Reconfigurable Intelligent Surfaces for Outdoor Visible Light Communications

Salah Abdeljabar, Mahmoud Wafik Eltokhey, and Mohamed-Slim Alouini

Abstract

The increasing dependence on light-emitting diode (LED)-based lighting is raising the interest in using visible light communication (VLC) to provide wireless coverage in outdoor scenarios, given its merits which include operating on huge unlicensed spectrum and minimizing the radio frequency (RF) interference. However, since line-of-sight (LOS) components dominate VLC signal reception, the performance of VLC systems is highly dependent on maintaining LOS and avoiding link blockages caused by user mobility. Interest in the utilization of reconfigurable intelligent surfaces (RISs) in VLC systems has been growing recently, as they offer solutions for improving the link robustness by providing spatial diversity. This work discusses the use of RISs in outdoor VLC systems, highlighting use cases for the RIS-assisted VLC in the unmanned aerial vehicle networks, vehicle-to-everything applications, and streetlight-based communication systems. In addition, it evaluates using simulations the impact of considering RISs on the outdoor VLC system performance in terms of link outage, before discussing possible directions for future research.

Introduction

The growing demand for high-speed connectivity and the increasing number of devices connected to the internet are raising the interest in using optical wireless communication solutions for supporting the radio frequency (RF) spectrum in meeting user data needs. In this regard, visible light communication (VLC), which utilizes the light-emitting diode (LED)-based lightings for providing simultaneous illumination and communication, is considered as interesting candidate to complement the congested RF systems, given its reliance on huge unlicensed spectrum, while offering efficient resource utilization and immunity against RF interference [1].

The growing increase in the number of Internet of Things (IoT) devices in outdoor scenarios is encouraging the use of VLC to help supporting data traffic offloading from congested RF systems and maximizing the network achievable throughput [1, 2]. By benefiting from the already-existing lighting infrastructure, the applications of VLC in outdoor scenarios include utilizing the LED-based streetlights to provide wireless coverage for pedestrians [1], and exploiting the front and back lights of the vehicles to support vehicle-to-everything (V2X) communications [3]. Also, VLC can be considered in the unmanned aerial vehicle (UAV)-based networks, where the UAVs utilize the LED-based luminaries to provide illumination and communications, which could be favored in applications such as search and rescue missions and supporting communication in hazardous locations [4]. However, as the line-of-sight (LOS) components have significant contributions to the received signals in VLC systems, the links are vulnerable to link blockage and shadowing. In addition, the link misalignment can affect the system performance, due to factors such as the limitations on the beam width and field-of-view (FOV) of the transmitters (Txs) and receivers (Rxs), respectively [1].

Reconfigurable intelligent surfaces (RISs) are structures with capabilities to reconfigure the incident waves propagation by employing smart controllers [5]. It was shown in [6] that using RISs can enhance the channel gain by up to five times compared to relying only on LOS link. Interest in utilizing RISs in outdoor VLC systems has been growing recently, offering solutions to address the challenges associated with user mobility [3, 4]. For UAV-assisted VLC networks, the authors in [4] studied the optimization of UAV deployment, RIS parameters, and user association to minimize the transmission power. For V2V networks, the work in [3] proposed a closed-form expression for calculating the number of RIS elements required to achieve target spectral and energy efficiencies.

The use of RISs in indoor VLC systems has been heavily studied, for instance, in [5] through providing comprehensive overview of RIS concepts, challenges, and potential applications, and in [7] by focusing on the specific use of liquid crystals in RISs at the VLC Tx. However, to the best of our knowledge, a thorough overview of the opportunities and challenges associated with using RISs in outdoor VLC systems has not been considered before. In this paper, we discuss the use of RISs in outdoor VLC scenarios, illustrating the opportunities they offer by their deployment in the UAV-based networks, V2X applications, and streetlight-based communication systems. In addition, we propose the utilization of the RISs for supporting outdoor-to-indoor VLC transmission. Moreover, we evaluate using simulations the link outage performance for RIS-assisted outdoor VLC systems, before discussing possible directions for future research.

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Outdoor VLC Channel

VLC can be realized by the use of intensity modulation/direct detection, where the LED-based luminaires act as Txs. Here, the LED transmission is modulated by the user data, while the user devices utilize photodetectors (PDs) for receiving the optical signals. In general, the VLC channel gain is dominated by the LOS received signal components, which are impacted by factors such as the orientations of the VLC Txs and Rxs as well as the link distance [1]. Note that, the outdoor VLC systems are more prone to performance degradation compared to the indoor VLC systems as they suffer from increased path loss due to the larger link distances and increased probability of link misalignment between the VLC Txs and Rxs due to higher mobility of the users. Moreover, the atmospheric conditions such as fog, haze, snow, and rain can affect the intensity of the received signals [1], impacting the choice of the type, size, and number of RIS elements [3]. Although VLC systems are affected by daylight, which degrades the signal-to-noise ratio (SNR) due to increased shot noise at Rxs, it has been shown that outdoor VLC systems can perform robustly on sunny days while avoiding direct sunlight. Note that, Gbps data rates were experimentally achieved using VLC links, for link distance up to 10 m in [8], and in the presence of solar irradiance in [9], which demonstrates the capability of VLC to provide high-speed connectivity in outdoor use cases. In general, the use of optical filtering could help in reducing the impact of noise caused by solar irradiance, while the reliance on automatic gain controller could help in minimizing the possibility of PD saturation [9].

RIS-Assisted VLC

According to the effects induced by the RIS elements on directing the incident VLC signals, they can be classified into specular reflecting, diffuse reflecting, and refracting elements. Figure 1 illustrates different forms of optical RISs.

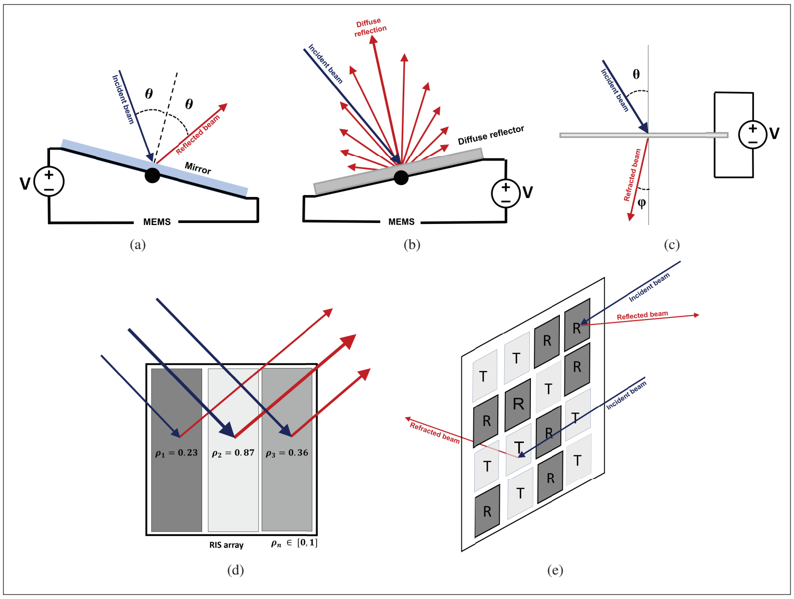

FIGURE 1. Illustration for a) mirror-based; b) diffuse reflecting; and c) refracting RISs, as well as examples of metasurface-based RISs that control the d) intensity by varying the reflectivity "ρ" of the RIS element and e) simultaneous reflection and refraction (through the elements "R" and "T," respectively) of the incident signals [10, 11].

Specular Reflecting RIS

Specular reflecting RISs rely on using elements that specularly reflect the incident signals. The induced change in the directivity of the reflected signals can be calculated using Snell's law of reflection, which could be controlled by varying the orientation of the reflecting elements [6]. They can be realized by using planar mirrors mounted on top of rotary motors or microelectromechanical systems (MEMS) for controlling their orientation. Additionally, liquid crystals with a thin layer, combined with backplanes, can be used to control the orientation of reflected beams. This can be achieved by adjusting the refractive index through the application of an external voltage [10]. Although specular reflections could have significant contribution to the received VLC signals, the resulting link performance is sensitive to errors in locating the Rxs. Figure 1a depicts an illustration of a specular reflecting RIS in the form of a mirror [11] rotated using MEMS.

Diffuse Reflecting RIS

Diffuse reflecting RISs utilize elements with abilities to diffusely reflect the incident signals, where the element orientation is varied for controlling the reflected signals. The realization of such RIS elements can be achieved by using Lambertian reflecting surfaces (e.g., structures covered by layers of plaster or plastic wall painting), where the intensity of the received signal components at the Rxs can be calculated using the Lambertian reflection model [12]. Note that, the intensity of the reflected signals is impacted by factors such as the power spectral density of the light source and the spectral reflectance of the diffuse reflecting element. In general, using diffuse reflecting RISs improves the link robustness against errors in locating the Rxs. However, this comes at the expense of lower received signal intensities compared to the specular reflecting RISs. Figure 1b shows an example of a diffuse reflecting RIS element with orientation rotated using MEMS.

Refracting RIS

Refracting RISs can configure the incident signals by controlling their passage through the RIS structure and steering the refracted beams in particular directions. This form of RISs can be realized by utilizing liquid crystal structures with adjustable refractive index that refract the incident signals according to the characteristics of the structure and the incident beams [5]. The use of refracting RISs opens the door for facilitating optical wireless communication between Txs and Rxs separated by semi-transparent sections [5]. Figure 1c presents an example of a refracting RIS element, highlighting the refraction of the incident signal through the RIS structure.

Metasurface-Based RIS

RISs could be designed using metasurface structures controlled by external stimulus (e.g., signals) to manipulate the incident wave properties [11]. The parameters that can be optimized using metasurface-based RISs include the reflectivity (i.e., intensity of reflected signals) and refractive index (i.e., refraction properties of the RIS structure). Figure 1d depicts an example of metasur-

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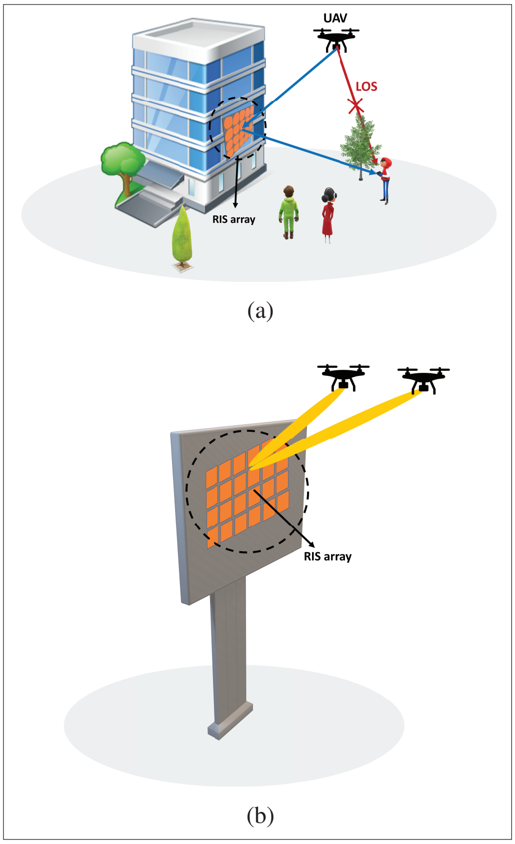

FIGURE 2. Illustration for use cases of RIS arrays to support (a) UAV-based VLC networks and (b) VLC-enabled inter-UAV communications.

face-based RIS array that tune the intensity of the reflected signals by varying the reflectivity, while Fig. 1d presents an example of simultaneous transmission and reflection (STAR) [10], in which the RIS array comprises reflecting and refracting structures that carries out reflection and refraction of the incident signals, respectively.

Outdoor RIS-Aided VLC Systems

In this part, we discuss the use of RISs in outdoor VLC scenarios, highlighting their potential to improve link quality and reliability. Note that, there are differences between the solutions used for realizing RISs operating in optical and RF spectrum due to the variances in the characteristics of the transmissions [13]. As highlighted earlier, optical RISs can be realized using various hardware implementations such as using (i) mirrors, (ii) Lambertian reflectors, (iii) liquid crystals, and (iv) metasurfaces in building RIS arrays. In general, the hardware implementations using (i), (ii), and (iii) are realizable using currently existing materials [5, 7, 10, 12, 13], offering low-complexity solutions for the development and deployment of RISs for VLC. Also, the alignment system proposed in [14] has shown abilities to support successful tracking of an object moving with speed up to 20 m/s (i.e., 72 km/hour) over 1 km distance.

Note that, mitigating LOS blockage and increasing link coverage by deployment of additional VLC APs may not be effective, as their placement targets mainly i) following the pedestrians/drivers illumination needs, (ii) mitigating any lighting disturbance for pedestrians/drivers, and (iii) satisfying aesthetic considerations. Also, the use of additional infrared-based APs may result in collectively exceeding the eye and skin safety limits on the received power levels due to the accumulation of reflected components from multiple APs, given the lack of control on the presence of reflecting objects (e.g., cars). Furthermore, introducing additional RF-based APs is constrained by the RF spectrum congestion and the RF-induced interference levels, which may result in degradation in communications systems performance and constraints on deployment in close proximity of RF-sensitive areas. On the other hand, the use of RIS-assisted VLC offers (i) efficient resource utilization by using the lighting infrastructure without the need for installing additional APs (i.e., significant modifications to the existing cellular architecture), (ii) minimized power consumption, (iii) operation in wide unregulated spectrum, and (iv) mitigation of RF interference, enabling supporting communications nearby RF-sensitive areas.

UAV-Based VLC

The use of multi-rotor UAVs for providing wireless coverage has been receiving an increasing interest, given their hovering capabilities that allow them to act as aerial base stations (BSs) [15]. However, considering RF transmission solutions at the UAV-based networks could cause interference for the existing terrestrial networks, and may constraint the network achievable throughput due to the limitations on the energy resources at the UAVs [4]. On the other hand, relying on VLC could offer advantages such as RF interference minimization and efficient resource utilization by supporting wireless connectivity by using the LED-based lightings at the UAV as APs. In spite of the advantages provided by UAV-based VLC networks, the LOS path obstruction and Tx-Rx misalignment could degrade the network performance and affect the link reliability. Here, the utilization of specular reflecting or diffuse reflecting RISs could help in mitigating the channel impairments and extending the network coverage [4], where the choice of the RIS array will depend on factors such as the user mobility in the considered scenario and the system needs in terms of achievable throughput. Figure 2 shows examples of using RISs in UAV-based VLC systems.

Mitigating Link Blockage: The use of RISs could assist energy-efficient UAV path planning to ensure reliable link performance while minimizing the power consumption by increasing the reliability of the non-LOS VLC links. In particular, by reflecting the VLC APs transmission towards the ground users, the RIS arrays can help in (i) increasing the SNR at the user devices; (ii) providing spatial diversity; and (iii) extending the AP coverage by handling users located outside the AP coverage area. Figure 2a shows example of the use of RIS array in UAV-based VLC network to support the non-LOS VLC links.

Enabling Inter-UAV Communications: The orientations of the LED lightings in the UAV-based VLC networks towards the ground user devices limit the APs capabilities to support inter-UAV communications, given the limitations on the beam width and FOVs of the Txs and Rxs at UAVs, respectively. By using RIS arrays installed on roadside infrastructure, inter-UAV communications could be facilitated by directing part of the VLC transmission from one UAV towards another UAV. Figure 2b illustrates the utilization of RIS array installed on billboards for supporting inter-UAV communication.

Relaying Transmission: The use of RISs in relaying UAVs transmission can help in transferring power and data to sensors over large areas using a limited number of UAVs, and providing coverage in cases of absence of LOS links between the UAVs and sensors. In addition, it can improve the energy efficiency of UAV networks by assisting the minimization of the transmission power of UAVs according to system requirements, and assisting in energy-efficient path planning of UAVs to reduce power consumption.

Assisting Handover: The mobility of users in outdoor environments can increase the rate of handovers between APs, which can be challenging to handle due to constraints on power and computational resources in UAV networks. The use of RIS arrays can reduce handover rates by allowing data transmission to users at cell edges to delay or skip the handover according to the AP loads. Additionally, it can support soft handovers between the APs, particularly in areas with no overlapping between APs coverage areas.

Offloading Traffic: The mobility of UAVs facilitates their use for offloading traffic from congested RF networks. However, the altitude of UAVs impacts the system performance as increasing heights results in decreasing signals strength while decreasing heights leads to decreasing coverage areas. RISs could assist optimizing the deployment of UAVs according to the network needs by enabling NLOS connectivity with users located outside the UAV coverage areas.

Outdoor-to-Indoor VLC

The wide dependence on LED-based lightings in outdoor scenarios opens the door for use cases where the indoor user devices receive VLC signals by relying on outdoor-to-indoor transmission. This could be achieved by using STAR-based RIS arrays (Fig. 1e) that support the refraction of the transmission of the LEDs located in outdoor areas towards the user devices inside buildings, as well as the reflection towards the ground users. Figure 3 depicts an example of the proposed outdoor-to-indoor VLC, where STAR-based RIS arrays installed on room windows could support: (i) refraction of the optical signals originating from VLC APs located outdoors (i.e., LED-luminaires installed at streetlights and UAVs) towards indoor users and (ii) reflection of the incident signals towards the ground user devices for assisting the outdoor VLC networks. Compared to existing solutions, the proposed scheme offers efficient resource utilization by benefitting from the already-existing infrastructure in supporting communications, presenting opportunities for decreasing the cost and deployment complexity.

Vehicular VLC

V2X communication facilitates the exchange of information between vehicles and other entities such as pedestrians, vehicles, road-side units, and infrastructures. It offers solutions to support a wide range of applications that include intelligent transportation systems, vehicle traffic optimization, and passenger infotainment. However, the growing number of autonomous vehicles and services facilitated through V2X communications are increasing the demand for high-speed wireless connectivity.

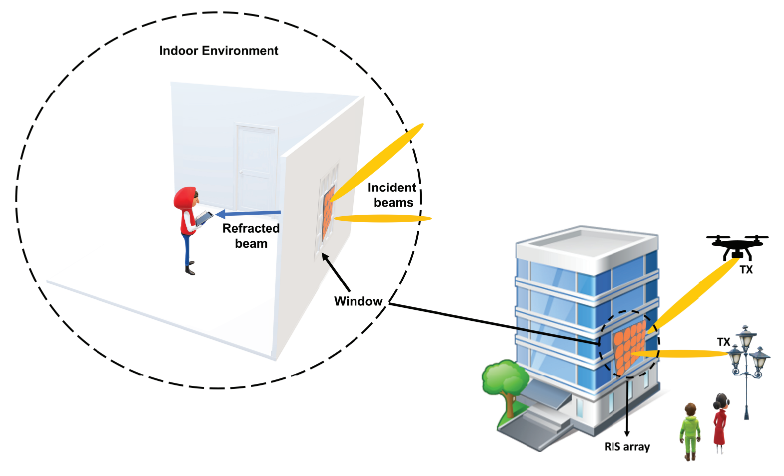

FIGURE 3. Illustration for RIS-assisted outdoor-to-indoor VLC link, where STAR-based RIS arrays installed on room window supports data transmission from the VLC Txs located in outdoor environment to indoor users.

On the other hand, the high mobility of the VLC Txs and/or Rxs in V2X scenarios could lead to link impairments due to factors such as LOS blocking and misalignment between the Txs and Rxs. Here, the link distances and the speed of the vehicles should be taken into consideration while choosing the type RIS elements considered (i.e., specular or diffuse reflecting RISs).

Mitigating Link Obstruction: The VLC-based links between vehicles located at intersecting roads may be obstructed by buildings or roadside infrastructures. Here, the use of RIS arrays installed at road intersections can facilitate the reflection of the signals to ensure robust non-LOS VLC links between the vehicles. Figure 4a illustrates an example of using RIS arrays to support V2V VLC links at road intersections.

Minimizing Impacts of Link Misalignment: Due to the constraints on the beam width of the vehicle head and tail lights, the limited FOV of the PDs, and the high mobility of the Txs and Rxs, the VLC-based V2V links are prone to link misalignment in various situations (e.g., parallel vehicles). The use of RIS arrays installed on roadside infrastructures or building facades can help in ensuring the connectivity in these cases, by reflecting the incident signals toward the vehicles located outside the coverage area of the VLC Txs. Figure 4b presents an example of the utilization of RISs to extend the coverage of a VLC Tx in the form of vehicle head light, where the link rely on the optimization of an RIS array installed on a streetlight for directing the incident signals arriving from one vehicle towards the other vehicle.

Supporting Multi-Hop Communications: The use of VLC could support vehicles platooning to ensure V2X link robustness against jamming and interference, as well as facilitating connectivity between vehicles in tunnels. The reliance on RISs can facilitate information exchange among platoon members. In addition, it can assist the communication, localization, and handover for vehicles entering and exiting the tunnels. In general, the use of RISs could support data forwarding

The deployment of RIS arrays in outdoor areas to support streetlight-based VLC can help in enhancing link performance by providing additional non-LOS paths between Txs and Rxs.

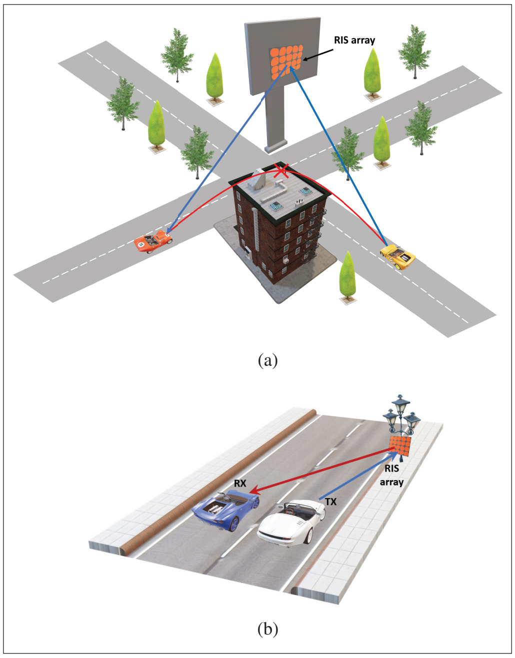

FIGURE 4. RIS-assisted V2X VLC realized a) between vehicles located at road intersections; and b) between parallel vehicles.

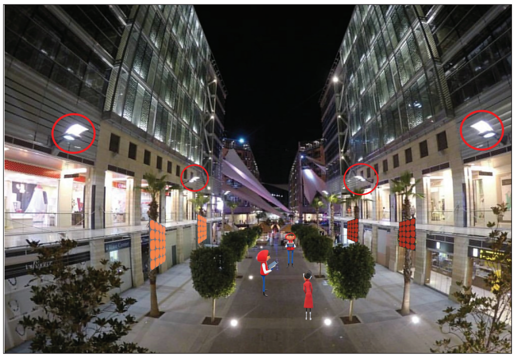

FIGURE 5. Walkway scenario in which the LED-based streetlights can be used as VLC APs, and RIS arrays can be installed on the palm trees to assist the wireless data transfer.

through multi-hop communications over long distances, especially for delay-tolerant applications, which could help in assisting communications in cases of dense intersections.

Streetlight-Based VLC

The growing interest in replacing the incandescent and fluorescent light bulbs by LED-based lightings, due to their advantages that include higher energy efficiency, has been encouraging their use in streetlights [1]. Here, the dependency on VLC could enable exploiting the large numbers of existing streetlights to support simultaneously the illumination purposes as well as the wireless data transfer in outdoor scenarios. The use cases include providing wireless coverage for pedestrians and vehicles as well as supporting the outdoor-to-indoor communications. On the other hand, the mobility of the Rxs could result in LOS link obstruction and misalignment. The deployment of RIS arrays in outdoor areas to support streetlight-based VLC can help in enhancing link performance by providing additional non-LOS paths between Txs and Rxs. An example of the use of RISs in streetlight-based VLC networks is presented in Fig. 5, where the streetlights on the sidewalk act as VLC APs.

Performance Evaluation

In this part, we highlight the outdoor VLC system performance in the presence of RISs by evaluating the link outage ratio in RIS-assisted streetlight-based and UAV-based VLC networks. Note that, considering the other outdoor VLC applications discussed in the previous section might involve distinct setups, channel models, and constraints, leading to varying numerical outcomes. Thus, the considered numerical evaluation serves as an illustration rather than a comprehensive evaluation of all the considered outdoor VLC scenarios. However, the fundamental impact of utilizing RISs is expected to remain consistent.

Multiple LED-based Txs mounted on streetlights and UAVs are considered as APs while specular reflecting RISs are placed at the roadside infrastructure. In general, the use of specular reflecting RISs (here in the form of mirrors with controllable orientation) offer advantages in terms of higher received signal intensities compared to diffuse reflecting RISs, at the cost of higher alignment requirements given the scattering of the beams in the communications environment by the diffuse reflecting RISs [12]. Compared to refracting RISs, reflecting RISs offer less deployment complexity, given their possible placement on one of the sides of the communications environment, in contrary to refracting RISs that require placement at certain locations to enable the incidence of sufficient amount of light and efficient pointing of the refracted beams towards the user devices [10]. Compared to metasurface-based RISs, given the current advancements in material science, reflecting RISs offer less realization complexity, as the RIS arrays can be constructed using off-the-shelf components such as mirrors [13]. For streetlight and UAV networks, 5 m × 5 m and 20 m × 20 m outdoor scenarios are considered, with APs at heights of 3 and 10 m, respectively, providing downlink data transmission for five users. Square RIS arrays are assumed, and the size of each RIS element is 10 cm × 10 cm with a 5 cm displacement between elements. Random Rx locations and orientations are considered following the model and the configuration in [12], with Rx height of 0.85 m. The transmit optical power by the APs are 1 W and 10 W in cases of streetlights and UAVs, respectively, while the system bandwidth, Rx FOV, and PD responsivity are considered to be 10 MHz, 60°, and 0.4 A/W, respectively. The noise power spectral density is 10^{-21} A^2/Hz while assuming the operation of APs at night time. Channel state information (CSI) estimation can be achieved using pilot symbols transmitted by the APs while using infrared-based links for uplink transmission [12].

We consider the models used in [12], where each RIS element is assumed to be associated with one Tx and one Rx at a time, which necessitates solving an association problem for choosing the Tx and Rx served by each RIS element [12]. The link outage ratio is evaluated by assessing the user achievable throughput, so that a user will be considered in outage if its achievable throughput drops below a threshold of 10 Mbps. The fitness function considered in the optimization problem target maximizing the fairness across all the user channel gains, which is calculated using Jain's fairness index [12], to ensure uniform network performance.

To solve the association problem, we consider optimizing the RISs using genetic algorithm (GA), given its robustness in handling integer-based non-convex optimization problems, and the combinatorial nature of the association problem in case of specular reflecting RISs, as shown in [12]. Given the stochastic nature of GA, the population size and number of generations are selected to be 200, driven by preliminary simulations that targeted balancing the computational efficiency with convergence to reliable solutions, to effectively generalize the algorithm applicability to random scenarios. Although we set the number of generations to 200, it is important to note that the GA often does not reach this limit due to implementing a convergence criterion based on fitness function tolerance. Specifically, we have set a maximum fitness function tolerance of 10^{-6}, so that the algorithm terminates prematurely if the change in the fitness value does not exceed the tolerance. This dynamic stopping criterion ensures computation efficiency without compromising the solution quality. For benchmarking, firstly we consider RIS element assignment to associate the Tx and Rx closest in distance to the RIS element to maximize sum-rate, which we refer to as min-distance algorithm. Secondly, we consider assigning each RIS element to associate the nearest Tx with the Rx that has the lowest LOS channel gain, which we refer to as the min-LOS algorithm. The results are compared with case of considering LOS only.

Figures 6a and 6b illustrate the convergence analysis for cases of streetlights and UAVs, respectively. In general, the curves reveal two key insights; (i) the rate of convergence to optimized solutions varies depending on the considered optimization problem, and (ii) the algorithm can often reach an optimized solution in a fraction of the initially considered number of generations.

Figures 6c and 6d show a comparison in terms of link outage ratio over different RIS array sizes between the cases of considering LOS only, RIS optimization using GA, and RIS elements association via the min-distance and min-LOS algorithms. The performance was averaged over 1000 random realizations. The results show higher link outage ratios in cases of UAVs compared to cases of streetlights due to the increase in AP heights and coverage area. Also, as expected, the link outage ratio improved with the presence of RISs due to the introduced spatial diversity in the system. In addition, the link outage ratio decreased by increasing the number of RIS elements as each RIS element provides an additional non-LOS path for the link between the associated Tx and Rx. It is noted that the min-LOS algorithm outperforms the min-distance algorithm due to the higher probability of directing the incident transmission towards Rxs in outage (i.e., due to low channel gains). Also, using GA optimization provides better performance compared to the min-distance and min-LOS algorithms since it targets increasing the homogeneity between the user channel gains to maximize fairness; hence, reducing the probability that a user achievable throughput falls below the outage threshold rate.

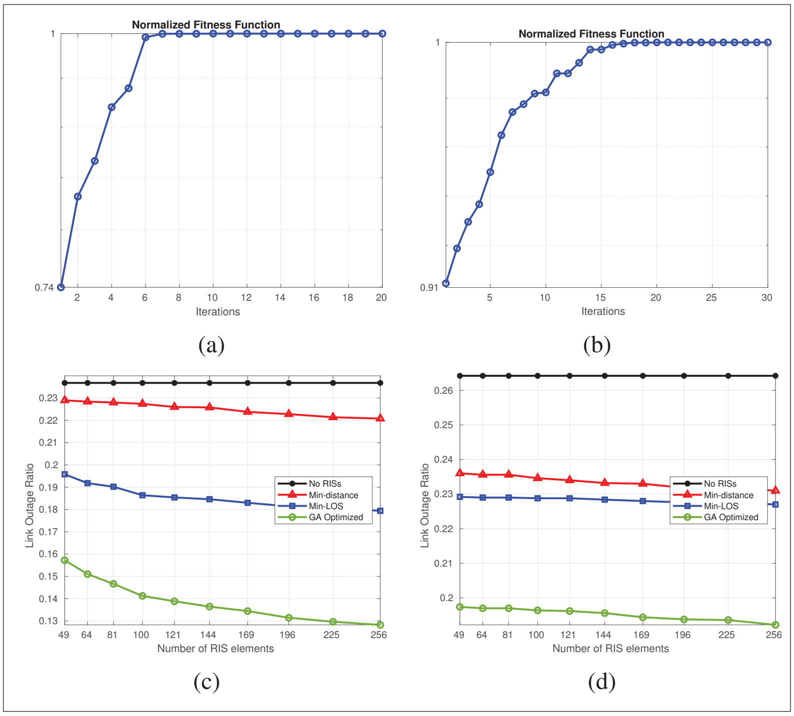

FIGURE 6. Performance evaluation: convergence analysis for cases of: a) streetlight-based and b) UAV-based networks, at (x, y) random Rx locations of (0.39, 0.06), (4.01. 4.07), (1.74, 3.24), (0.25, 3.73), (1.05, 4.18) m; and link outage ratio for (c) streetlight-based and (d) UAV-based networks, averaged over 1000 random realizations. APs are located at (x, y) locations of (1.5, 0), (3.5, 0), (1.5, 5), and (3.5, 5) in case of streetlights and at (5, 5), (15, 5), (5, 15), and (15, 15) in case of UAVs. The RIS array is centred at (2.5, 0) and (10, 0), at heights of 1.5 and 2.5 m for cases of streetlights and UAVs, respectively.

Challenges and Directions for Future Research

Channel Modeling and Characterization

Enabling reliable system design and performance analysis of the RIS-assisted VLC systems mandates accurate characterization of the channel. However, considering RISs in outdoor scenarios brings unique challenges for the VLC channel modeling due to factors such as the mobility of the Txs and Rxs, the considerable impact of the atmospheric conditions on the system performance, and the link performance degradation due to ambient lights. Therefore, accounting for inaccurate/outdated CSI as well as the effects of atmospheric conditions such as fog, haze, snow, and rain in channel modeling could allow efficient design of the RIS arrays.

Hybrid Designs of RIS Arrays

The differences in the characteristics of the RIS elements that can be used in VLC systems opens the door for designing RIS arrays comprising different types of elements to target improving different performance metrics. In general, the use of specular reflecting RIS elements would target enhancing the received VLC signal intensity, while the dependence on diffuse reflecting RIS elements could support the user mobility by relaxing the link alignment requirements.

The use of RIS elements with capabilities to reflect the RF transmission along with optical RISs opens the door for supporting hybrid VLC/RF transmissions using the same RIS array.

Conclusions

This work discussed the use of the RISs in outdoor VLC scenarios. It started with presenting a classification for the RIS types according to how they direct the incident signals. Following this, it illustrated the use of RIS arrays for supporting the UAV networks by minimizing the impact of link blockage, extending link coverage, and enabling inter-UAV communications. In addition, the use of RIS for supporting outdoor-to-indoor communications was proposed, before discussing the use of RISs to facilitate the V2X communications, by minimizing the effects of link misalignment and the limited coverage area of the Txs. Moreover, the use of RISs to support the streetlight-based VLC was discussed, before highlighting using simulations the impact of optimizing the RIS array on the streetlight-based and UAV-based systems performance. Finally, it discussed possible directions for future research.

By benefiting from the already-existing infrastructure, obtaining user position data in future works could rely on (i) VLC positioning technologies, especially in cases where the LED lightings (i.e., APs) are oriented towards the ground user devices; (ii) RF-based systems, given the use of VLC to address the challenges associated with RF spectrum congestion; and (iii) camera-based and radar-based surveillance systems. In general, as specular reflecting RISs require precise CSI and continuous alignment with the users, future works may consider diffuse reflecting RISs in applications involving high mobility and/or inaccuracy in locating receivers [12], such as V2X applications, as they have less stringent alignment requirements.

References

[1] A. R. Ndjiongue and H. C. Ferreira, "An Overview of Outdoor Visible Light Communications," *Trans. Emerging Telecommunications Technologies*, vol. 29, 2018, no. 7, e3448.

[2] G.-Y. Lin *et al.*, "On Advanced Relay Schemes to Support Throughput-Hungry IoT Applications," *IEEE Internet of Things Magazine*, vol. 6, 2023, no. 3, pp. 20–24. DOI 10.1109/IOTM.001.22002358.

[3] H. B. Eldeeb *et al.*, "Energy and Spectral Efficiency Analysis for RIS-Aided V2V-Visible Light Communication," *IEEE Communications Letters*, vol. 27, 2023, no. 9, pp. 2373–77. DOI 10.1109/LCOMM.2023.3290025.

[4] Y. Cang *et al.*, "Joint Deployment and Resource Management for VLC-Enabled RISs-Assisted UAV Networks," *IEEE Trans. Wireless Commun.*, posted on 2022, p. 1-1. DOI 10.1109/TWC.2022.3165853.

[5] S. Aboagye *et al.*, "RIS-Assisted Visible Light Communication Systems: A Tutorial," *IEEE Commun. Surveys & Tutorials*, vol. 25, 2023, no. 1, 251–88.

[6] A. M. Abdelhady *et al.*, "Visible Light Communications via Intelligent Reflecting Surfaces: Metasurfaces vs. Mirror Arrays," *IEEE Open J. Commun. Society,* vol. 2, 2020, pp. 1–20.

[7] S. Aboagye *et al.*, "Liquid Crystal-Based RIS for VLC Transmitters: Performance Analysis, Challenges, and Opportunities," *IEEE Wireless Commun.*, posted on 2023, pp. 1–8. DOI 10.1109/MWC.002.2300041.

[8] E. Xie *et al.*, "Over 10 Gbps VLC for Long-Distance Applications Using a GaN-Based Series-Biased Micro-LED Array," *IEEE Photonics Technology Letters*, vol. 32, 2020, no. 9, pp. 499–502, DOI 10.1109/LPT.2020.2981827.

[9] M. Sufyan Islim *et al.*, "The Impact of Solar Irradiance on Visible Light Communications," *Journal of Lightwave Technology*, vol. 36, 2018, no. 12, pp. 2376–86. DOI 10.1109/JLT.2018.2813396.

[10] A. R. Ndjiongue *et al.*, "Double-Sided Beamforming in VLC Systems Using Omni-Digital Reconfigurable Intelligent Surfaces," *IEEE Commun. Mag.*, posted on 2023, pp. 1–7. DOI 10.1109/MCOM.002.2300043.

[11] V. Jamali *et al.*, "Intelligent Reflecting Surface Assisted Free-Space Optical Communications," *IEEE Commun. Mag.*, vol. 59, 2021, no. 10, pp. 57–63. DOI 10.1109/MCOM.001.2100406.

[12] S. Abdeljabar *et al.*, "Sum Rate and Fairness Optimization in RIS-Assisted VLC Systems," *IEEE Open J. Communications Society*, vol. 5, 2024, pp. 2555–66. DOI 10.1109/OJCOMS.2024.3389093.

[13] Q. Zhang *et al.*, "Hardware Implementation of A Mirror Array-Based Optical Intelligent Reflecting Surface for VLC: Prototype and Experimental Results," *Optics Express,* vol. 32, 2024, no. 11, 19,252–64.

[14] N. Sun *et al.*, "Self-Alignment FSOC System With Miniaturized Structure for Small Mobile Platform," *IEEE Photonics Journal*, vol 14, 2022, no. 6, pp. 1–6. DOI 10.1109/JPHOT.2022.3193112.

[15] M. Ali Jamshed *et al.*, "Synergizing Airborne Non-Terrestrial Networks and Reconfigurable Intelligent Surfaces-Aided 6G IoT," *IEEE Internet of Things Mag.*, 2024, no. 2, 4pp. 6–52. DOI 10.1109/IOTM.001.2300242.

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