and related works have progressed from the micrometer to NIR range and, then, visible light range. Recently, a novel transparent

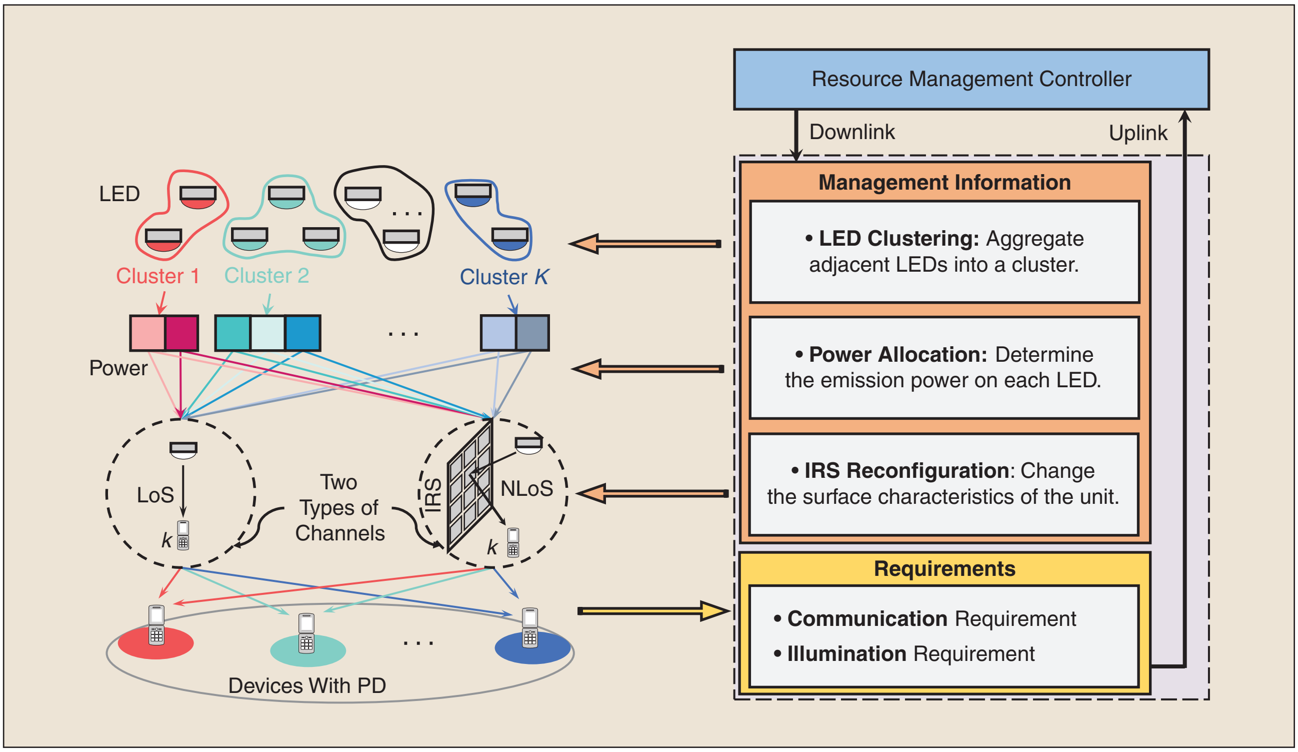

FIGURE 5 The resource management in an IRS-aided VLC system.

dynamic metasurface that can manipulate the reflection and penetration of EM waves in a highly transparent package has gained much attention. This brand-new metasurface has realized a 0–360° reflection in the RF range, and, consequently, is considered of great promise in VLC. Furthermore, the approaches to improving the performance of metasurfaces remain to be further investigated, including more accurate steering angles and lower energy consumption.

- *Physical layer*: An RF/VLC heterogeneous architecture should be adopted in the framework of Figure 6, where RF technology can satisfy the communication requirements when the lights are off, and the RF uplink will not cause discomfort to human eyes. Second, an ultrahigh-resolution positioning technique based on terahertz or VLC technology can provide richer spatial information, which is indispensable in an IRS configuration since the misalignment of transceivers and reflectors can dramatically affect the photon reception. Then, physical layer security is a key problem in wireless communications, and the signal of the eavesdropper can be weakened or canceled by adding a tuned reflected signal from an RF IRS [2]. Though the light intensity in VLC is hard to decrease through destructive interference, the signal-to-interference-plus-noise ratio of the eavesdropper can be weakened by deliberately introducing interferences; i.e., the signals of other users are reflected to the eavesdropper by the IRS. Moreover, the reflected MIMO VLC channel modeling is of high significance in analyzing the IRS-aided MIMO capacity, which is vital to improve VLC data rates in the future.
- *Network layer*: Given the complexity of the channel-fading status, device mobility, and real-time requirements, it is not easy to search for an instantaneous solution in a huge feasible space. Therefore, data-driven AI technology can be exploited in the proposed framework to ameliorate system policy decisions. By integrating the uploaded parameters and useful historical information, the neural network can understand the system status comprehensively and produce instructions for resource management and transmission mode selection. Furthermore, edge and cloud computing technologies are of high significance in current communication systems, which can also be included in the framework. Specifically, the data and models are exchanged between the local neural networks and edge servers, and the cloud performs as a supervisor to integrate information from different regions and provide effective guidance for local network training.

Conclusions

This article highlights three advantages provided by IRS-aided VLC: larger signal coverage area, more relaxed illumination requirements, and faster communication speed relying on the received power enhancement. Considering the unique features of visible light, a VLC IRS differs greatly from an RF IRS on the signal model and hardware architectures, thus resulting in great significance for investigating IRS-aided VLC techniques. In the future, the concepts of smart cities and intelligent transportation will enter our lives and put forward increasing requests for next-generation communications. Hopefully, the

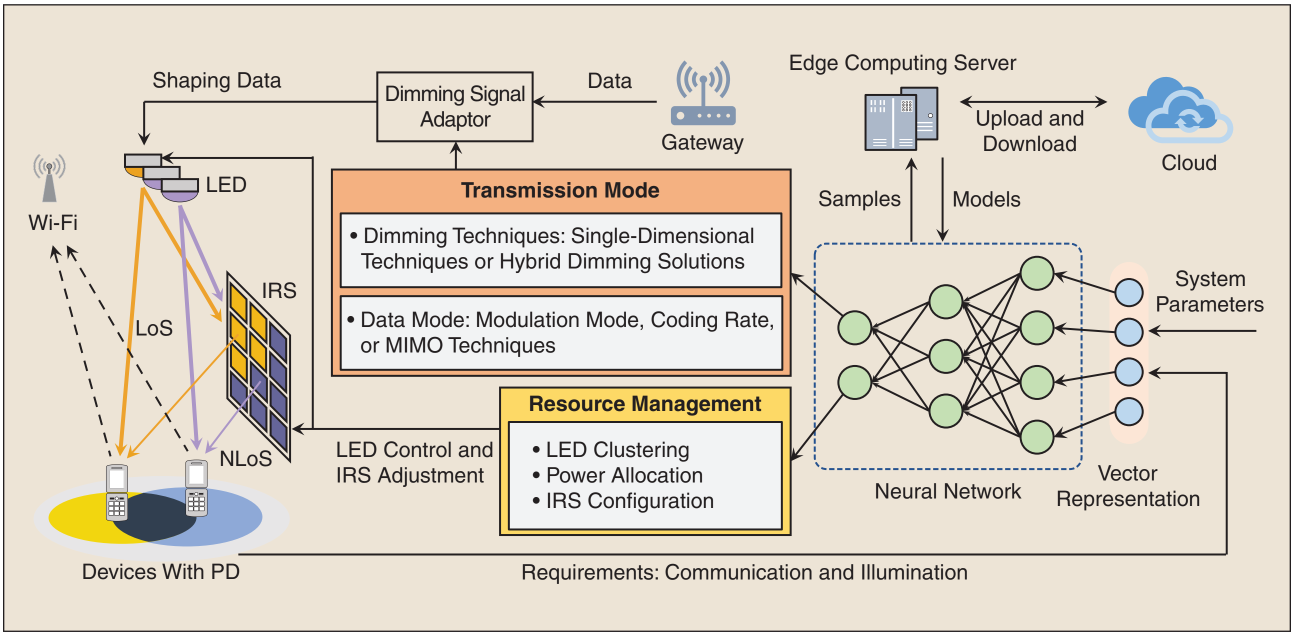

FIGURE 6 The future applications of IRS-aided VLC integrated with emerging techniques.

programmability and passivity of the IRS surface can make it shine in future VLC systems, and the purpose of the article is to provide some meaningful guidance for future researchers.

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