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Resource allocation exploiting reflective surfaces to minimize the outage probability in VLC

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Abstract—Visible light communication (VLC) is a technology that complements radio frequency (RF) to fulfill the ever-increasing demand for wireless data traffic. The ubiquity of light-emitting diodes (LEDs), exploited as transmitters, increases the VLC market penetration and positions it as one of the most promising technologies to alleviate the spectrum scarcity of RF. However, VLC deployment is hindered by blockage causing connectivity outages in the presence of obstacles. Recently, optical reconfigurable intelligent surfaces (ORISs) have been considered to mitigate this problem. While prior works exploit ORISs for data or secrecy rate maximization, this paper studies the optimal placement of mirrors and ORISs, and the LED power allocation, for jointly minimizing the outage probability while keeping the lighting standards. We describe an optimal outage minimization framework called JOINTMINOUT and present solvable heuristics. We provide extensive numerical results and show that the use of ORISs may reduce the outage probability by up to 67% with respect to a no-mirror scenario and provide a gain of hundreds of kbit/J in optical energy efficiency with respect to the presented benchmark.

Index Terms—Line-of-sight (LoS) link blockage, mirrors, optimal placement, outage probability, optical reconfigurable intelligent surfaces (ORIS), visible light communication (VLC).

I. INTRODUCTION

VISIBLE light communication (VLC) has recently emerged as a technology to complement traditional radio-frequency (RF) in the mission of satisfying the ever-increasing demand for wireless data traffic. RF resources are becoming crowded and fragmented, and the research community is looking for alternatives to meet the requirements beyond 5G. VLC presents unique characteristics such as unused and unlicensed bands, off-the-shelf elements, higher security in the physical layer due to a better signal containment, and a ubiquitous light-emitting diode (LED)-based lighting infrastructure to exploit for communications [1]. The first VLC-related standards were published by ITU-T [2] and IEEE [3] [4], but VLC industrialization efforts have only been addressed in the recently published IEEE 802.11bb standard [5], where VLC

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has been brought into the WiFi ecosystem to push its mass market adoption. Even so, VLC still presents severe issues that prevent it from a massive adoption, among which are link blockages causing connectivity outages in the presence of obstacles that make VLC unreliable [6]. Prior works show that this issue can be partially solved by cooperative techniques [7] or relaying schemes [8], leveraging the high reuse factor of resources when operating in very small cells (usually referred to as atto-cells) created by VLC when it is integrated as a cellular network [9]. In this work we exploit reflective surfaces and optimize resource allocation to minimize the outage probability in VLC.

Reconfigurable intelligent surfaces (RISs) have been studied in RF for short distances employing millimeter and sub-millimeter waves [10], [11], and for long distances employing lower frequencies [12]. RIS can be managed dynamically, and it is foreseen to be one fundamental pillar of 6G networks [13], [14]. It has emerged as a solution to the skip-zone problem in RF [15]. However, although link blockage is one of the main drawbacks of VLC, we can only find a few studies of optical RIS (ORIS) in the VLC literature [16]. Unlike RIS systems in RF, ORIS-assisted VLC systems do not suffer from small scale fading as the system uses intensity modulation with direct detection (IM/DD), and the detection area is very large compared to the optical wavelength. That is, while RIS in RF must pay special attention to the phase of each element in the RIS matrix to achieve the largest gain, ORIS must focus on forwarding the impinging light power to the right direction [17]. Therefore, RIS-assisted RF studies cannot be directly adapted to VLC systems.

ORISs have been proposed to engineer non-line-of-sight (NLoS) paths in VLC and then to enhance its wireless communication capability. Recent research in ORIS-assisted VLC includes indoor [18], [19], free space [20], [21], vehicular [22] and unmanned aerial vehicle [23] applications. Published works have addressed channel modeling in ORIS-aided VLC systems in the time-domain [24] and in the frequency-domain [17]. Two types of ORIS have been proposed in the literature: metasurfaces and mirrors. The former is based on the meta-atom geometry and can actuate over the wavelength, amplitude, and polarization of the light signal, among others. The latter is based on Snell's law to modify the reflection angle by changing the mirror orientation. Although metasurfaces show a great potential as ORIS in VLC, deployed on walls and to improve the receiver performance [25]–[28], few products can be found on the market. The excellent reflection performance of mirrors, together with the recent progress in micro-electromechanical systems (MEMS) used to manage mirror orientation, position mirrors as an imminent

ORIS material of choice for VLC [29].

Few works invoking mirrors as ORIS in VLC systems can be found in the literature: [30] and [31] proposed a rate maximization problem to determine the optimal orientation of the mirror array elements and the association between light source and mirror to strengthen the NLoS link; the authors in [18] maximized the overall spectral efficiency by optimizing the user association and power allocation; other recent works studied the secrecy rate [32], [33]; and [19] proposed an optimal mirror placement to maximize the illumination uniformity, and then associated users and LEDs to maximize the minimum signal-to-interference-plus-noise power ratio (SINR).

In this paper, we refer to *mirrors* when they are static and flat against the wall, and *ORISs* when installed into MEMS structures to provide them with a mobile orientation. We evaluate both options to minimize the outage probability in an indoor VLC scenario by jointly optimizing the optical power allocated per LED and the number and location of mirrors (or ORIS). As this is a difficult problem, we target the theoretical limit of the outage probability in our study by limiting our analysis to a single user. We consider any user location and orientation by uniformly distributing a single user and analyzing the frequency of occurrence for each optimal mirror placement. Note that this is key in the design of a mirror- or ORIS-aided VLC scenario, as the installation of mirrors and ORIS elements is fixed; changing the mirrors and ORIS elements placement for each case (user position and orientation) is not practical. Thus, the mirrors or ORIS elements placement should be optimized such that their contribution is maximized. We name our optimization problem JOINTMINOUT.

Despite the fact that outage is one of the biggest problems in VLC, this is, to the authors' knowledge, the first work that considers reflective surfaces to minimize the outage probability. We build upon our prior work where we simplified the scenario to a single serving LED for each user and considered only those users with a line-of-sight (LoS)-link blocked [34]. Besides, in [34], a diffuse channel path loss was generalized and illumination constraints were not considered. The main contributions of this paper are summarized as follows:

- We introduce three possible reflecting elements in a room: wall, mirror, and ORIS, and we explain the fundamentals of their diffuse and specular reflections. In our system, we do not have a pre-established mirror/ORIS structure, but we optimize the number of mirror/ORIS elements and their location. We show that diffuse wall reflections cannot be ignored, as done in prior ORIS-assisted VLC works. Besides, we show that NLoS contributions from mirrors/ORISs can be even larger than the LoS.
- We compare the coverage that mirror and ORIS approaches can achieve, and we derive equations to evaluate such coverage in both cases. We show that the furthest user location to be supported by a mirror depends on the LED position and the field of view (FoV) semi-angle of the receiver, whereas it only depends on the FoV semi-angle in the ORIS case.
- We formulate our JOINTMINOUT optimization problem to minimize the outage probability while minimizing one

of the two available resources, the number of mirrors (or ORISs) and the total optical power allocated among LEDs. Unlike [34], we consider a scenario where all LEDs distributed in the room may contribute to the same user. We introduce communication and illumination constraints and re-formulate them to be solved by common convex optimization (CVX) tools. Then, we propose two single-objective functions leading to two solution approaches.

- The resulting problems are NP-complete, and we propose an alternating optimization heuristic algorithm to solve them. The results are compared with a non-alternating heuristic algorithm as a benchmark and a no-mirror scenario.
- We offer some insights on deploying the mirrors or ORISs to minimize the outage probability. Simulation results show that mirrors or ORISs, if optimally located along the wall, can reduce the outage probability up to 67% compared to a no-mirror scenario, as well as providing considerable optical energy efficiency gains while keeping a low complexity profile.

The structure of the paper is as follows. Section II introduces the system model, including LoS and NLoS channel gains for every reflector type, a comparison between mirror and ORIS performance, and the figures of merit used in this paper. Section III formulates the optimization problem. The algorithms proposed to solve the optimization problem are presented in Section IV, and detailed results and discussions are contained in Section V. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

The considered indoor VLC scenario has L LEDs distributed in the room, denoted by $l = \{0, \dots, L-1\}$. All LEDs may contribute to the same user, i.e., they cooperate to transmit the same information to the user. LEDs are modeled as point sources due to their small dimensions, and detectors are small enough to not perceive irradiance variations along their surface. Then we can also assume single-point detectors. In this paper, we study a single user whose location is uniformly distributed inside the room. Multiple users could be easily served invoking multiple access techniques such as time-division multiple access. We assume that the user equipment and LED are looking upwards and downwards, respectively. The communication performance relies on LoS and NLoS links defined as follows.

A. LoS channel gain

The LoS channel gain from LED l to the user follows a Lambertian emission model as [35]

$$H_l^{\text{LoS}} = \begin{cases} \frac{(m+1) \cdot A_{\text{PD}}}{2\pi d_l^2} \cos^m(\phi_l) \cos(\varphi_l) & 0 \leq \varphi_l \leq \Psi \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

where $m = -1/\log_2(\cos(\phi_{1/2}))$ is the Lambertian index of the LED that models the radiation pattern defined by its half-power semi-angle $\phi_{1/2}$. The parameter A_{PD} stands for the active photodetector (PD) area, d_l is the Euclidean distance between LED l and the user, and ϕ_l and φ_l are the irradiance and incidence angles, respectively, as represented in Fig. 1a. The FoV semi-angle of the PD is denoted by Ψ .

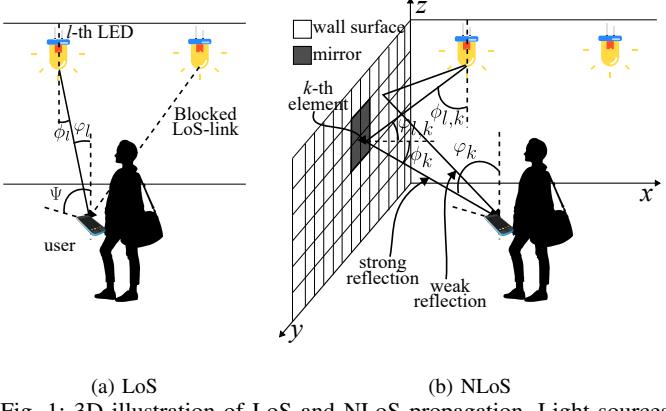


Fig. 1: 3D illustration of LOS and NLOS propagation. Light sources are located on a horizontal plane on the ceiling of the room.

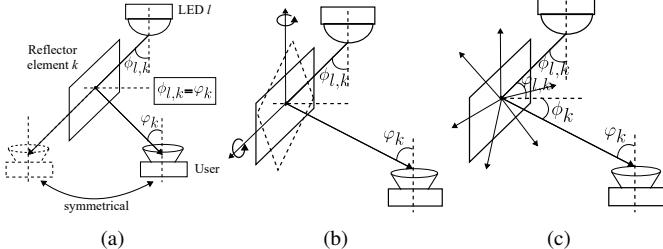


Fig. 2: Three types of reflecting surfaces considered: (a) mirror (specular channel), (b) mobile mirror = ORIS (specular channel), and (c) wall (diffuse channel).

B. NLoS channel gain

The NLoS channel in VLC can be composed of specular and diffuse reflections. Specular reflections refer to those that follow a unique direction; the main losses occur due to the medium absorption. The primary specular reflectors in VLC are mirrors. Differently, diffuse reflections occur when the reflector does not present a homogeneous surface and, when light impinges onto it, the light scatters in multiple directions, producing a considerable power loss when targeting one specific receiver.

In this paper, we consider that each wall is divided into a grid of $K_y \times K_z = K$ elements, denoted by $k = \{0, \dots, K-1\}$ as represented in Fig. 1b. Each element is either selected as a mirror surface or as a standard wall material. Within the mirror category, this can be: (1) installed in a MEMS structure to create a mobile mirror, which we here refer to as an ORIS; or (2) installed following the wall orientation without mobility, which we simply refer to as a mirror. These two mirror surfaces, together with the wall surface, are depicted in Fig. 2. We assume that blockage between reflectors is negligible. The NLoS channel gain produced by each is detailed in the following:

1) Mirror reflection (specular): The planar surface reflects the incident light with the same angle, following Snell's law of reflection [36], due to its static and flat-against-the-wall placement. Since the mirror orientation is fixed, the irradiance angle from LED l to the mirror reflecting point k ($\phi_{l,k}$) equals the incident angle from the reflecting point k to the PD (φ_k). The NLoS channel gain produced by a mirror can be modeled as [29]

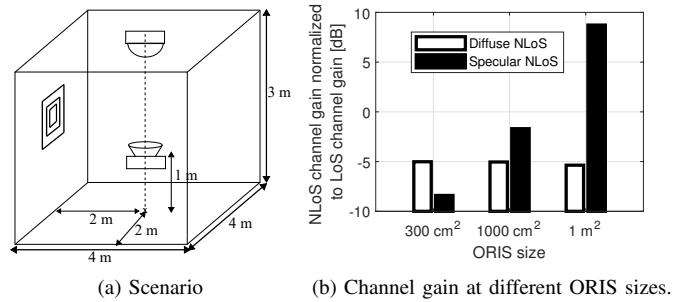


Fig. 3: Comparison between diffuse and specular (ORIS) contributions with respect to LoS contribution.

$$H_{l,k}^{\text{mirror}} = \begin{cases} \hat{r} \cdot \frac{(m+1) \cdot A_{\text{PD}}}{2\pi(d_{l,k} + d_k)^2} \cos^{m+1}(\phi_{l,k}) & 0 \leq \varphi_k \leq \Psi \text{ \&} \\ & \varphi_k = \phi_{l,k} \text{ at some point in element } k, \\ 0 & \text{otherwise,} \end{cases} \quad (2)$$

where \hat{r} stands for the reflection coefficient of a specular surface (e.g. mirror or ORIS), $d_{l,k}$ and d_k are the Euclidean distance from LED l to reflector element k , and from reflector element k to the user, respectively. Note that a specular reflection is equivalent to considering a user positioned at the image point, where the total distance is the sum of the two distances in the path LED→mirror→user, as represented in Fig. 2a.

2) *Mobile mirror (ORIS) reflection (specular)*: In this case the channel model can be formulated as [29]

$$H_{l,k}^{\text{ORIS}} = \begin{cases} \hat{r} \cdot \frac{(m+1) \cdot A_{\text{PD}}}{2\pi(d_{l,k} + d_k)^2} \cos^m(\phi_{l,k}) \cos(\varphi_k) & 0 \leq \varphi_k \leq \Psi \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

Due to its installation into a MEMS structure, the ORIS orientation mobility controls the reflected path direction, as shown in Fig. 2b, so that the impinging light power is forwarded to the direction where the user is located.

3) *Wall reflection (diffuse)*: As Fig. 2c shows, the light impinging onto a wall surface is reflected in multiple directions. The channel gain can be modeled as [37]

$$H_{l,k}^{\text{wall}} = \begin{cases} \tilde{r} \cdot \frac{(m+1)A_{\text{PD}}}{2\pi d_{l,k}^2 q_k^2} A_k \cos^m(\phi_{l,k}) \cos(\varphi_{l,k}) \cos(\phi_k) \cos(\varphi_k) & 0 \leq \varphi_k \leq \Psi \\ 0 & \text{otherwise,} \end{cases} \quad (4)$$

where \tilde{r} is the reflection coefficient of the wall surface element k with area A_k . The angles $\varphi_{l,k}$ and ϕ_k stand for the incident and irradiance angles in the surface element k , respectively. In contrast to the specular reflection, it is worth noticing that the distances are multiplied instead of added (see denominators in (2), (3) and (4)).

Prior literature has demonstrated that, in an ORIS-aided VLC scenario, the diffuse contribution is negligible in comparison to the specular NLoS contribution and, consequently, only the specular NLoS reflections are considered [18]. However, this is not true for a small number of ORIS elements that create a small ORIS total size. Consider a scenario with the geometry represented in Fig. 3a, where there is a single LED and a user, both located in the middle of the room. The parameters are $\phi_{1/2} = 80^\circ$, $A_{PD} = 1\text{ cm}^2$, $\tilde{r} = 0.2$, $\hat{r} = 0.99$ and the size of every ORIS element is $0.13 \times 0.2\text{ cm}^2$. Fig. 3b plots

the channel gain contributions from the diffuse and specular reflections, both normalized to the LoS gain, when the ORIS have different total sizes. When the ORIS is small, the diffuse contribution is larger than the specular one, though the latter overcomes the diffuse one quickly as the total ORIS size increases. The specular reflection becomes even larger than the LoS contribution when the total ORIS size is large. In this paper, we aim to study the number and location of ORIS and mirror elements to obtain a minimum outage probability. This means that we are not setting up an ORIS structure by default that may be large enough so that the diffuse contributions may be disregarded. Therefore, in our study we must consider both diffuse and specular reflections.

The second observation one can make from Fig. 3b is that the NLoS contributions are no longer negligible, as the NLoS gain can be significantly larger than the LoS gain in an ORIS-enhanced system. This is different from a non ORIS-aided VLC scenario, in which NLoS contributions have been typically disregarded when a LoS link exists [38].

C. Overall VLC channel gain

We model the reflector element placement with a binary variable $\beta_{l,k} \in \{0, 1\}$, $\forall l = 0, 1, \dots, L-1$, $\forall k = 0, 1, \dots, K-1$. The variable $\beta_{l,k}$ associates the LED l with the reflector element k to contribute to the user. It takes a value of 1 when the element k is a specular reflector (ORIS or mirror), and a value of 0 when it is a diffuse reflector (wall). The NLoS channel gain from LED l generated by the reflector element k is thus formulated as

$$H_{l,k}^{\text{NLoS}}(\beta_{l,k}) = H_{l,k}^{\text{wall}} + (H_{l,k}^{\text{spec}} - H_{l,k}^{\text{wall}}) \cdot \beta_{l,k} \quad (5)$$

where the specular reflector can be either an ORIS or a mirror whose NLoS channel gain is defined as

$$H_{l,k}^{\text{spec}} = \begin{cases} H_{l,k}^{\text{ORIS}} & \text{if the specular reflector is an ORIS} \\ H_{l,k}^{\text{mirror}} & \text{if the specular reflector is a mirror.} \end{cases} \quad (6)$$

Due to the intrinsic characteristic of specular reflections, every single element k can forward the light power of at most a single LED, i.e.,

$$\sum_l \beta_{l,k} \leq 1, \forall k. \quad (7)$$

Then, the overall VLC channel gain from LED l to the user can be formulated as

$$H_l(\beta_{l,k}) = I_l \cdot H_l^{\text{LoS}} + \sum_k I_{l,k} \cdot H_{l,k}^{\text{NLoS}}(\beta_{l,k}), \quad (8)$$

where I_l and $I_{l,k}$ are Boolean variables that take a value of 0 when the LoS link from LED l or NLoS link from LED l passing through reflecting element k are blocked, respectively, and 1 otherwise. Blockage may be generated by the user's own body (self-blocking), by other users, or by the presence of static objects such as furniture, pillars, etc. Therefore, the design of the reflector placement and the LED-reflector association denoted by $\beta_{l,k}$ are key to the system performance.

D. Mirror vs. ORIS NLoS contribution

It is well known that an ORIS, due to its mobile orientation, potentially provides a greater communication performance than what a conventional mirror may achieve. This performance directly depends on the emission pattern of the LED,

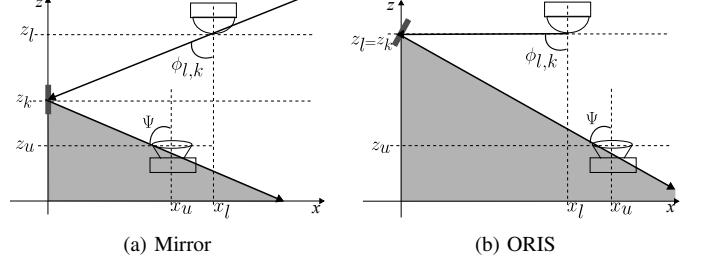


Fig. 4: Geometrical graphs of maximum distances reached by mirror and ORIS.

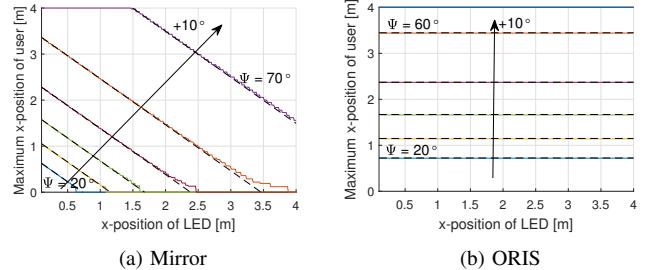


Fig. 5: How Ψ influences the maximum distance with respect to the wall where a user can be located to receive a NLoS contribution from a mirror or an ORIS. Parameters considered are $z_u=1$ m and $z_l=3$ m. Solid colored line: Simulation. Dashed black line: theoretical (10) and (11) for mirror and ORIS, respectively.

which is defined by its half-power semi-angle ($\phi_{1/2}$), in addition to the PD FoV semi-angle (Ψ) and the geometry of the scenario. For illustrative purposes, let us consider a 2D scenario with a single LED and a user's PD located at coordinates $\{x_l, z_l\}$ and $\{x_u, z_u\}$, respectively. All reflecting elements are installed in one wall and the location of the k -th reflecting element is determined by the coordinates $\{0, z_k\}$. The mirror and ORIS 2D geometric scenarios are depicted in Fig. 4.

In the case of a mirror, the maximum horizontal distance from the wall, x_u , that a user may occupy and still see the reflection is limited by the PD FoV semi-angle. According to (2), a non-zero NLoS mirror channel gain occurs when irradiance angle from LED l to k and incidence angle in the PD are the same. In the extreme case where the user is as far away from the wall as possible, we have $\Psi = \phi_{l,k}$. The shadowed area in Fig. 4a is where the user could be located to receive a NLoS contribution from a mirror. The area is limited by

$$z < -\tan\left(\frac{\pi}{2} - \Psi\right) \cdot x + z_k. \quad (9)$$

Substituting $z_k = z_l - x_l / \tan \Psi$ in (9), we can formulate the maximum user distance as

$$x_{u,\max} = \frac{z_u + \frac{x_l}{\tan \Psi} - z_l}{-\tan\left(\frac{\pi}{2} - \Psi\right)}. \quad (10)$$

Note that the maximum horizontal distance with respect to the wall for the user so that it can receive contributions from the mirror depends on the PD height (z_u), the LED location $\{x_l, z_l\}$ and the PD FoV semi-angle (Ψ).

Differently, in the case of an ORIS, since the mirror can be optimally oriented, the maximum horizontal distance, x_u , that a user may occupy and still receive some reflection is limited by the location of the highest ORIS, which is the location making φ_k the smallest. In the most extreme case, we consider that ORIS elements may be placed as high as the ceiling. Then, the maximum x distance from the wall where the user could

receive a contribution from such ORIS is such that $\varphi_k = \Psi$, and it is formulated as

$$x_{u,\max} = (z_l - z_u) \cdot \tan \Psi. \quad (11)$$

The shadowed area in Fig. 4b is the one where the user could be located to receive a NLoS contribution from an optimally oriented ORIS. Note that, unlike the mirror case, the maximum wall-user distance does not depend on the LED horizontal location (x_l) and thus, an ORIS can potentially cover a much larger area than a conventional mirror.

1) *Influence of FoV semi-angle (Ψ)*: Let us consider a scenario where the user and LED are located at a height of $z_u = 1\text{ m}$ and $z_l = 3\text{ m}$, respectively. The FoV semi-angle can be in the range of 20° to 70° , and the LED can be located (x_l) 0 to 4 m from the wall containing the reflector. Figs. 5a and 5b plot the maximum x-position of a user ($x_{u,\max}$) for different LED positions (x_l) and FoV semi-angles (Ψ), when considering either a mirror or an ORIS as a reflecting surface, respectively. As expected from (10), the dependence of the maximum user distance on the LED's position limits the impact of using mirrors for a mirror-assisted VLC scenario. As an example, when the $\Psi = 40^\circ$, the LED position must be at least 1.5 m to support users that are located at a distance shorter than 1.5 m from the wall, and thus a very small portion of the room area may be covered. We validate this analytical result from (10) and (11) for mirror and ORIS, respectively, (dashed lines in Figs. 5a and 5b) with simulations (solid lines). These results encourage the use of ORIS elements rather than conventional mirrors whenever possible.

2) *Influence of half-power semi-angle ($\phi_{1/2}$) in the ORIS case*: Intuitively, the LED beamwidth determines the power impinging at each surface element, and then it has an effect on the NLoS contribution received by the user. Fig. 6a plots the H_{l,k^*} gain, where k^* is the reflecting element with the largest contribution and whose placement (height) is represented in Fig. 6b for $x_l = 1\text{ m}$ and $x_l = 3\text{ m}$. Note that for short x_l distances, the more directive the LED is, the better, whereas we can see the opposite effect for large x_l values. However, differences obtained in channel gains are insignificant except when the LED is very separated from the wall, for which wider LED beams are preferable. This indicates that the selection of $\phi_{1/2}$ is not that important for the communication performance relying on specular NLoS, and that the $\phi_{1/2}$ configuration must be preferably selected according to illumination constraints. In Fig. 6b, the optimal height location varies depending on $\phi_{1/2}$ and the x-position of the user, and we observe that the more directive the LED is, the lower the ORIS must be located on the wall.

E. Figures of merit

Let us define \mathbf{P} as the vector containing all P_l , $\forall l$ values, and $\boldsymbol{\beta}$ as the matrix containing all $\beta_{l,k}$, $\forall l, k$ values, respectively. Assuming that we transmit within the system bandwidth, the signal-to-noise power ratio (SNR) can be computed as

$$\gamma(\mathbf{P}, \boldsymbol{\beta}) = \frac{\left(\rho \sum_l \sum_k P_l H_l(\beta_{l,k}) \right)^2}{N_0 B}, \quad (12)$$

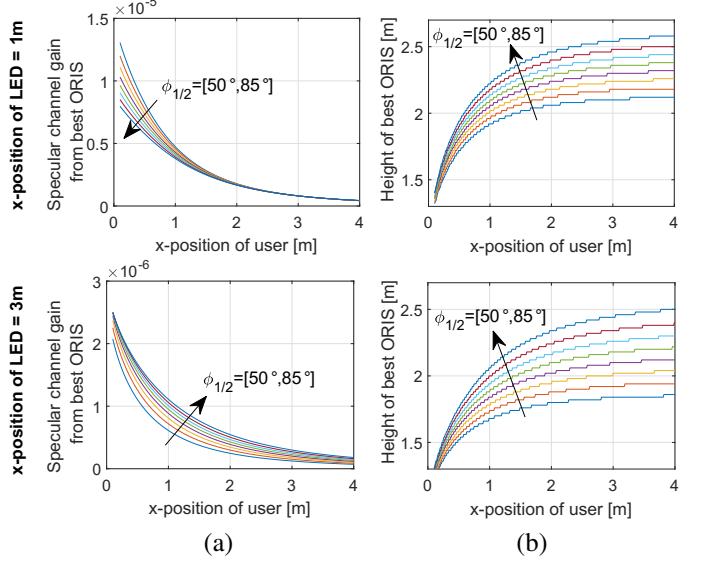


Fig. 6: How $\phi_{1/2}$ influences (a) the NLoS gain contribution and (b) the best ORIS placement for two LED placements of 1 m and 3 m from the wall containing the reflective element.

where ρ is the PD responsivity, P_l is the optical power transmitted by LED l , N_0 is the power spectral density of the additive white Gaussian noise (AWGN) at the receiver mainly produced by shot and thermal noise [37], and B is the communication bandwidth.

The *outage probability* is defined as the probability that a user has an SNR lower than the required SNR, called the SNR threshold (γ_{th}), and can be written as

$$P_{\text{out}}(\mathbf{P}, \boldsymbol{\beta}, \gamma_{\text{th}}) = \Pr\{\gamma(\mathbf{P}, \boldsymbol{\beta}) < \gamma_{\text{th}}\} = \Gamma_{\gamma_{\text{th}}}, \quad (13)$$

where $\Gamma_{\gamma_{\text{th}}}$ is the cumulative distribution function (CDF) of $\gamma(\mathbf{P}, \boldsymbol{\beta})$ evaluated at γ_{th} .

The *optical energy efficiency* is defined as the data rate (measured in bits/s) that can be transmitted per unit of power (measured in W). This is equivalent to the number of bits that can be transmitted per unit of energy (J), expressed as bit/J and, invoking the tight lower bound of VLC system capacity [39], it can be formulated as

$$\eta_{\text{opt}} = \begin{cases} \frac{\frac{B}{2} \log_2 \left(1 + \frac{\exp(1)}{2\pi} \cdot \gamma \right)}{\sum_l P_l} & \text{if } \gamma \geq \gamma_{\text{th}} \\ 0 & \text{otherwise.} \end{cases} \quad (14)$$

III. OPTIMIZATION PROBLEM FORMULATION

We aim to minimize the outage probability in a mirror- or ORIS-assisted VLC scenario while satisfying the illumination requirements in a room. For this, we propose the deployment of specular reflecting elements (mirrors or ORISs), which will allow us to understand to what extent they can enhance VLC performance.

A. Objective functions

The main goal is to minimize the outage probability defined as (13). Let us refine the CDF of the SNR as $\Gamma_{\gamma_{\text{th}}}(\mathbf{Q}) = \Pr\{\gamma[\mathbf{Q}, \mathbf{P}(\mathbf{Q}), \boldsymbol{\beta}(\mathbf{Q})] < \gamma_{\text{th}}\}$ considering a random variable \mathbf{Q} describing the user location and orientation. The random variable $\mathbf{B}_{\gamma_{\text{th}}}(\mathbf{Q})$ is an indicator function of $\gamma[\mathbf{Q}, \mathbf{P}(\mathbf{Q}), \boldsymbol{\beta}(\mathbf{Q})]$ defined as

$$B_{\gamma_{th}}(Q) = \begin{cases} 0, & \text{if } \gamma(Q, \mathbf{P}(Q), \boldsymbol{\beta}(Q)) < \gamma_{th}, \\ 1, & \text{if } \gamma(Q, \mathbf{P}(Q), \boldsymbol{\beta}(Q)) \geq \gamma_{th} \end{cases}, \quad (15)$$

where the LED distributed power \mathbf{P} and the matrix of reflector element placements $\boldsymbol{\beta}$ depend only on the user location and orientation Q . We can now redefine the outage probability in (13) as $\Pr\{B_{\gamma_{th}}(Q) = 0\} = \Pr\{\gamma(Q, \mathbf{P}(Q), \boldsymbol{\beta}(Q)) < \gamma_{th}\}$. Instead of solving this mathematically, we opt to compute a sample average that can be solved by simulations. Then,

$$\begin{aligned} & \Pr\{\gamma(Q, \mathbf{P}(Q), \boldsymbol{\beta}(Q)) \geq \gamma_{th}\} \\ &= \mathbb{E}[B_{\gamma_{th}}(Q)] \approx \frac{1}{N} \sum_{i=1}^N \Pr\{\gamma(q_i, \mathbf{P}(q_i), \boldsymbol{\beta}(q_i)) \geq \gamma_{th}\}, \end{aligned} \quad (16)$$

where each q_i is a realization of Q . For a large N value, this approximation approaches the mathematical solution. We optimize $\mathbf{P}(q)$ and $\boldsymbol{\beta}(q)$ for each q value, as we assume that the power allocation and mirror location can be adapted for each q value. Note that, in practice, varying the power allocation can be easily done, but varying the mirror location cannot. However, we aim to determine the mirror placement with the highest occurrence, which allows us to make such an assumption, and obtain an outage probability limit. That is, our results provide for the highest occurrence of locally optimal solutions as a guide to fixing the ORIS/mirrors placement.

Defining $b(q)$ as a realization of the random variable $B_{\gamma_{th}}(Q)$ in (15), i.e.,

$$b(q) = B_{\gamma_{th}}(Q) \Big|_{Q=q}, \quad (17)$$

we may compute the set $\{[\mathbf{P}(q), \boldsymbol{\beta}(q)]\}$ that maximizes $b(q)$. Note that the set of functions $\{[\mathbf{P}(q), \boldsymbol{\beta}(q)]\}$ that maximizes $b(q)$ is typically infinite because it is binary valued. Considering this, as well as the management of available resources, we propose three objective functions (\mathcal{O}) that could be applied to our optimization problem:

- $\mathcal{O}_1 = b(q)$, which focuses on the outage event of the user under study defined in (17).
- $\mathcal{O}_2 = \sum_l \sum_k \beta_{l,k}(q)$, which focuses on the number of mirror (or ORIS) elements deployed.
- $\mathcal{O}_3 = \sum_l P_l(q)$, which focuses on the amount of optical power allocated.

Ideally, we can formulate a multi-objective optimization problem that maximizes \mathcal{O}_1 , while minimizing \mathcal{O}_2 and \mathcal{O}_3 . However, when \mathcal{O}_2 increases, \mathcal{O}_3 may be decreased as lower power may be considered, and vice versa. Then, these are conflicting objective functions that cannot be optimized in conjunction, and it may lead, again, to an infinite number of Pareto-optimal solutions [40]. To solve this issue we propose to define single-objective functions with some priorities, leading to a single optimal solution. Then, the outage event formulated in \mathcal{O}_1 is prioritized, and \mathcal{O}_2 and \mathcal{O}_3 are considered as regularization terms. Specifically, we propose the following optimization problem:

$$[\widehat{\mathbf{P}(q)}, \widehat{\boldsymbol{\beta}(q)}] = \arg \max_{\mathbf{P}(q), \boldsymbol{\beta}(q), b(q)} \mathcal{O}^*, \quad (18)$$

where \mathcal{O}^* can be either

$$\mathcal{O}_1^* = b(q) - \epsilon \cdot \sum_l \sum_k \beta_{l,k}(q) \quad \text{or} \quad \mathcal{O}_2^* = b(q) - \epsilon \cdot \sum_l P_l(q), \quad (19)$$

where ϵ is an infinitesimal value that forces the algorithm towards a unique optimal solution that minimizes the number of mirrors (or ORISs) employed in \mathcal{O}_1^* , or the amount of optical power allocated in \mathcal{O}_2^* , while prioritizing the outage event represented by variable $b(q)$. For the remainder of the paper, we remove the functional dependence of b , \mathbf{P} and $\boldsymbol{\beta}$ on q for notation simplicity as we consider the same objective functions for every user location and orientation.

An optimization problem can be solved with off-the-shelf software if constraints are linear, bilinear or quadratic, in both convex and non-convex optimization problems [41]. In the following, we analyze both communication and illumination constraints.

B. Communication constraints

We follow the big- M approach to turn the conditional statement in (15) into two linear inequalities [42], where M is considered as an upper bound of γ for every possible user location in the room:

$$\gamma(\mathbf{P}, \boldsymbol{\beta}) \geq \gamma_{th} - M \cdot (1 - b), \quad (20)$$

$$\gamma(\mathbf{P}, \boldsymbol{\beta}) < \gamma_{th} + M \cdot b. \quad (21)$$

These inequalities define the b variable, for our purpose, in such a way that both constraints are linear in b when the user is in outage ($b = 0$) and also when the user is not in outage ($b = 1$). That is, when the optimal solution is that user is in outage, i.e., $b = 0$, (20) is satisfied because M is a very large value to fulfill $\gamma(\mathbf{P}, \boldsymbol{\beta}) \geq \gamma_{th} - M$, and (21) is also satisfied because $\gamma(\mathbf{P}, \boldsymbol{\beta}) < \gamma_{th}$, which is the intrinsic definition of being in outage. Differently, when the optimal solution is that user is not in outage, i.e., $b = 1$, (20) is satisfied because $\gamma(\mathbf{P}, \boldsymbol{\beta}) \geq \gamma_{th}$, which is the intrinsic definition of not being in outage, and (21) is also satisfied because M is a very large value to fulfill $\gamma(\mathbf{P}, \boldsymbol{\beta}) < \gamma_{th} + M$.

Note that $\gamma(\mathbf{P}, \boldsymbol{\beta})$ is neither linear, nor bilinear, nor quadratic with respect to the variables P_l and $\beta_{l,k}$ (see (12)), since the summation in the numerator is squared, leading to cubic terms. To simplify its formulation, we create a new variable that denotes the multiplication between the optical power transmitted by LED l , i.e. P_l , and the binary variable $\beta_{l,k}$:

$$\varrho_{l,k} = P_l \cdot \beta_{l,k}, \quad (22)$$

which leads to the matrix $\boldsymbol{\varrho}$ containing all $\varrho_{l,k} \forall l, k$ values. Thus, the SNR in (12) can be re-formulated as in (23) at the top of the next page, where the formulation between curly brackets can be re-written as the sum of terms listed in Table I, whose degrees with respect to the variables P_l and $\varrho_{l,k}$ are also included. As we can see, these terms and therefore, all communication constraints, are no longer cubic, and they can be formulated and solved with off-the-shelf software.

C. Illumination constraints

The design of a VLC network must pay special attention to not infringe on the primary functionality of a lighting system. First, the *average illuminance* E_{avg} in the whole area must be larger than a threshold E_{th} , i.e., $E_{avg} \geq E_{th}$, which is determined by the type of activity carried out in the space.

$$\gamma(\mathbf{P}, \boldsymbol{\varrho}) = \frac{\rho^2}{N_0 B} \cdot \left\{ \sum_l \left[I_l \cdot P_l \cdot H_l^{\text{LoS}} + \sum_k I_{l,k} \cdot \left(P_l \cdot H_{l,k}^{\text{wall}} + \varrho_{l,k} \cdot \left(H_{l,k}^{\text{spec}} - H_{l,k}^{\text{wall}} \right) \right) \right]^2 \right. \\ \left. + 2 \sum_{l'=1}^{L-1} \sum_{l=0}^{l'-1} \underbrace{I_l \cdot P_l \cdot H_l^{\text{LoS}}}_{R_l^{\text{LoS}}(P_l)} + \sum_k I_{l,k} \cdot \underbrace{\left(P_l \cdot H_{l,k}^{\text{wall}} + \varrho_{l,k} \cdot \left(H_{l,k}^{\text{spec}} - H_{l,k}^{\text{wall}} \right) \right)}_{R_{l,k}^{\text{NLoS}}(P_l, \varrho_{l,k})} \right] \cdot \left[I_{l'} \cdot P_{l'} \cdot H_{l'}^{\text{LoS}} + \sum_k I_{l',k} \cdot \underbrace{\left(P_{l'} \cdot H_{l',k}^{\text{wall}} + \varrho_{l',k} \cdot \left(H_{l',k}^{\text{spec}} - H_{l',k}^{\text{wall}} \right) \right)}_{R_{l',k}^{\text{NLoS}}(P_{l'}, \varrho_{l',k})} \right] \right\} \quad (23)$$

TABLE I: Terms of γ in (23), and their degrees (Qu: quadratic, Bi: bilinear) with respect to P_l and $\varrho_{l,k}$.

Term	Degree
$\sum_l I_l \cdot (R_l^{\text{LoS}}(P_l))^2$	Qu
$\sum_l \sum_k I_{l,k} \cdot (R_{l,k}^{\text{NLoS}}(P_l, \varrho_{l,k}))^2$	Qu, Bi
$2 \sum_l \sum_{k'=1}^{K-1} \sum_{k=0}^{k'-1} I_{l,k} I_{l,k'} R_{l,k}^{\text{NLoS}}(P_l, \varrho_{l,k}) \cdot R_{l,k'}^{\text{NLoS}}(P_l, \varrho_{l,k'})$	Qu, Bi
$2 \sum_l I_l \cdot R_l^{\text{LoS}}(P_l) \cdot \sum_k I_{l,k} \cdot R_{l,k}^{\text{NLoS}}(P_l, \varrho_{l,k})$	Qu, Bi
$2 \sum_{l'=1}^{L-1} \sum_{l=0}^{l'-1} I_l \cdot I_{l'} \cdot R_l^{\text{LoS}}(P_l) \cdot R_{l'}^{\text{LoS}}(P_{l'})$	Bi
$2 \sum_{l'=1}^{L-1} \sum_{l=0}^{l'-1} I_l \cdot R_l^{\text{LoS}}(P_l) \cdot \sum_k I_{l',k} \cdot R_{l',k}^{\text{NLoS}}(P_{l'}, \varrho_{l',k})$	Bi
$2 \sum_{l'=1}^{L-1} \sum_{l=0}^{l'-1} I_{l'} \cdot R_{l'}^{\text{LoS}}(P_{l'}) \cdot \sum_k I_{l',k} \cdot R_{l',k}^{\text{NLoS}}(P_{l'}, \varrho_{l',k})$	Bi
$2 \sum_{l'=1}^{L-1} \sum_{l=0}^{l'-1} \left(\sum_k I_{l,k} \cdot R_{l,k}^{\text{NLoS}}(P_l, \varrho_{l,k}) \right) \cdot \left(\sum_k I_{l',k} \cdot R_{l',k}^{\text{NLoS}}(P_{l'}, \varrho_{l',k}) \right)$	Bi

For example, a library requires a larger average illuminance than a residential space [43]. The average illuminance in a room is formulated as

$$E_{\text{avg}} = \frac{1}{N} \cdot \sum_n E_v(n), \quad (24)$$

where $n = \{0, \dots, N-1\}$ are all the possible sensing points that cover the whole room area, and $E_v(n)$ is the illuminance at point n defined as

$$E_v(n) = \frac{K_{e/v}}{A_{\text{PD}}} \cdot \sum_l P_l H_l^{\text{LoS}}(n), \quad (25)$$

where $K_{e/v}$ (measured in lm/W) is the luminous efficacy of the white light that the LED generates, and $H_l^{\text{LoS}}(n)$ is the LoS channel gain from LED l to the room point n , computed as (1). Note that the illuminance is computed only with the LoS contribution, since illumination must be guaranteed regardless of reflections; it cannot depend on the wall material and color, which can change as the space is decorated after the lighting has been installed.

The second illumination constraint to fulfill is that the illuminance at every point n must be lower than or equal to a maximum value E_{max} , i.e., $E_v(n) \leq E_{\text{max}}, \forall n$. This constraint is required for eye safety purposes.

The third and last illumination constraint to satisfy is that the *lighting uniformity* U must be larger than a minimum U_{min} , i.e. $U \geq U_{\text{min}}$, where the lighting uniformity is defined as

$$U = \frac{\min_n E_v(n)}{E_{\text{avg}}}. \quad (26)$$

Note that U is not a linear function with respect to the variable P_l . To linearize U we formulate a new variable $E_{\text{min}} = \min_n E_v(n)$, which leads to the following two new constraints

$$E_{\text{min}} \geq U_{\text{min}} \cdot E_{\text{avg}} \quad \text{and} \quad E_{\text{min}} \leq E_v(n), \forall n. \quad (27)$$

D. Solvable optimization problem

Note that the objective functions in Section III-A are linear and, together with the re-arrangements introduced in Section III-B and Section III-C, our optimization problem can be formulated as a mixed-integer programming (MIP) problem with linear, bilinear and quadratic constraints. It now complies with all features to be solved by a non-convex solver such as Gurobi and CVX interface [41], [44]. We formulate our JOINTMINOUT optimization problem as

$$\text{JOINTMINOUT: } \max_{\beta, b, \mathbf{P}, E_{\text{min}}} \mathcal{O}_1^* \text{ (or } \mathcal{O}_2^*) \quad (28)$$

subject to

$$\begin{cases} \text{Resource constraints} & \begin{cases} \text{C1 : } \sum_l \sum_k \beta_{l,k} \leq N_{\text{max}} \\ \text{C2 : } \sum_l \beta_{l,k} \leq 1, \forall k \end{cases} \\ \text{Communication constraints} & \begin{cases} \text{C3 : } \gamma(\mathbf{P}, \boldsymbol{\varrho}) \geq \gamma_{\text{th}} - M \cdot (1 - b), \\ \text{C4 : } \gamma(\mathbf{P}, \boldsymbol{\varrho}) < \gamma_{\text{th}} + M \cdot b, \end{cases} \\ \text{Illumination constraints} & \begin{cases} \text{C5 : } \frac{K_{e/v}}{N A_{\text{PD}}} \cdot \sum_l \sum_n P_l H_l^{\text{LoS}}(n) \geq E_{\text{th}} \\ \text{C6 : } E_{\text{min}} \geq U_{\text{min}} \cdot \frac{K_{e/v}}{N A_{\text{PD}}} \cdot \sum_l \sum_n P_l H_l^{\text{LoS}}(n) \\ \text{C7 : } E_{\text{min}} \leq \frac{K_{e/v}}{A_{\text{PD}}} \cdot \sum_l P_l H_l^{\text{LoS}}(n), \forall n \\ \text{C8 : } \frac{K_{e/v}}{A_{\text{PD}}} \cdot \sum_l P_l H_l^{\text{LoS}}(n) \leq E_{\text{max}}, \forall n \end{cases} \\ \text{Definition of variables} & \begin{cases} \text{C9 : } \varrho_{l,k} = P_l \cdot \beta_{l,k}, \forall l, k \\ \text{C10 : } P_l \geq 0, \forall l \\ \text{C11 : } \beta_{l,k} \in \{0, 1\}, \forall l, k \\ \text{C12 : } b \in \{0, 1\} \\ \text{C13 : } E_{\text{min}} \geq 0 \end{cases} \end{cases}$$

We maximize the objective function subject to the following constraints: C1-C2 refer to the maximum possible number of mirrors (or ORISs) given by N_{max} , and to the LED-mirror association defined in (7); C3-C4 invoke the Big- M approach to define the outage variable b ; C5 defines the average illuminance constrained at a minimum value of E_{th} ; C6 defines the illuminance uniformity constrained at a minimum value of U_{min} ; C7 refers to the minimum illuminance E_{min} along the whole room required to define illuminance uniformity in C6; C8 defines the maximum illuminance along the whole room; and C9-13 include definitions for all the variables used in the optimization problem.

If we assume the variable P_l is known and fixed for all LEDs, C5-C10 and C13 are not needed, and the problem becomes a 0-1 integer linear program. This is one of Karp's 21 NP-complete problems and requires exponential time with respect to the input size to solve [45]. We can solve this for small enough problems and with enough computational resources,

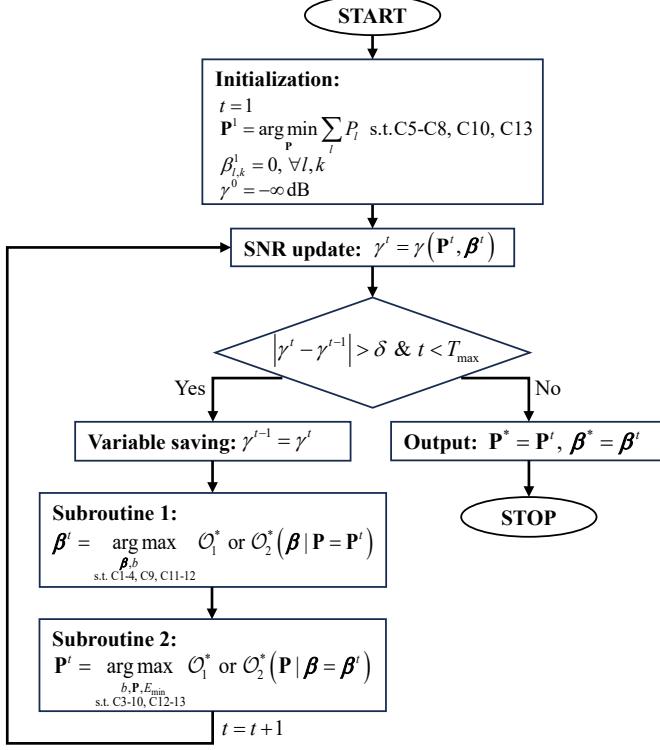


Fig. 7: Proposed generalized alternating optimization algorithm.

but the problem becomes intractable when considering realistic scenarios. The input size equals $K \cdot L$, which is very large as the value of K must be in the hundreds so that the walls are partitioned into sufficiently small elements to get an accurate NLoS channel representation. Including an unknown power allocation P_l , $\forall l$ as a new variable makes the problem even more difficult to solve, requiring heuristic approaches.

IV. PROPOSED HEURISTIC ALGORITHMS

We propose two heuristic alternating iterative algorithms to solve the JOINTMINOUT problem, and we compare their performance to the benchmark that can be formulated as a non-iterative optimization algorithm.

A. Proposed alternating optimization (AO) algorithms

We have two resources that must be studied: number of mirrors (or ORIS) and their placement, which is defined by the parameter β , and power allocated to each LED l , defined by the parameter \mathbf{P} . To solve the JOINTMINOUT optimization problem detailed in (28), we propose an alternating optimization (AO) algorithm that divides the problem into two subroutines to find the global optimization variables \mathbf{P} and β iteratively, subject to fixing one of them each time, until the problem converges.

A flow diagram of the general AO algorithm proposed is included in Fig. 7. The algorithm starts with the initialization of variables for iteration $t = 1$: the output power for each LED l contained in \mathbf{P}^1 , is initially set as the minimum power required to comply with the illumination constraints defined in (28); and the algorithm is initialized with no mirrors deployed, i.e. $\beta_{l,k}^1 = 0, \forall l, k$. The two variables under study at iteration t are denoted as \mathbf{P}^t and β^t . Then, at each iteration, the SNR value γ^t is updated to be compared with the value of the SNR

Algorithm 1: Pseudo-code for subroutine 1 for the MM approach

```

Data: Nmax, Il,k, Hl,kspec, Plt, ∀l, k
Result: βt
if Il,kHl,kspecPlt ≠ 0 then
  N = 0
  while γ(Pt, βt) < γth and N ≤ Nmax do
    {l*, k*} = arg maxl ∈ L, k ∈ K' suml sumk Il,kHl,kspecPlt
    s.t. K' = {k ∈ K | |K'| = N}
    suml βl,k = 1, ∀k ∈ K'
    βl,kt = 1, ∀{l, k} ∈ {l*, k*}
    N = N + 1
  end
end
  
```

in the previous iteration, γ^{t-1} . The variables β^t and \mathbf{P}^t are iteratively updated as follows:

- Subroutine 1 computes β^t that maximizes the function \mathcal{O}_1^* (or \mathcal{O}_2^*) for a given $\mathbf{P} = \mathbf{P}^t$. Only the constraints depending on β^t are considered, which correspond to resource and communication constraints (C1-4), and some definitions (C9, C11-12).
- Subroutine 2 computes \mathbf{P}^t that maximizes the function \mathcal{O}_1^* (or \mathcal{O}_2^*) for a given $\beta = \beta^t$ obtained in subroutine 1. Only constraints depending on \mathbf{P} are considered, which correspond to C3-10 and C12-13.

The algorithm leaves the loop when the problem converges, i.e. the SNR changes less than an infinitesimal δ value with respect to the previous iteration, or when the number of iterations t , i.e., execution time, exceeds T_{max} . Depending on the resource to conserve, either the number of mirrors (or ORISs) or the amount of power allocated, we perform \mathcal{O}_1^* or \mathcal{O}_2^* , respectively. Both focus on maximizing b , i.e., prioritizing solutions for which $b = 1$ and the user is not in outage.

Subroutine 1 is an integer linear programming problem where the unknown variables are binary. Although we have simplified the problem with respect to JOINTMINOUT, this is still NP-complete. Thus, we propose two heuristic algorithms that replace subroutine 1, one for each resource to conserve (number of mirrors or optical power):

1) *Minimum Mirrors (MM) approach:* This approach minimizes the number of mirrors (or ORIS) employed, then allocating as much power as the constraints allow and exploiting mirrors (or ORISs) only as a last resort. The pseudo-code for the heuristic MM approach to solve subroutine 1 is described in Algorithm 1. The variables required to perform the algorithm are N_{max} , $I_{l,k}$, $H_{l,k}^{spec}$ and P_l^t , $\forall l, k$. The algorithm computes the optimal $\{l, k\}$ that satisfies $\gamma(\mathbf{P}^t, \beta^t) > \gamma_{th}$ while minimizing the number of mirrors (or ORISs) that contribute to increasing the SNR.

2) *Minimum Power (MP) approach:* As a commitment to the environment, this approach minimizes the power transmitted by the LEDs while exploiting mirrors (or ORIS) as much as possible. The pseudo-code describing the heuristic MP approach replacing subroutine 1 is described in Algorithm 2. The MP approach selects the N_{max} best $\{l, k\}$ -pairs that

Algorithm 2: Pseudo-code for subroutine 1 for the MP approach

Data: N_{\max} , $I_{l,k}$, $H_{l,k}^{\text{spec}}$, P_l^t , $\forall l, k$

Result: β^t

if $I_{l,k}H_{l,k}^{\text{spec}}P_l^t \neq 0 \forall l, k$ **then**

$$\{l^*, k^*\} = \arg \max_{l \in L, k \in K'} \sum_l \sum_k I_{l,k} H_{l,k}^{\text{spec}} P_l^t$$

s.t. $K' = \{k \in K \mid |K'| = N_{\max}\}$

$\sum_l \beta_{l,k} = 1, \forall k$

$\beta_{l,k} = 1, \forall \{l, k\} \in \{l^*, k^*\}$

end

maximize the total received reflection so that the transmitted power can be minimized.

In both cases, the mirror (or ORIS) selection β^t obtained in subroutine 1 is used in subroutine 2, which can be solved by simple linear programming optimization.

B. Benchmark and no-mirror scenario

To the best of the authors' knowledge, this is the first work that studies the outage probability performance in an indoor mirror- or ORIS-assisted VLC scenario. As introduced in Section I, prior mirror- or ORIS-assisted VLC works focused on SINR, data rate or secrecy rate maximization. It is thus difficult to compare our proposal to previous works.

As our benchmark, we consider a typical room whose lighting infrastructure satisfies the required illumination conditions in an energy-efficient manner, i.e., minimum total optical power, which can be formulated as

$$\mathbf{P}^* = \arg \min_{\mathbf{P}, E_{\min}} \sum_l P_l \quad (29)$$

subject to C5 – 8, C10, C13.

Then, the room is provided with mirrors (or ORISs) that contribute to minimizing the outage probability. This is defined by the variable β and computed with the heuristic MM approach to solving subroutine 1 represented in Algorithm 1. For the benchmark, this process is not iterated (non-alternating), accepting these one-shot values as final.

We also compare our results with a scenario without mirrors (neither stationary nor ORIS), and the optical power allocated is computed by (29).

C. Complexity analysis

As mentioned earlier, the JOINTMINOUT optimization problem is a variant of a MIP, which is NP-complete and requires exponential time with respect to the input number of variables to be solved. There is no algorithm able to solve it in polynomial time, and thus, it is intractable to solve in a reasonable time. We propose two heuristic approaches whose complexity orders are much lower and analyzed as follows. Table II includes a summary of the complexity for each of the algorithms under evaluation in this paper.

Both MM and MP approaches are alternating algorithms. Let us obtain the worst-case complexity order by assuming that the number of iterations in the proposed generalized alternating algorithm is T_{\max} . The MM approach to subroutine 1 (Algorithm 1) carries out N_{\max} times a *selection sort*

TABLE II: Complexity of the algorithms proposed.

Algorithm		Complexity
Optimal		Exponential: MIP
Heuristics	JOINTMINOUT	
	MM	Polynomial: $O(T_{\max} N_{\max} L^2 K^2)$
	MP	Polynomial: $O(T_{\max} L^2 K^2)$
	Benchmark	Polynomial: $O(N_{\max} L^2 K^2)$
No mirror		Polynomial: $O((L^2 + L + 1)^2(2n + L + 3))$

algorithm, leading to a complexity order of $O(N_{\max} L^2 K^2)$. Differently, the MP approach to subroutine 1 (Algorithm 2) carries out a single *selection sort algorithm*, leading to a complexity order of $O(L^2 K^2)$. In both approaches, subroutine 2 is a linear programming problem whose complexity order can be approximated in practice as $O(v^2 c)$, where v is the number of variables and c is the number of constraints [46]. After converting quadratic into linear variables, there are $v = L^2 + L + 2$ variables and $c = 2n + L + 5$ constraints in subroutine 2. Since the number of wall elements is much larger than the number of LEDs ($K >> L$), the complexity of subroutine 1 exceeds that of subroutine 2, and the global complexity order can be approximated as $O(T_{\max} N_{\max} L^2 K^2)$ for the MM approach and $O(T_{\max} L^2 K^2)$ for the MP approach.

The benchmark algorithm is a linear programming solution similar to subroutine 2, followed by the MM heuristic approach (subroutine 1 - Algorithm 1). As stated above, the complexity of subroutine 1 exceeds that of subroutine 2, and therefore the complexity of the benchmark algorithm can be approximated as $O(N_{\max} L^2 K^2)$. The no-mirror algorithm is computed only by (29), which is a linear programming problem with a complexity of $O((L^2 + L + 1)^2(2n + L + 3))$.

V. RESULTS AND DISCUSSION

In this section, we present comprehensive simulation results for the proposed mirror- or ORIS-aided VLC system. Without loss of generality, we consider a residential room of $4 \times 4 \times 3$ m, with a total of $L = 4$ LEDs deployed in a symmetric 2-by-2 lattice with coordinates [1, 1], [1, 3], [3, 1] and [3, 3] m. Though we consider NLoS contributions from the four walls, only one wall is provided with mirror (or ORIS) capabilities. Each wall is divided into $K = K_x \times K_y = 30 \times 15 = 450$ elements.

Due to the deterministic characteristics of the VLC channel, we assume an object model for the link-path blockage [47]. The proposed model considers only self-blocking, i.e., a situation of an empty room where blockages of LoS and NLoS paths are produced by the body of the person holding the user device. However, this study could be easily extended to other scenarios with static objects such as pillars or furniture, which are even easier to model due to their immobility, or with other users moving around, which typically produce less probable blockage. Specifically, in this paper, the human body is modeled by a cylinder of height 1.75 m and radius 0.15 m, holding a device provided with a single PD looking upwards and separated at a distance of 0.3 m from the body, with a horizontal angle following a uniform distribution $\mathcal{U}[0, 2\pi]$ [47].

We assume an LED with a typical luminous efficacy of 280 lm/W (theoretical values for white LEDs can be above 300 lm/W [48]), and we consider a scenario where the required minimum average illuminance is 500 lux, with a maximum

TABLE III: Simulation parameters.

Notation	Parameter description	Value	Unit
-	LED height	3	[m]
-	User device height	1	[m]
$\phi_{1/2}$	Half-power semi-angle of the LED	80	[deg.]
\tilde{r}	Reflection coefficient of wall	0.2	[\cdot]
\hat{r}	Reflection coefficient of mirror/ORIS	0.99	[\cdot]
ρ	PD responsivity	1	[A/W]
A_{PD}	PD physical area	1	[cm 2]
Ψ	FoV semi-angle of the PD	[30, 40, 50]	[deg.]
B	Communication bandwidth	20	[MHz]
N_0	Power spectral density of the AWGN	$2.5 \cdot 10^{-20}$	[W/Hz]
$K_{e/v}$	Luminous efficacy of LEDs	280	[lm/W]
γ_{th}	SNR threshold	[10 - 50]	[dB]
N_{max}	Maximum number of mirrors or ORIS elements	128	[\cdot]
E_{th}	Minimum average illuminance required	500	[lux]
E_{max}	Maximum illuminance allowed at each point	800	[lux]
U_{min}	Illuminance uniformity	0.5	[\cdot]
T_{max}	Maximum number of iterations of the AO algorithm	20	[\cdot]

illuminance allowed at each point of 800 lux, and a minimum illuminance uniformity of 0.5. Note that these are the minimum illumination conditions for a typical office scenario in which writing, typing or reading tasks are carried out [43]. As argued in Section II-D, because the NLoS path loss will not be heavily affected by the $\phi_{1/2}$ parameter considering the presented scenario, we select the $\phi_{1/2}$ value to preferably satisfy illumination requirements, i.e., wide enough to support the lighting uniformity. More detailed simulation parameters are shown in Table III.

Note that the communication bandwidth and PD physical area selected for our simulations are 20 MHz and 1 cm 2 , respectively, which are within the ranges of actual systems [38] and aligned with the principles of ultra-reliable non-rate-centric broadband communication for the Internet of Everything [49]. Besides, note that the simulation parameters allow us to work in a small detector regime that, together with our LED point-source assumption and the neglected inter-element blockage, allows us to apply the specular reflection channel model formulated in (2) and (3) for mirror and ORIS cases, respectively.

A. Comparison between using mirrors, ORISs, and no mirrors

Let us consider a scenario where either mirrors or ORISs are deployed optimally to support each realization of the user's position. We run the proposed AO algorithm for the MP approach to see the contribution of mirrors or ORISs and compare their performance with a scenario where there are no mirrors. Fig. 8 plots the outage probability reduction obtained with respect to a scenario without mirrors. The use of ORIS elements allows an outage reduction of up to 0.67, 0.58 and 0.46 when $\Psi=50^\circ$, $\Psi=40^\circ$ and $\Psi=30^\circ$, respectively. Mirrors, due to their immobility, provide lower outage reductions of about 0.48, 0.39 and 0.33 for $\Psi=50^\circ$, $\Psi=40^\circ$ and $\Psi=30^\circ$, respectively. Note that there is a higher gap among the maximums of the outage probability reduction curves in the case of ORIS as compared to the case of mirrors; this is because the mobility of ORIS gives them one more degree of freedom to enhance

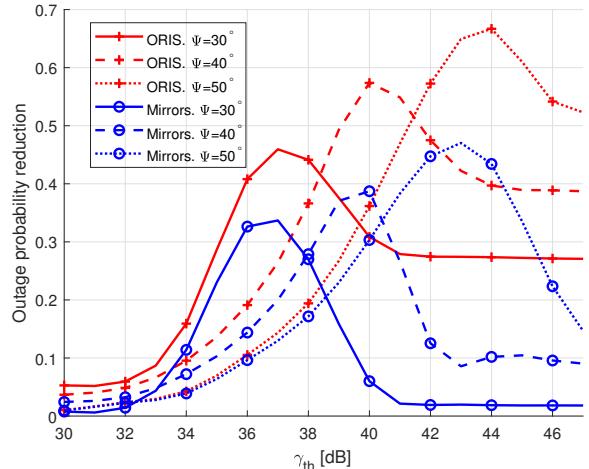


Fig. 8: Outage probability reductions obtained with MP approach when using ORIS (i.e. mirrors with mobile orientation) or mirror elements with respect to a no-mirror scenario for different Ψ angles.

the NLoS path and, as a consequence, to reduce the outage probability at a larger extent when the FoV angle increases. Thus, whenever possible, ORIS should be deployed. However, when the extra complexity of ORIS deployment due to its mobile orientation is not affordable, the deployment of mirrors will also provide a considerable outage reduction.

B. Optimal placement of mirrors

After evaluating the maximum gain obtained when either ORISs or mirrors are deployed, we analyze the optimal fixed placement for these elements in each of the suggested approaches. We consider a $\gamma_{th} = 40$ dB. Let us first analyze the optimal placement of ORISs and mirrors with the MM approach, represented in Figs. 9 and 10, respectively, for three different Ψ angles. The figures reflect the placements of mirrors/ORISs that contribute to closing the SNR gap the most often. Note that, in the case of ORIS, the optimal placement is high on the wall, while in the case of mirrors, their lack of mobility imposes an optimal placement halfway up the wall. Also, note that the optimal reflector position is much clearer at higher Ψ values where the contributions from NLoS are more important (see Section II-D).

The optimal placement of ORISs and mirrors when invoking the MP approach is represented in Figs. 11 and 12, respectively. Again, darker pixels indicate a higher probability. Unlike the MM approach, the MP approach exploits ORISs (or mirrors) as much as possible, and then the shape of the optimal placement zone is not as well defined as when invoking the MM approach. The optimal placement of ORIS for the MP approach is in the upper edge of the wall; in any room, ORIS elements so installed provide much improvement in outage probability. In fact, ORIS located at such a high level on the wall is unlikely to impact the utilization of the space, i.e., other objects or decorations can still be placed in the middle of the wall, as they normally would be.

Due to the benefits of using ORISs compared to mirrors, we consider only ORIS elements for the results in the following sections.

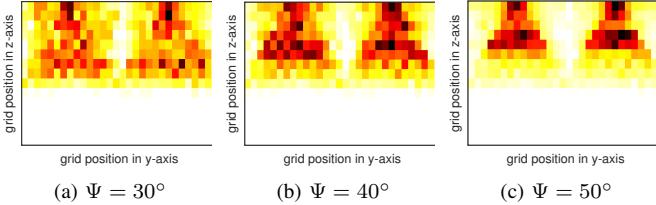


Fig. 9: Heatmaps of optimal ORIS placement on the wall for MM approach when $\gamma_{\text{th}}=40$ dB at different FoV semi-angles. Darker pixels indicate a higher probability.

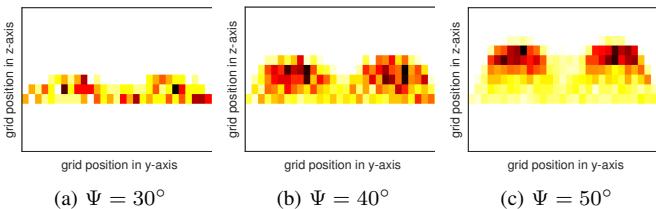


Fig. 10: Heatmaps of optimal mirror placement on the wall for MM approach when $\gamma_{\text{th}}=40$ dB at different FoV semi-angles. Darker pixels indicate a higher probability.

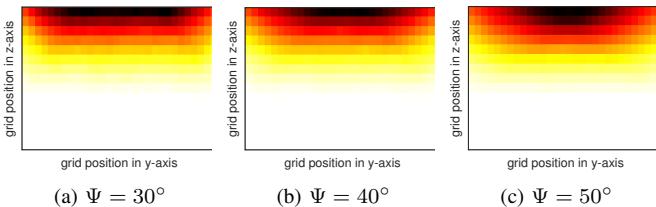


Fig. 11: Heatmaps of optimal ORIS placement on the wall for MP approach when $\gamma_{\text{th}}=40$ dB at different FoV semi-angles. Darker pixels indicate a higher probability.

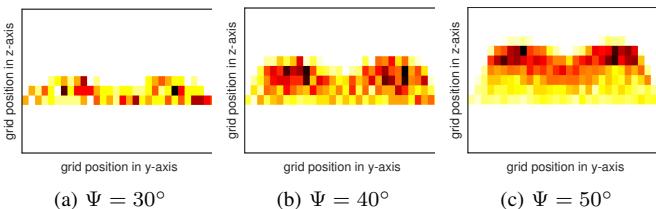


Fig. 12: Heatmaps of optimal mirror placement on the wall for MP approach when $\gamma_{\text{th}}=40$ dB at different FoV semi-angles. Darker pixels indicate a higher probability.

C. Comparison between the benchmark, no-mirror, and the MM and MP proposed algorithms

First, we compare the performance obtained with the MM and MP proposed approaches to the non-alternating benchmark and a no-mirror scenario for a range of γ_{th} values from 10 dB (low demanding wireless services) to 50 dB (high demanding wireless services), shown in Fig. 13. The SNR threshold range includes all the values required to demodulate 2-PAM through 256-PAM at a bit error rate (BER) equal to 10^{-6} in an IM/DD system [50]. These results are depicted for three different Ψ values. The smaller the Ψ , the higher the outage probability is because less contribution is received from neighboring LEDs as well as from reflecting elements. In fact, for $\Psi=30^\circ$, there is an outage probability floor, which means that there are some room areas that cannot be reached by any light source and where the user will be in outage. A zero-outage probability is obtained for larger Ψ values and $\gamma_{\text{th}} < 25$ dB. When comparing the three approaches, both MM and MP provide similar results in terms of outage probability, considerably improving upon the benchmark and no-mirror scenarios. As an example, for $\gamma_{\text{th}} = 40$ dB and

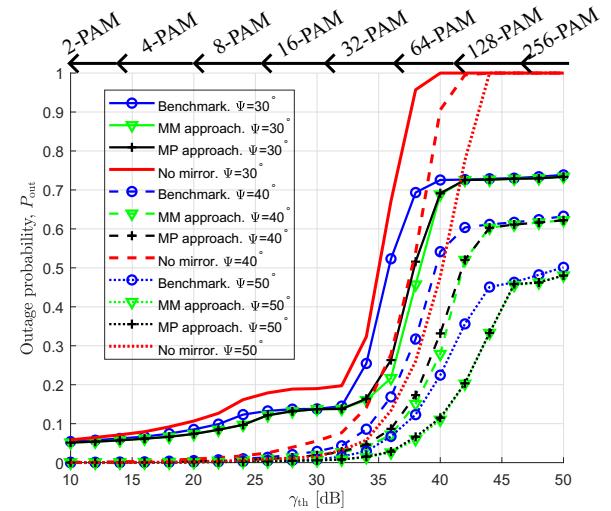


Fig. 13: Outage probability vs. γ_{th} for the benchmark, no-mirror case, and MM and MP proposed algorithms using different Ψ .

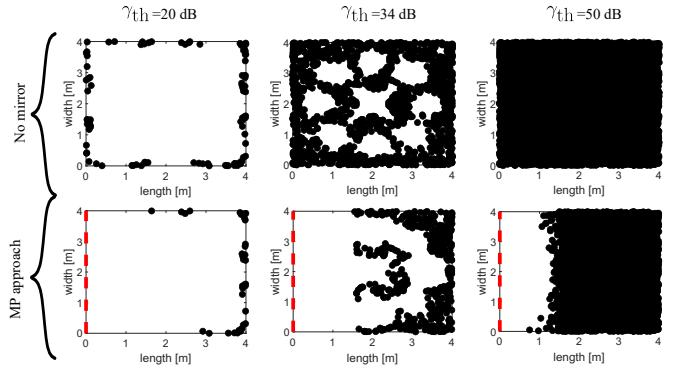


Fig. 14: Top view of the room showing, using black circles, the location of users ($\Psi = 40^\circ$) in outage for different γ_{th} values for a Monte Carlo simulation of 10^4 trials. The no-mirror (first row) and ORISs using MP (second row) approaches are invoked. The red dashed line on the left wall represents where ORISs are deployed.

$\Psi=50^\circ$, both proposed approaches, MM and MP, reduce the outage probability by two and five times with respect to the benchmark and no-mirror scenarios, respectively. This means that, for the same outage probability performance, the proposed AO algorithms enable more demanding services requiring high γ_{th} values.

Fig. 14 shows realizations for the location of users that are in outage assuming $\gamma_{\text{th}}=20$ dB, $\gamma_{\text{th}}=34$ dB or $\gamma_{\text{th}}=50$ dB for the no-mirror and MP approaches, for a simulation of 10^4 trials. The results clearly show how the MP approach supports those users located close to the wall provided with ORIS elements, even at high γ_{th} values. In contrast, if no mirror is provided, the entire area can easily be in outage. Note that if all walls were provided with ORIS elements, the outage probability would dramatically decrease to almost zero, at the expense of a higher complexity and coordination among ORIS elements located on different walls.

D. Analyzing resources used

Let us now evaluate the two available resources to conserve: total power ($\sum_l P_l$), and the number of ORIS elements ($\sum_l \sum_k \beta_{l,k}$). Fig. 15 plots the average total optical power as

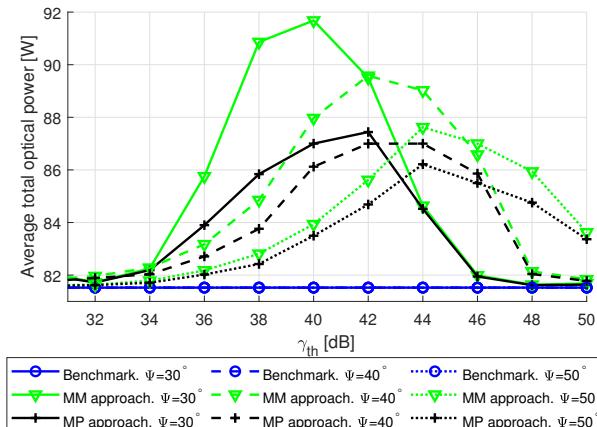


Fig. 15: Average total optical power vs. γ_{th} for the benchmark, MM, and MP proposed algorithms using different Ψ .

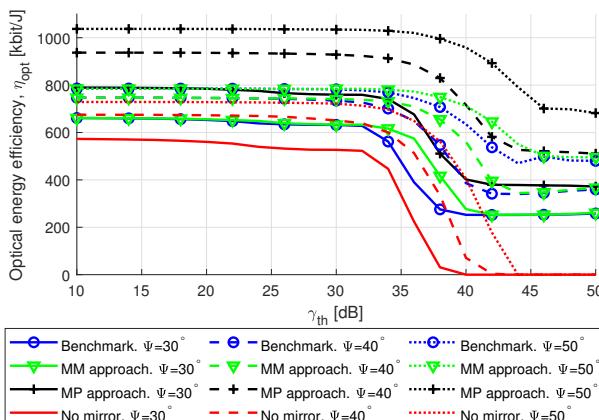


Fig. 16: Optical energy efficiency vs. γ_{th} for benchmark, no-mirror case, and MM and MP proposed algorithms when using different Ψ .

a function of γ_{th} . Though both MM and MP provide a similar outage probability performance, the MM approach achieves this performance by increasing the transmitted power. Both approaches increase the transmitted power when γ_{th} becomes more demanding, but decrease it when it becomes so large that the user can no longer be supported at all. The benchmark keeps the total optical power constant regardless of the γ_{th} value; this is because the variables are computed as one shot optimizations of \mathbf{P} and β independent from each other. Note that the power consumption in a no-mirror scenario is the same as for the benchmark.

Results shown in Fig. 13 and Fig. 15 are combined to compute the optical energy efficiency formulated in (14). Fig. 16 shows the optical energy efficiency as the required γ_{th} varies. The MP approach is much more efficient than any other approach, and this difference increases for larger Ψ values.

We now evaluate the number of ORIS elements required to achieve the outage probability obtained in Fig. 13. This is represented in Fig. 17 for the entire γ_{th} range. The advantage of the MP approach in optical energy efficiency comes at a cost of requiring a much larger number of ORIS elements. The larger the Ψ , the more ORIS elements can be exploited as the user may receive larger NLoS contributions. Conversely, the MM and benchmark algorithms only exploit ORIS elements when it is strictly necessary, i.e., at high γ_{th} values when they cannot allocate more transmitted power per LED to support

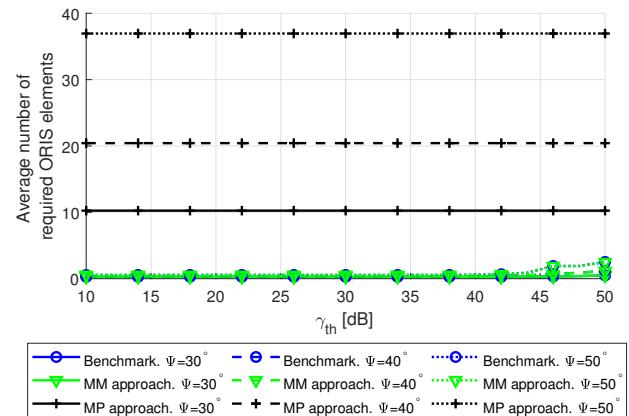


Fig. 17: Number of ORIS elements required vs. γ_{th} for the benchmark, MM, and MP proposed algorithms using different Ψ .

TABLE IV: Probability of the number of iterations required for convergence of the proposed MP and MM alternating iterative algorithms over a range of γ_{th} values, assuming ORIS elements are deployed and $\Psi = 50^\circ$.

(a) MP approach			(b) MM approach		
Iterations	≤ 4	T_{\max}	Iterations	≤ 4	T_{\max}
$\gamma_{\text{th}} = [10, 28] \text{ dB}$	100.00%	0.00%	$\gamma_{\text{th}} = [10, 24] \text{ dB}$	100.00%	0.00%
$\gamma_{\text{th}} = (28, 50] \text{ dB}$	99.69%	0.31%	$\gamma_{\text{th}} = (24, 50] \text{ dB}$	99.73%	0.26%

users due to the illumination constraints.

E. Convergence time for the AO algorithms proposed

The number of iterations for convergence of the proposed AO algorithm is represented in Table IV for all γ_{th} values considered. Both MM and MP approaches need less than 5 iterations to converge, which is encouraging for a real deployment. Note that there are few user positions that need a large number of iterations, i.e., they do not converge and reach $T_{max} = 20$ in the AO algorithm. However, these users are rare (< 0.50%) and do not affect the global system performance.

VI. CONCLUSION

In this paper, we formulated an optimization problem called JOINTMINOUT to minimize the outage probability in a room with multiple LEDs, where a wall can be provided either with mirrors or with ORIS elements, and where the user body is considered as possibly blocking the LoS and NLoS links. A range of required SNRs is evaluated subject to multiple standard illumination constraints imposed to guarantee the dual functionality of VLC. We have geometrically analyzed the capability of ORISs and mirrors for supporting users. Since the optimization problem is intractable due to being NP-complete, we proposed two heuristic iterative approaches and compared their performance to a benchmark and a no-mirror scenario. Numerical results show that the proposed approaches provide reductions in the outage probability of up to 67%. Besides, the convergence of the proposed approaches is analyzed, showing that a small number of iterations is required. We have also studied the optimal placement of ORISs and mirrors for each proposed approach, and our results determined that an ORIS-aided VLC scenario invoking the MP approach provides considerable gains in outage probability and energy efficiency.

while the optimal ORIS deployment is high on the wall and does not affect the room's usage because they are not placed at a standing or sitting human eye level.

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VII. BIOGRAPHY SECTION



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