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User-Centric Cell Formation for Blind Interference Alignment in Optical Wireless Networks

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***Abstract*—Visible light communication (VLC) is considered a promising technology for providing high data rates in indoor environments. In this sense, each optical access point (AP) in a VLC network can be managed as a small cell usually referred to as attocell. Therefore, the received signal is subject to both multi-user interference (MUI) and inter-cell interference (ICI). In this work, we propose a user centric (UC) cell formation approach jointly with the use of blind interference alignment (BIA) in order to manage the interference. We formulate an optimization problem based on maximizing the sum utility of users rates for the sake of jointly finding the optimal cell formation and minimizing the limitations of BIA, i.e., the noise enhancement and the required coherence time given by the mobility of the users. This problem can be solved through exhaustive research, which involves an unpractical complexity. After that, we decouple the main problem into two sub-problems that may be solved separately. The simulation results show that the proposed schemes are more suitable for VLC networks than the considered benchmark schemes.**

I. Introduction

Visible light communication (VLC) systems have been considered as a means of moving part of the indoor data traffic, which is usually satisfied by using microwave bands of the spectrum, to the optical domain. In this sense, VLC networks offer a huge and unlicensed bandwidth, which makes this technology attractive for the sixth generation of communications and beyond [1]. In comparison to traditional radio frequency (RF) communication systems, VLC networks have several features such as high bandwidth density, high security and low energy consumption. However, the implementation of VLC poses some challenges that must be addressed such as the fact that an optical access point (AP) can only cover a small area of few square meters in comparison with an RF AP. Besides, VLC networks require separated downlink and uplink transmissions. Consequently, VLC can be considered as a complementary technology to cellular communication RF systems.

In VLC indoor environments, several light sources are usually employed to provide uniform illumination as well as ensuring the coverage. In this sense, each light source can be considered as a small cell referred to as an attocell, and therefore, VLC naturally configures as a multi-user multiple-input single-output (MU-MISO)systems. From the cellular communication perspective, VLC is subject to both multi-user interference (MUI) and inter-cell interference (ICI), which are crucial issues that can significantly affect the performance of cellular systems. Recently, interference management in VLC networks based on transmit precoding (TPC) schemes such as zero-forcing (ZF) or minimizing the mean square error (MMSE) have been proposed in [2], [3]. However, these schemes require accurate channel state information at the transmitters (CSIT) in order to align the interference correctly. In addition, they are limited by the constraints of VLC systems such as ensuring the non-negativity of the transmitted signal or the correlation among the channel response of the users.

In the meantime, a scheme referred to as blind interference alignment (BIA) was proposed for RF systems for the sake of aligning the interference without the need for CSIT [4]. This scheme is characterized by its positive precoding matrices. In this context, the implementation of BIA schemes for VLC results in avoiding the constraints mentioned above. However, by combining VLC systems with BIA schemes, several crucial issues must be taken into consideration such as the length of the supersymbol and the increasing noise. In [5], the authors proposed a special detector, which is composed of multiple photodiodes referred to as reconfigurable photodetector. This detector has the ability to vary the orientation of each photodiode, and thus provide several linearly independent channel responses, which are required to apply BIA. It is shown that, BIA schemes can provide higher user rates compared to traditional TPC schemes. However, BIA schemes demand high signal to noise ratio (SNR) to align the interference correctly with minimum error.

For ICI management, various network topologies can be implemented for VLC systems. In [6]–[8] a network centric (NC) design is proposed to minimize the ICI. However, the NC approach leads to constructing static cells, which are fixed over time regardless of the distribution of users. As a consequence, unbalance the load among NC cells is expected, as well as degrading the achievable rate of users located at the edges of NC cells. From this point, a network topology from the user centric (UC) perspective considering the implementation of BIA is proposed in [7], [8]. The UC design divides the whole VLC area into multiple elastic cells in regards to the distribution of users. Therefore, these UC cells can be updated according to any changes in the VLC network such as the mobility of users or optical AP might be turned on or off. In this sense, each cell is composed of several optical APs merged together to serve multiple users based on BIA schemes. It is shown that, BIA based on the UC approach is more suitable for VLC than traditional BIA schemes due to enhancing the SNR.

In contrast to the works mentioned above, in this work, we formulate an optimization problem that can jointly determine the optimal number of users and optical APs within each cell, while relaxing the limitations of BIA. The optimal solution can be found through exhaustive search. However, this solution is impractical due to its high cost in terms of complexity. Therefore, we propose a sub-optimal algorithm based on decoupling the original problem into two sub-problems of users sets and optical APs sets. The simulation results demonstrate that the sub-optimal algorithm can provide a solution significantly close to the exhaustive search with much less complexity. Moreover, BIA based on the proposed algorithms is more suitable for VLC than considering traditional BIA schemes, conventional TPC schemes or maximum ratio combining (MRC) [9].

II. System Model

We consider a VLC indoor network composed of L, $l = \{1, \ldots, L\}$, optical APs serving K, $k = \{1, \ldots, K\}$, users randomly distributed on the receiving plane. Moreover, each user is equipped with a reconfigurable photodetector able to provide at least $M = L$ linearly independent channel responses denoted as preset modes, where M is the number of photodiodes used in the receiver, more details in [5]. Thus, the transmitted signal by the set of optical APs at time n is given by

$$\mathbf{x} = [x_1[n] \ldots\ldots x_L[n]]^T \in \mathbb{R}_+^{L\times 1}, \quad (1)$$

where $x_l[n]$ is the signal transmitted by optical AP l. Focussing on user k, the received signal at time n is

$$y^{[k]}[n] = \mathbf{h}^{[k]}(m^{[k]}[n])^T \mathbf{x}[n] + z^{[k]}[n], \quad (2)$$

where $\mathbf{h}^{[k]}(m^{[k]}[n])^T \in \mathbb{R}_+^{L\times 1}$ is the channel vector between L optical APs and user k at specific preset mode m selected by reconfigurable photodetector at time n. Moreover, $z^{[k]}[n]$ is defined as a real valued additive white Gaussian noise with zero mean, and having a total variance given by the sum of contributions from both the shot noise and the thermal noise, i.e., $\sigma_z^2 = \sigma_{shot}^2 + \sigma_{thermal}^2$ [10].

It is interesting to mention that, the optical APs do not have any information, i.e., do not have any CSIT, except the coherence time of the network and the topological distribution of the users. Furthermore, the selected preset mode by user k at time n, for instance $m^{[k]}[n]$, is predetermined and known beforehand.

A. VLC channel model

The reconfigurable photodetector as is shown in Fig. 1, composed of a set of photodiodes $m = \{1.....M\}$. These photodiodes can be allocated on a geometrical pattern such as the pyramid geometrical structure, and orientated perpendicularly upwards to provide a set of preset modes [5]. Let us now define the optical channel, which has Line-of-Sight (LoS) component denoted as h_{LoS} and non-LoS (NLoS) component denoted as h_{NLoS} caused by the multi-path propagation. It is worth mentioning that, each user is equipped with a reconfigurable photodetector providing a wide field-of-view (FoV), and therefore, the LoS optical component can be considered as the largest portion of the received optical power. Given this point, the diffuse component can be neglected, i.e., $h_{NLoS} = 0$, for the sake of simplicity [11]. In particular, LoS optical channel gain between optical AP l and photodiode m of user k at time n defined as DC gain is given by [12]:

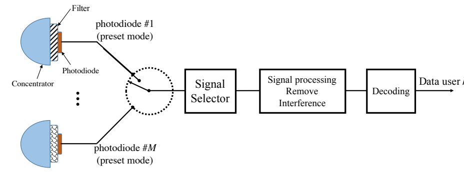

Fig. 1. Architecture of the reconfigurable photodetector.

$$h_{LoS}^{[k,l]}(m) = \begin{cases} \dfrac{\delta_m A_m}{d_{lm}^2} R_0(\phi_k(m)) s(\varphi_k(m)) \cos^r(\varphi_k(m)) & 0 \leq \varphi_k \leq \Psi_F \\ 0 \qquad \text{if } \varphi_k(m) \geq \Psi_F, \end{cases} \quad (3)$$

where δ_m and A_m denote the responsivity coefficient and the physical area of the photodiode m, respectively, and d_{lm} is the average distance between the optical AP l and the photodiode m, which can be given by the sum of the square of the horizontal distance between them d_{ho}^2 and the square of the height of the room d_{he}^2, i.e., $d_{lm}^2 = d_{ho}^2 + d_{he}^2$. Moreover, R_0 denotes the Lambertian radiation intensity, $R_0 = \dfrac{v+1}{2\pi}\cos^v(\phi)$, where $v = \dfrac{-\ln 2}{\ln(\cos(\phi_{1/2}))}$ is the order of Lambertian emission, and $\phi_{1/2}$ is the transmitter semiangle. Finally, $s(\varphi_k(m)) = T(\varphi_k(m)) \times g(\varphi_k(m))$, where $T(\varphi_k(m))$ and $g(\varphi_k(m))$ are the gains of the optical filter and concentrator, respectively, and r is the coefficient associated with its FoV angle Ψ_F.

III. Blind Interference Alignment

BIA scheme was first proposed in [4] to avoid the cost of providing CSIT in RF networks. To apply BIA in cellular networks, each user must have the ability to switch its radiation pattern among a sequence of symbol extensions. The reconfigurable receiver was first presented in [5] with the aim of applying BIA for VLC networks. In this section, the methodology of BIA is briefly described for a toy example, and then the general case is considered.

Let us consider a simple VLC network composed of $L = 2$ optical APs providing illumination and data service to $K = 2$ users. In this sense, the reconfigurable photodetector of each user follows a switching pattern as described in Fig. 2. The switching patterns of both users compose the supersymbol for the considered case. The signal transmitted at a symbol extension, i.e., time slot, is defined as $\mathbf{x}[n] = \begin{bmatrix} x_1[n] & x_2[n] \end{bmatrix}^T$, Time slot

	1	2	3
User 1	$\mathbf{h}^{[1]}(1)$	$\mathbf{h}^{[1]}(2)$	$\mathbf{h}^{[1]}(1)$
User 2	$\mathbf{h}^{[2]}(1)$	$\mathbf{h}^{[2]}(1)$	$\mathbf{h}^{[2]}(2)$

[t] (time slot)

Fig. 2. BIA supersymbol for $L = 2$ optical APs serving $K = 2$ users. Each color represents a preset mode

where $x_l[n]$ is the signal of the optical AP l. Moreover, the signal transmitted over the entire supersymbol, which comprises three time slots, is

$$\mathbf{X} = \begin{bmatrix} \mathbf{x}[1] \\ \mathbf{x}[2] \\ \mathbf{x}[3] \end{bmatrix} = \begin{bmatrix} \mathbf{I}_2 \\ \mathbf{I}_2 \\ \mathbf{0}_2 \end{bmatrix} \mathbf{u}^{[1]} + \begin{bmatrix} \mathbf{I}_2 \\ \mathbf{0}_2 \\ \mathbf{I}_2 \end{bmatrix} \mathbf{u}^{[2]}, \quad (4)$$

where $\mathbf{u}^{[k]} = \begin{bmatrix} u_1^{[k]} & u_2^{[k]} \end{bmatrix}^T$ is the vector of symbols intended to user k, and $u_l^{[k]}$ is the symbol transmitted by optical AP l to user k. Moreover, $\mathbf{I}_2$ and $\mathbf{0}_2$ are the 2×2 identity and zero matrices, respectively. Still referring to Fig. 2, the supersymbol comprises two parts; Block 1 represented by the symbol extension 1 where both users are receiving their information simultaneously, and Block 2 represented by the symbol extensions 2 and 3 during them the users are receiving their information in orthogonal fashion, i.e., in a dedicated time slot. Notice that, for this toy example, 2 DoF are intended to each user during the entire supersymbol.

Focussing on user 1, the signal received during the entire supersymbol can be written as

$$\begin{bmatrix} y^{[1]}[1] \\ y^{[1]}[2] \\ y^{[1]}[3] \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{h}^{[1]}(1)^T \\ \mathbf{h}^{[1]}(2)^T \\ \mathbf{0}_{2,1}^T \end{bmatrix}}_{\text{rank}=2} \mathbf{u}^{[1]} + \underbrace{\begin{bmatrix} \mathbf{h}^{[1]}(1)^T \\ \mathbf{0}_{2,1}^T \\ \mathbf{h}^{[1]}(1)^T \end{bmatrix}}_{\text{rank}=1} \mathbf{u}^{[2]} + \begin{bmatrix} z^{[1]}[1] \\ z^{[1]}[2] \\ z^{[1]}[3] \end{bmatrix}. \quad (5)$$

Notice that, the desired signal $\mathbf{u}^{[1]}$ is contained in a full-rank matrix $\begin{bmatrix} 1 & 1 & 0 \end{bmatrix}^T$, while the interference received due to transmission to user 2 is aligned into one dimension over the vector $\begin{bmatrix} 1 & 0 & 1 \end{bmatrix}^T$, i.e., the interference is aligned in a rank-1 matrix. This is because of the orthogonality between the symbols $\mathbf{u}^{[1]}$ and $\mathbf{u}^{[2]}$ that can be easily checked since they are transmitted independently over the second and third time slots. Consequently, user 1 dedicates the third time slot to measure the interference due to the transmission of $\mathbf{u}^{[2]}$ and subtract it afterwards. Similarly, user 2 can cancel the interference caused by the transmission of the symbol intended to user 1, i.e., $\mathbf{u}_1^{[1]}$, by measuring it at the second time slot. Still focussing on user 1, the signal received after subtracting the interference can be written as

$$\begin{bmatrix} y^{[1]}[1] - y^{[1]}[3] \\ y^{[1]}[2] \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{h}^{[1]}(1)^T \\ \mathbf{h}^{[1]}(2)^T \end{bmatrix}}_{\mathbf{H}^{[1]}} \mathbf{u}^{[1]} + \begin{bmatrix} z^{[1]}[1] - z^{[1]}[3] \\ z^{[1]}[2] \end{bmatrix}. \quad (6)$$

Notice that, the interference is completely removed and $\mathbf{H}^{[1]} = \begin{bmatrix} \mathbf{h}^{[1]}(1)^T & \mathbf{h}^{[1]}(2)^T \end{bmatrix}^T \in \mathbb{R}_+^{2\times 2}$ is a full rank matrix given by the preset modes of the reconfigurable photodetector, which provides linearly independent channel responses. Thus, 2 DoF in $\mathbf{u}^{[1]}$ can be decoded by solving the linear equation system (6). Similarly, user 2 can decode 2 DoF contained in symbol $\mathbf{u}^{[2]}$, which is transmitted over the time slots $\{1, 3\}$. As a result, each user achieves 2 DoF during a supersymbol comprising 3 time slots. Therefore, $\frac{4}{3}$ sum-DoF can be achieved in a scenario composed of $L = 2$ optical APs serving $K = 2$ users in the absence of CSIT. Notice that, conventional orthogonal transmission schemes such as TDMA are limited to a sum-DoF equals to 1.

Considering a Broadcast (BC) general case with L optical APs and K users, BIA scheme provides $(L-1)^{K-1}$ alignment blocks per user containing L DoF each. In this sense, the entire supersymbol must comprises

$$\Lambda_{\text{BIA}} = (L-1)^K + K(L-1)^{K-1}, \quad (7)$$

time slots. Therefore, the achievable sum-DoF per time slot is

$$\text{DoF}_{\text{BIA}} = \frac{LK(L-1)^{K-1}}{(L-1)^K + K(L-1)^{K-1}} = \frac{LK}{L+K-1}. \quad (8)$$

Moreover, for a BC general case, the achievable rate of the user k considering BIA is [4],

$$R_{\text{BIA}}^{[k]} = \frac{1}{L+K-1} \log_2 \left(\mathbf{I} + P_{\text{str}} \mathbf{H}^{[k]} {\mathbf{H}^{[k]}}^H {\mathbf{R}_z}^{-1} \right), \quad (9)$$

where P_{str} is the power allocated to each stream, $\mathbf{H}^{[k]} = \begin{bmatrix} \mathbf{h}^{[k]}(1) & \dots & \mathbf{h}^{[k]}(L) \end{bmatrix}^T \in \mathbb{R}^{L\times L}$ is the channel matrix of the user k, and $\mathbf{R}_z = \begin{bmatrix} K\mathbf{I}_{L-1} & 0 \\ 0 & 1 \end{bmatrix}$ is the covariance matrix of the noise.

IV. User Centric Design

Applying the BIA scheme explained in Section III directly to VLC networks results in a full connectivity network, i.e., all users are connected to all optical APs. Although this approach completely cancels the interference, it is not suitable for VLC networks with high density, since it generates a great increase in noise (see (6)) and a huge length of the supersymbol. Alternatively, BIA schemes must be modified in order to become more suitable for VLC networks.

One way of enhancing the performance of BIA schemes is to consider a network centric (NC) approach. This approach relies on forming several static cells, each consists of multiple optical APs grouped in a static way to serve multiple users belong to their coverage area. It is worth mentioning that, the NC approach has a number of drawbacks that must be considered such as it is not responsive to the changes in the network topology where an optical AP might be turned off or on, and the static cells are formed regardless of the distribution of the users. These issues might lead to inequality in the load among the constructed cells. Moreover, the NC approach cannot minimize the ICI due to its static deployment [6], [7]. These limitations lead to the need for an alternative approach for VLC networks. In this sense, a UC approach has been proposed in [7], [8] for VLC networks. In this case, the cells are constructed from the UC perspective, and change dynamically with the network topology and the users mobility. In comparison to the NC approach, the UC design has a high complexity with additional signalling while it gives the best result in terms of the ICI mitigation and overcoming the constraints of BIA. In the following, an optimization problem is formulated to form several optimal UC cells based on maximizing the sum utility of users rates, and under the constraints of BIA, i.e., the number of users and optical APs within each cell, to ensure a high SNR, which relaxes the limitations of BIA.

Let us first introduce some notation, where C is the set of constructed cells, and each cell $c \in C$ is composed of a set of optical APs $\mathcal{V}_{\mathcal{L}_c}$ containing $|\mathcal{V}_{\mathcal{L}_c}| = \mathcal{V}_{\mathcal{L}_c}$ optical APs, and a set of users $\mathcal{V}_{\mathcal{K}_c}$ containing $|\mathcal{V}_{\mathcal{K}_c}| = \mathcal{V}_{\mathcal{K}_c}$ users. In order to avoid the interference among the C cells, the optical APs and users of each cell must be unique elements, i.e.,$\mathcal{V}_{\mathcal{L}_c} \cap \mathcal{V}_{\mathcal{L}'_c} = \emptyset$ and $\mathcal{V}_{\mathcal{K}_c} \cap \mathcal{V}_{\mathcal{K}'_c} = \emptyset$. Now, we carry out the optimal and sub-optimal UC designs.

A. Optimal UC design

In this section, we formulate an optimization problem where we divide the whole VLC area into several optimal cells from the UC perspective. First, we consider a setting where a user k receives a data rate denoted by $R^{[k,l]}$ from an optical AP l. Recall that, each user is equipped with a reconfigurable photodetector providing a wide FoV. Thus, each of the K users is able to connect to most of the optical APs. Given this point, the optimal cells that maximize the sum of the users rates are determined by searching all the possible user-optical AP combinations. In this sense, two new variables are introduced: $x^{[l,c]}$ and $e^{[k,c]}$, which are given by

$$x^{[l,c]} = \begin{cases} 1 & \text{if AP } l \text{ is in the cell } c \\ 0 & \text{otherwise,} \end{cases} \tag{10}$$

and

$$e^{[k,c]} = \begin{cases} 1 & \text{if user } k \text{ is in the cell } c \\ 0 & \text{otherwise,} \end{cases} \tag{11}$$

respectively. Notice that, our aim is to jointly find the optimal UC cells and align the interference among the users within each cell. Specifically, the objective function is based on maximizing the sum utility of the users rates within each cell under the constraints of BIA, i.e., the length of the supersymbol and the noise increase, and therefore, the optimization problem is formulated as

$$\begin{aligned} c*(\mathcal{V}_{\mathcal{L}_c}, \mathcal{V}_{\mathcal{K}_c}) = \arg\max_{x,e} \quad & \sum_{l\in L}\sum_{k\in K} x^{[l,c]} e^{[k,c]} \log(R^{[k,l]}) \\ \text{s.t.} \quad & \sum_{l\in L} x^{[l,c]} = \mathcal{V}_{\mathcal{L}_c}, \\ & \sum_{k\in K} e^{[k,c]} = \mathcal{V}_{\mathcal{K}_c}, \\ x^{[l,c]} \in \{0,1\}, e^{[l,c]} \in & \{0,1\}, \mathcal{V}_{\mathcal{L}_c} < L, \mathcal{V}_{\mathcal{K}_c} < K, \end{aligned} \tag{12}$$

where $\log(R^{[k,l]})$ is the logarithmic utility function of the achievable rate of the user k from the optical AP l. It is worth mentioning that, this function naturally achieves fairness among the users. Moreover, the first constraint introduces the set of optical APs $\mathcal{V}_{\mathcal{L}_c}$, while the second constraint is given by the set of users $\mathcal{V}_{\mathcal{K}_c}$. Finally, the last constraint limits the number of optical APs and users per cell, and ensures that the length of the supersymbol is shorter than the case of full connectivity, i.e.,

$$(\mathcal{V}_{\mathcal{L}_c} - 1)^{\mathcal{V}_{\mathcal{K}_c}} + \mathcal{V}_{\mathcal{K}_c}(\mathcal{V}_{\mathcal{L}_c} - 1)^{\mathcal{V}_{\mathcal{K}_c}-1} < \Lambda_{\text{BIA}}. \tag{13}$$

The optimization problem in (12) is not tractable, and not easy to solve. More explicitly, the achievable user rate based on BIA cannot be obtained before the cells are already formed. In the following; we consider a user k belonging to a cell c, which is composed of $\mathcal{V}_{\mathcal{L}_c}$ optical APs serving $\mathcal{V}_{\mathcal{K}_c}$ users. The signal received by user k during the symbol $\mathbf{u}_\ell^{[k,c]}$, where ℓ corresponds to an alignment block, i.e. resource block allocated based on BIA, $\ell = \{1, \dots, (\mathcal{V}_{\mathcal{L}_c}-1)^{\mathcal{V}_{\mathcal{K}_c}-1}\}$, carries $\mathcal{V}_{\mathcal{L}_c}$ DoF after canceling the interference, can be written as

$$\mathbf{y}^{[k,c]} = \mathbf{H}^{[k,c]}\mathbf{u}_\ell^{[k,c]} + \sum_{c'=1, c'\neq c}^{C} \sqrt{\alpha_{c'}^{[k,c]}}\mathbf{H}^{[k,c']}\mathbf{u}_\ell^{[k,c']} + \mathbf{z}^{[k,c]}, \tag{14}$$

where $\mathbf{H}^{[k,c]}$ is the channel matrix of the user k. It contains $\mathcal{V}_{\mathcal{L}_c}$ linearly independent channel responses given by

$$\mathbf{H}^{[k,c]} = \begin{bmatrix}\mathbf{h}^{[k,c]}(1) & \dots & \mathbf{h}^{[k,c]}(\mathcal{V}_{\mathcal{L}_c})\end{bmatrix} \in \mathbb{R}_+^{\mathcal{V}_{\mathcal{L}_c}\times 1}, \tag{15}$$

$\alpha_{c'}^{[k,c]}$ is the signal-to-interference ratio (SIR) of user k due to other cells $c \neq c'$, and $\mathbf{u}_\ell^{[k,c']}$ defines the interfering symbols received from the neighboring cells during the reception of the desired symbol $\mathbf{u}_\ell^{[k,c]}$. Interestingly, since the UC approach is considered for the sake of constructing multiple cells, each with unique elements, the interfering signal can be simply treated as noise. Finally, $\mathbf{z}^{[k,c]}$ is the noise after the interference subtraction defined by a covariance matrix, i.e.,

$$\mathbf{R}_{\mathbf{z_p}} = \begin{bmatrix} (\mathcal{V}_{\mathcal{K}_c})\mathbf{I}_{\mathcal{V}_{\mathcal{L}_c}-1} & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix}. \tag{16}$$

Therefore, according to [4], the data rate achieved by the user k belonging to cell c is

$$R^{[k,c]} = B^{[k,c]}\mathbb{E}\left[\log\det\left(\mathbf{I}_L + P_{\text{str}}\mathbf{H}^{[k,c]}{\mathbf{H}^{[k,c]}}^H\mathbf{R}_{\tilde{\mathbf{z}}}^{-1}\right)\right], \tag{17}$$

where $B^{[k,c]} = \dfrac{(\mathcal{V}_{\mathcal{L}_c} - 1)^{\mathcal{V}_{\mathcal{K}_c}-1}}{(\mathcal{V}_{\mathcal{L}_c} - 1)^{\mathcal{V}_{\mathcal{K}_c}} + \mathcal{V}_{\mathcal{K}_c}(\mathcal{V}_{\mathcal{L}_c} - 1)^{\mathcal{V}_{\mathcal{K}_c}-1}} = \dfrac{1}{\mathcal{V}_{\mathcal{K}_c} + \mathcal{V}_{\mathcal{L}_c} - 1}$ is the ratio of alignment blocks allocated for each of the $\mathcal{V}_{\mathcal{K}_c}$ users over the entire supersymbol, and

$$\mathbf{R}_{\tilde{\mathbf{z}}} = \mathbf{R}_{\mathbf{z_p}} + P_{\text{str}}\sum_{c'=1}^{C}\alpha_{c'}^{[k,c]}\mathbf{H}^{[k,c']}{\mathbf{H}^{[k,c']}}^H, \tag{18}$$

is the covariance matrix of the noise plus the interference received from other cells $c \neq c'$.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of LED transmitters per optical AP	1
Bandwidth for each VLC AP	20 MHz
Physical area of the photodiode	15 mm^2
Transmitter semi-angle	45 deg
Receiver FoV	70 deg
Detector responsivity	0.53 A/W
Gain of optical filter	1.0
Noise power spectral density for optical AP	$10^{-22} A^2/Hz$
NC cells	4

As a consequence, the maximum value of (12) can be achieved by searching the optimal user-optical AP combinations. This is obtained by exhaustively searching all the possible combinations. Recall that, VLC networks are usually composed of a high number of optical APs serving multiple users, and therefore, this joint problem has an excessive computational complexity given by $\left(\prod_{l=1}^{L}(K)\right)$ to form the first cell. In the following, the problem in (12) is decoupled into two sub-problems that can be solved separately. As a consequence, the computational complexity is reduced, while providing a solution significantly close to the optimal solution given by solving (12).

B. Sub-optimal UC design

In this approach, we first determine C sets of users based on the K-means algorithm, and then the optical APs set for each users set is calculated based on the received optical power [7].

1) Users sets formation: The K-means algorithm is one of the most popular clustering algorithms that can classify the users through an iterative procedure into several optimal groups [13]. The basic clustering procedure of the K-means starts with initializing C cells randomly or based on some prior knowledge. After that, the prototype matrix is calculated for each cell by assigning each user to the nearest cell center, and then recalculating the prototype matrix of each cell based on the current partition. This procedure is continued until there is no change in the centroid of each cell.

Let us consider that, C centroids are selected randomly, each corresponding to a cell with a centroid at the $i-$th iteration denoted as $\xi_c(i) = (x_{\xi_c(i)}, y_{\xi_c(i)})$, where $c \in C$, and $(x_{\xi_c(i)}, y_{\xi_c(i)})$ are the initial coordinates of the cell centroid. At the first iteration, the centroid of a cell c is represented by the location of a user k, i.e., (x_k, y_k), which is selected randomly. After that, each user is assigned to the closest centroid, i.e.,

$$k = \arg\min_{k \in K} \ \mathrm{dist}(k, \xi_c(i)), \tag{19}$$

where $\mathrm{dist}(k, \xi_c(i))$ is the Euclidean distance between the user k and the centroid $\xi_c(i)$ of the cell c at the $i-$th iteration, which is equal to $\mathrm{dist}(\xi_c(i), k) = \sqrt{(x_k - x_{\xi_c(i)})^2 + (y_k - y_{\xi_c(i)})^2}$. As a consequence, the centroid of the cell c is updated to

$$\xi_c(i+1) = \left(\frac{x_{\xi_c(i)} + x_k}{2}, \frac{y_{\xi_c(i)} + y_k}{2}\right). \tag{20}$$

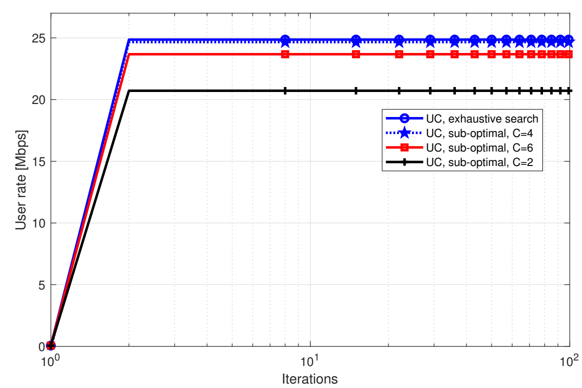

Fig. 3. Average user rate over 100 iterations for the proposed schemes.

It is updated based on the coordinates of the newly included user. Notice that, if more than one user satisfies (19) through a given iteration i, only one user is assigned randomly. The same procedure must be repeated iteratively until there is no change in the centroid of the cell c. Finally, C optical cells are constructed each with a unique set of users i.e., $\mathcal{V}_{\mathcal{K}_c} \cap \mathcal{V}_{\mathcal{K}'_c} = \emptyset$.

2) Optical APs sets formation: In this step, the corresponding set of optical APs for each of the C cells that result from the last step is determined. In order to guarantee the maximization of the received optical power, the optical APs set $\mathcal{V}_{\mathcal{L}_c}$ of the cell c must include the optical APs that have minimum distance to the centroid ξ_c. As a consequence, a threshold distance has to define, denoted as d_{th}. This distance determines the threshold power level, which is denoted as P_{th}. In this sense, each optical AP that satisfies the following condition

$$P_l^{[c]} \geq P_{th}, \tag{21}$$

where $P_l^{[c]}$ is the optical power received by the $\mathcal{V}_{\mathcal{K}_c}$ users of the cell c from an optical AP l, will be included in the optical APs set $\mathcal{V}_{\mathcal{L}_c}$. It is worth mentioning that, if one optical AP satisfies the condition (21) with more than one cell, it is randomly assigned to one of them for the sake of avoiding the interference, i.e., $\mathcal{V}_{\mathcal{L}_c} \cap \mathcal{V}_{\mathcal{L}'_c} = \emptyset$. Taking into account the limitations of BIA, i.e., the length of the supersymbol and the noise increase, the number of optical APs belonging to each set is limited by

$$\mathcal{V}_{\mathcal{L}_c} \leq L_{max}, \tag{22}$$

where L_{max} is the maximum number of optical APs per cell, which can result in relaxing the requirements of BIA [1] [8]. Following the same procedure, C sets of optical APs are constructed.

Finally, by combining each set of users with its corresponding optical APs set, i.e., $\mathcal{V}_{\mathcal{K}_c} \cup \mathcal{V}_{\mathcal{L}_c} = c$, C cells are constructed.

[1]Notice that, the number of users within each cell, which is also a vital parameter in the limitations of BIA whether the coherence time constraint or the noise increase, is calculated based on the optimality of the K-means algorithm. Therefore, different numbers of C must be tried until the optimal number of users per cell is found.

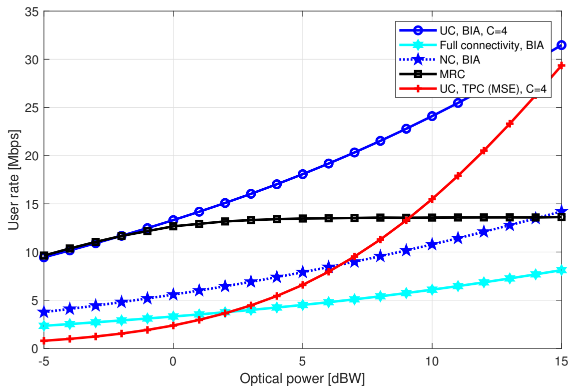

Fig. 4. Average user rate versus the transmitted optical power per optical AP for the proposed scheme in comparison with several benchmark schemes.

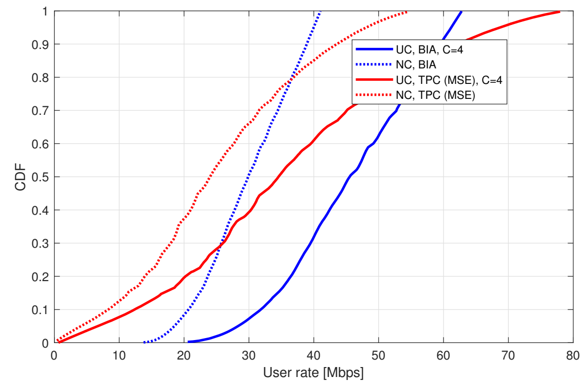

Fig. 5. CDF of the user rate for the proposed scheme in comparison with TPC scheme.

V. Simulation Results

In this section, we investigate the performance of the proposed schemes based on BIA for a VLC network in an indoor scenario. Specifically, we consider a hall (15 m $\times$15 m $\times$3 m) covered by $L = 16$ optical APs uniformly deployed on the ceiling serving $K = 20$ users randomly distributed. Moreover, each user is equipped with a reconfigurable photodiode that provides at least L preset modes. Our simulation is carried out for random independent snapshots of the users distributions. The other parameters are summarized in Table I.

In Fig. 3, the optimality of the proposed schemes is depicted in term of the achievable user rate versus a set number of iterations. It is shown that, the optimal solution provided by the exhaustive research achieves 25 Mbps user rate over 100 iterations. On the other hand, it is expected that the performance of the proposed sub-optimal solution is highly affected by the value of C. Considering three different values of C, $C = \{2, 4, 6\}$, it can be seen that $C = 4$ is the optimal number of cells that can provide a user rate significantly close to 25 Mbps, i.e., the number of cells that results in the balance between minimizing the ICI and overcoming the limitations of BIA. This is because, assigning a number of cells equals to 2 might lead to constructing cells with a large size, i.e., a high number of users and optical APs within each cell, and therefore, the performance of BIA is degraded due to the channel coherence time limitation and the increasing noise. While, the number 6 of cells means that several cells are constructed, each with a small size, resulting in a high ICI among them. From now on, we consider the sub-optimal solution of $C = 4$ due to its low complexity given by $O(IKC)$, where I is the total number of iterations, compared with the optimal solution.

In Fig. 4, the comparison between the proposed schemes and other benchmark schemes is shown in terms of the user rate against the optical power. It can be seen that, BIA based on the UC design achieves higher user rate than NC or full connectivity approaches. The NC and full connectivity approaches are limited by the ICI, and the number of both users and optical APs, respectively. The figure further shows that, BIA is more suitable for VLC than the TPC scheme, which requires a high optical power that can harm the human vision for the sake of providing user rate close to BIA. Besides, MRC is inferior to BIA due to the fact that it is highly subject to the ICI especially for optical powers higher than 5 dBW.

Finally, the cumulative distribution function (CDF) of the user rate considering different scenarios is plotted in Fig. 5. It is shown that, the curves of BIA are less sloped indicating a fair rate distribution among users when UC or NC approaches are implemented. For the UC approach, 50% of users achieve a user rate higher than 45 Mbps, while for the NC design, 50% of users achieve a user rate higher than 30 Mbps. On the other hand, the rate distribution of the TPC scheme is pretty unfair among users, where only 30% of users achieve a user rate higher than 45 Mbps and 32 Mbps implementing UC and NC approaches, respectively.

VI. Conclusions

In this work, a UC formation is proposed for a VLC network taking into account the limitations of BIA schemes. We first formulated an optimization problem that aims to find the optimum UC cells through exhaustive search. Despite the optimality of this approach, it is not a practical solution due to its high complexity. To make the problem more tractable to solve, it is decoupled into two sub-problems, i.e., users sets and optical APs sets formations, that can be solved separately with less complexity. The results demonstrate that the proposed schemes are more suitable for the VLC network than implementing NC or full connectivity approaches. Moreover, BIA is superior to TPC and MRC schemes. In the future work, we will formulate UC optimization problems for VLC networks with high mobility considering the requirement of users in order to ensure the high quality of service based on BIA.

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