The Role of WiFi in LiFi Hybrid Networks Based on Blind Interference Alignment

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The role of WiFi in LiFi hybrid networks based on Blind Interference Alignment

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***Abstract*—Visible light communications (VLC) have been proposed as a means of moving part of the indoor traffic to the optical spectrum. The deployment of LED lights for data transmission forming attocells in the cellular networks known as Light-Fidelity (LiFi) interacts with other radiofrequency (RF) based networks such as WiFi or femtocells. Since LED lights illuminate a small confined area and interfere with other LED lights, the hybrid network composed of the LiFi and RF systems can be employed for resource management allocating each user to a specific network. In this work, we consider the use of a novel inference management scheme for LiFi known as Blind Interference Alignment (BIA) that avoids both the multi-user and the intercell interference. However, BIA schemes are limited by noise increase due to interference subtraction and the channel coherence block requirement, which increase with the number of user served by the LiFi network. It is shown that the hybrid LiFi/RF network allow to relax the requirements for BIA implementation and increase the sum-rate of the whole network.**

I. Introduction

White light emitting diodes (LEDs) have been widely used because of lifetime, eco-friendliness, and lighting efficiency. The use of LED technology for providing illumination can be employed for data transmission by modulating the optical intensity usually, which is usually referred to as visible light communications (VLC). Due to the limited availability of the radio frequency (RF) spectrum, the increasing number of mobile devices and the extensive use of data-demanding mobile applications VLC is considered as a promising technology for the fifth generation of mobile communications and beyond [1]. From the network perspective the use of VLC Access Points (AP) and its interaction with other elements of the cellular network is known as Light-Fidelity (LiFi) [2].

VLC systems are usually composed by several APs denoted as *attocells* [2]. Although each AP provides lightning in a small confined area, VLC systems are subject to multi-user interference and also to intercell interference among the attocells. Moreover, VLC systems require to define a naturally separated uplink and downlink. Notice that uplink transmission is not usually carried out through an optical channel [3]. The use of auxiliary radio access networks such as WiFi or pico/femto cells is usually proposed for this issue. Thus, the hybrid network composed of the LiFi and RF systems can be exploited for optimization of the load balancing [4], [5]. At this point, the hybrid LiFi/RF networks presents a new paradigm able to improve the overall efficiency through a vertical handover to the complementary network when a user is limited by interference, network load or simply the receiving lighting is obstructed by an element of the scenario.

Managing the interference without the need of orthogonal resource allocation, i.e. dividing the time/bandwidth among the number of users, is a inherited problem from RF cellular networks. In this sense, several transmit precoding schemes such as zero forcing (ZF) or interference alignment (IA) have been proposed during the last decade [6]. However, these schemes require accurate Channel State Information at the Transmitter (CSIT) and cooperation among transmitters. In [7], [8] an alternative scheme referred to as Blind Interference Alignment (BIA) based on exploiting the channel correlations of the users, which are equipped with a reconfigurable antenna each, is proposed to achieve the optimum Degrees of Freedom (DoF) without CSIT. The implementation of BIA schemes require to equip each user with a reconfigurable photodetector, which concept is introduced in [9]. However, BIA schemes require a channel coherence length and a SNR large enough to create a predefined pattern denoted as supersymbol to remove the interference by measuring and subtracting it afterwards. In [10] the authors analyze the use of BIA in practical RF-based networks. However, the proposed approach results useless for hybrid LiFi/RF networks.

In this work we analyze the use of BIA in a hybrid LiFi/RF network for maximizing the achievable rate in the whole network. We consider the use of network BIA (nBIA) [8] for VLC based on differentiating between private users located in the inner area of a single attocell that can treat the intercell interference as noise and shared users at the cell-edge receiving a useful signal from several attocells. Notice that this approach avoids the interference among the LiFi users. However, the achievable rate decreases as the number of users served by the LiFi network and the BIA supersymbol results more demanding in terms of channel coherence. We analyze the vertical handover to the RF network of the users that penalize the achievable rate for the BIA scheme of the LiFi network. Simulation results show that this approach achieves a considerable increase of the rate in the whole network regarding the use of a single system to serve all the users.

II. System Model

We consider a LiFi/WiFi hybrid system as is shown in Fig. 1. This hybrid network provides data service in an indoor

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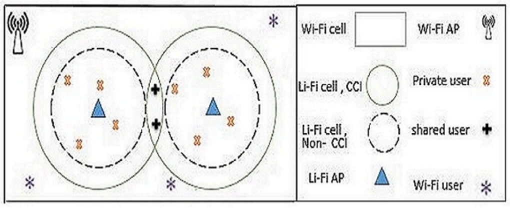

Fig. 1: Topological management in a hybrid LiFi/RF network.

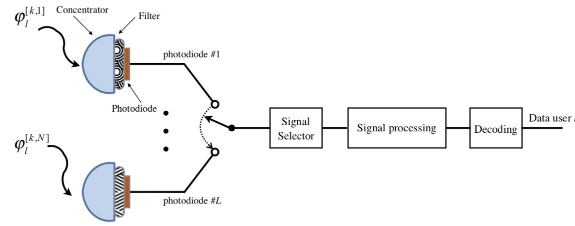

Fig. 2: Scheme of the reconfigurable receiver. Each photodiode provides a linearly independent response (preset mode) connected through a selector to a single signal processing chain.

area employing L LiFi APs, $li = \{li_1, \ldots, li_m\}$ equipped with N_L LEDs each and a single WiFi AP. In this scenario, a set of $k_{hyb} = [k_1, \ldots, k_{hyb}]$ users equipped with a reconfigurable photodetector (see Fig. 2) are uniformly distributed. Each LiFi AP employs the same modulation bandwidth for data transmission generating co-channel interference (CCI). Although each LiFi AP provides lightning in a confined area, the neighbouring attocells overlaps generating intercell interference. On the other hand, the RF system covers the entire indoor area. Assuming this architecture, each user is either connected to a LiFi AP or to the RF AP for downlink wireless communications. Therefore, the K_{tot} users can be split between K_{li} LiFi and K_{wi} RF users. Moreover, the LiFi users are subject to a topological approach differentiating between k_p private users per attocell and k_s shared users depending on the intercell interference [8].

Each LiFi AP $li \in L$ sends data to a set of private users $k_{p,li} = [p_{1,li}, \ldots, p_{k_{p,li},li}]$ located in Non-CCI area as well as a set of shared users $k_s = [s_1, \ldots, s_{k_s}]$ located in CCI area. As in [9] each private user is equipped with a reconfigurable photodetector that can switch among N_L preset modes that provide a linearly independent channel response each. Denoting the signal transmitted by the set of LiFi APs at time n as

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

where $\mathbf{x}^{[li]}[n] \in \mathbb{R}_+^{N_L\times 1}$ is the signal transmitted by the LiFi AP li. Thus, the signal received by the private user $p_{k,li}$ is

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

where $i^{[p_{k,li}]}$ is the preset mode selected by the private user $p_{k,li}$ and $z^{[p_{k,li}]}$ is real valued additive white Gaussian noise with zero mean and variance σ_z^2 and

$$\mathbf{h}^{[p_{k,li}]} = [\mathbf{h}^{[p_{k,li},1]^T} \ldots \mathbf{h}^{[p_{k,li},li]^T} \ldots \mathbf{h}^{[p_{k,li},L]^T}] \quad (3)$$

$$a \approx \left[\mathbf{0}_{a,1}^T, \ \mathbf{h}^{[p_{k,li},li]^T}, \ \mathbf{0}_{b,1}^T\right] \in \mathbb{R}_+^{M\times 1} \quad (4)$$

with $a = \sum_{li'=1}^{li-1} N_L$, $b = \sum_{li'=li+1}^{L} N_L$ and $0_{c\times 1}$ is a vector of zeros of dimension $c \times 1$. In (1) $\mathbf{x}^{[li]}[n] \in \mathbb{R}_+^{N_L\times 1}$ is the signal sent by LiFi AP li at time n. In (3) $\mathbf{h}^{[p_{k,li},li]}(i)^T = [h_1^{[p_{k,li},li]}(i)^T \ldots h_{N_L}^{[p_{k,li},li]}(i)^T] \in \mathbb{R}_+^{N_L\times 1}$ is the channel coefficients between LEDs of li LiFi AP and the private user $p_{k,li}$ when photodiode, is selected from the set of preset modes $i \in [1, 2, \ldots N_L]$. From (3) we assume that the private users of attocell li are close enough to its AP, and therefore, they are not subject to interference because of transmission from the other LiFi APs $li \neq li'$. Notice that no data sharing among the LiFi APs is required to serve the private users.

Similarly, the signal received by shared user s_k at time n can be written as

$$y^{[s_k]}[n] = \mathbf{h}^{[s_k]}(i^{[s_k]}[n])^T \mathbf{x}[n] + z^{[s_k]}[n]. \quad (5)$$

where, removing the preset mode for the sake of simplicity, $\mathbf{h}^{[s_k]} = [\mathbf{h}^{[s_k,1]} \ldots \mathbf{h}^{[s_k,L]}] \in \mathbb{R}_+^{M\times 1}$ is the channel vector that contains the contribution of the L LiFi APs of the network.

Where $\mathbf{x}[n]$ is as defined in (2), $M = \sum_{li'}^{L} N_L$ and $h^{[s_k,li]}(i) \in \mathbb{R}_+^{N_L\times 1}$ denoting the channel between LEDs of the AP li and the shared user s_k at mode i. Because the location of shared users as in figure (1), It is assumed that shared users can receive signals from all LiFi APs. We assume that the switching pattern functions $i^{[p_{k,li}]}[n]$ and $i^{[s_k]}[n]$ are predetermined and known beforehand. On the contrary, the APs do not have any CSIT and they does not have more information than the coherence time.

A. LiFi channel model

Simlilarly to other works we consider that the effect of the light reflection on walls, ceil and floor are neglectable. Since only the Line-of-Sight component is considered, the channel between the LED transmitter l and the preset mode i of the reconfigurable photodetector of the user k is [11]

$$h^{[k,l]}(i) = \begin{cases} \dfrac{\delta A}{d_{k,l}^2} R_0(\phi) T(\vartheta_i) g(\vartheta_i) cos^r(\vartheta_i), 0 \leq \vartheta \leq \Theta_F \\ 0, \vartheta_i \geq \Theta_F \end{cases} \quad (6)$$

where δ denotes the responsivity coefficient, A is the physical area of the photodiode, $d_{k,l}^2$ is the distance between transmitter and receiver and r is the coefficient of the photodiode associated to the field-of-view (FOV) angle Θ_F. Moreover, $R_0(\phi)$ denotes the Lambertian radiation intensity $R_0 = \dfrac{m+1}{2\pi} cos^m(\phi)$,where $m = \dfrac{-\ln(2)}{\ln(cos(\phi_{1/2})}$ is the order of Lambertian emission and $\phi_{1/2}$ is the transmitter semiangle. Denoting the incidence angle of the photodiode i, which provides the i-th preset mode, as ϑ_i $T(\vartheta_i)$ and $g(\vartheta_i)$ are the optical filter and concentrator gain, respectively.

Due to the characteristics of LED, the signal transmitted by the LEDs must be a non-negative real value. Notice that BIA approaches ensures the non-negativity of the transmitted signal. Moreover, the output optical power is only linear over a limited drive current range $[I_{Min}, I_{Max}]$ where I_{Min} is the turn on current of the LED and I_{Max} corresponds to the maximum input that ensures both the linear response of the LED and the human eye safety. Within this range, each LED provides an output power $[0, P_{Max}]$.

B. Wi-Fi channel model

The considered RF system operates in the frequency band of 2.4 GHz. Moreover, orthogonal resource allocation based on OFDM is proposed to manage the multiuser interference. Therefore, the available bandwidth in the RF spectrum is divided among Q subcarriers. Uniform allocation assigning $\frac{Q}{K_{wi}}$ subcarriers to each RF users is assumed. For an indoor scenario, the channel gain of the OFDM channel can be modeled as [4]

$$g^{[k_{wi}]} = \sqrt{10^{\frac{-L(d)}{10}}}h_r \tag{7}$$

where $g^{[k_{wi}]}$ is the requency response of the channel between the WiFi AP and the user k_{wi} and h_r is the Rayleigh distribution with a variance 2.46 dB that characterizes each subcarrier [5]. The large-scale fading because of path losses is given by

$$L(d) = L(d_0) + 10m\log_{10}\left(\frac{d}{d_0}\right) + X_\mu \tag{8}$$

where $L(d_0) = 47.9$ dB is the reference path loss at $d_0 = 1$ mm, $m = 1.6$ is the path loss exponent and X_μ corresponds to the shadowing component modeled by a Gaussian distribution with zero mean and standard deviation 1.8 dB.

III. Achievable rates for hybrid LiFi/WiFi networks based on BIA

Unlike other schemes for hybrid LiFi/RF networks [5], the LiFi network based on BIA is not subject to interference but for the number of users, which determines the rate degradation and the length of the required coherence block. The subtraction of the $k_s + k_p$ terms of interference involves a proportional increase of the noise. Furthermore, the implementation of nBIA requires a supersymbol in which the physical channel must remain constant. Specifically, the length of the nBIA supersymbol is

$$\mathcal{L}_{\mathrm{nBIA}} = \mathcal{L}_{\mathrm{B1}} + \mathcal{L}_{\mathrm{B2-P}} + \mathcal{L}_{\mathrm{B2-S}} \tag{9}$$

where

$$\mathcal{L}_{\mathrm{B1}} = (N_L-1)^{k_p}(M-1)^{k_s} \tag{10}$$

$$\mathcal{L}_{\mathrm{B2-P}} = k_p\left((N_L-1)^{k_p-1}(M-1)^{k_s}\right) \tag{11}$$

$$\mathcal{L}_{\mathrm{B2-S}} = k_s\left((N_L-1)^{k_p}(M-1)^{k_s-1}\right) \tag{12}$$

For the proposed nBIA approach [8], the private user achieves N_L DoF, i.e., data streams, during an alignment block comprising N_L symbol extensions. Since the channel state of each private user varies among N_L preset modes of the reconfigurable photodetector [9], it can decode N_L data streams. Specifically, following [8], the signal received by the private user $p_{k,li}$ during the symbol $\mathbf{u}_\ell^{[p_{k,li}]}$, which carries N_L DoF after interference subtraction can be written as

$$\mathbf{y}^{[p_{k,li}]} = \mathbf{H}^{[p_{k,li}]}\mathbf{u}_\ell^{[p_{k,li}]} + \sum_{li'=1, li'\neq li}^{L}\sqrt{\alpha_{li'}^{[p_{k,li}]}}\mathbf{H}^{[p_{k,li'}]}\mathbf{u}_\ell^{[p_{k,li'}]} + \mathbf{z}^{[p_{k,li}]}, \tag{13}$$

where $\alpha_{li'}^{[p_{k,li}]}$ s the signal-to-interference (SIR) of the private user $p_{k,li}$ regarding the LiFi AP li', which is treated as noise according to the proposed topological approach, and $\mathbf{u}_\ell^{[p_{k,li'}]}$ is the interfering symbol of the neighbouring LiFi AP during the reception of the symbol of interest $\mathbf{u}_\ell^{[p_{k,li}]}$ and

$$\mathbf{H}^{[p_{k,li}]} = \begin{bmatrix}\mathbf{h}^{[p_{k,li}]}(1) & \dots & \mathbf{h}^{[p_{k,li}]}(N_L)\end{bmatrix} \in \mathbb{R}_+^{N_L\times 1}, \tag{14}$$

is the channel matrix of the user $p_{k,li}$ that contains the N_L linearly independent channel responses and $\mathbf{z}^{[p_{k,li}]}$ is the noise after interference subtraction defined by a covariance matrix

$$\mathbf{R}_{\mathbf{z_p}} = \begin{bmatrix}(k_p+k_s)\mathbf{I}_{N_L} & \mathbf{0} \\ \mathbf{0} & 1\end{bmatrix}. \tag{15}$$

Therefore, according to (13), the user-rate achieved by the private user $p_{k,li}$ is

$$R^{[p_{k,li}]} = B_p\mathbb{E}\left[\log\det\left(\mathbf{I}_{N_L} + P_{str}\mathbf{H}^{[p_{k,li}]}\mathbf{H}^{[p_{k,li}]^H}\mathbf{R}_{\tilde{\mathbf{z}}_\mathbf{p}}{}^{-1}\right)\right] \tag{16}$$

where $B_p = \frac{(M-1)}{(M-1)(N_L+k_p-1)+k_s(N_L-1)}$ is the rate of alignment blocks per private user over the supersymbol length and

$$\mathbf{R}_{\tilde{\mathbf{z}}_\mathbf{p}} = \mathbf{R}_{\mathbf{z_p}} + P_{str}\sum_{li'=1}^{L}\alpha_{li'}^{[p_{k,li}]}\mathbf{H}^{[p_{k,li'}]}\mathbf{H}^{[p_{k,li'}]^H} \tag{17}$$

is the covariance matrix of the noise plus interference due to transmission from other LiFi AP, which is treated as noise.

Similarly, each shared user achieves M DoF in each alignment block of the shared user s_k. Along each alignment block the channel state of each shared user varies among M preset modes. Thus, denoting $\mathbf{u}_\ell^{[s_k]} \in \mathbb{R}^{M\times 1}$ as the symbol that contains the M DoF during the ℓ-th alignment block, the signal received by the shared user s_k after interference subtraction is

$$\mathbf{y}^{[s_k]} = \mathbf{H}^{[s_k]}\mathbf{u}_\ell^{[s_k]} + \mathbf{z}^{[s_k]} \tag{18}$$

where

$$\mathbf{H}^{[s_k]} = \begin{bmatrix}\mathbf{h}^{[s_k]}(1) & \dots & \mathbf{h}^{[s_k]}(M)\end{bmatrix} \in \mathbb{R}_+^{M\times 1} \tag{19}$$

is the channel matrix for the shared user s_k, which contains M preset modes of its reconfigurable photodetector and $\mathbf{z}^{[s_k]}$ is the resulting covariance matrix after interference subtraction

$$\mathbf{R}_{\mathbf{z_s}} = \begin{bmatrix}(k_p+k_s)\mathbf{I}_M & \mathbf{0} \\ ,\mathbf{0} & 1\end{bmatrix} \tag{20}$$

Therefore, the rate achieved by the shared user s_k is given by

$$R^{[s_k]} = B_s\mathbb{E}\left[\log\det\left(\mathbf{I} + P_{str}\mathbf{H}^{[s_k]}\mathbf{H}^{[s_k]^H}\mathbf{R}_{\mathbf{z_s}}{}^{-1}\right)\right] \tag{21}$$

where $B_s = \frac{(N_L-1)}{(M-1)(N_L+k_p-1)+k_s(N_L-1)}$.

For the RF system we consider the use of OFDM with Q subcarriers assigning a set of subcarrier to each user in orthogonal fashion, i.e., avoiding the multi-user interference. Since there is just one Wi-Fi AP, the SINR is equivalent to SNR on each subcarrier, it can be expressed as

$$SNR^{[k_{wi}]} = \frac{|g^{[k_{wi}]}|^2\Delta P_w}{N_w\Delta B_w}, \tag{22}$$

where ΔP_w is the transmit power allocated to each sub-carrier; ΔB_w is the modulation bandwidth of each sub-carrier and N_w

is the noise power spectral density in Wi-Fi link. It is assumed that the transmit power is allocated equally to each sub-carrier. Thus, $\Delta P_w/\Delta B_w = \frac{P_w}{B_w}$, where P_w and B_w are the total transmit power and modulation bandwidth for a Wi-Fi AP. Therefore, the achieved rate by the RF user k_{wi} is

$$R^{[k_{wi}]} = \sum_{q=1}^{Q/K_{wi}} \Delta B_w \log 2 \left(1 + SNR^{[k_{wi}]}\right) \tag{23}$$

IV. Hybrid LiFi/WiFi user selection

A simple illustration of the considered scenario is shown in Fig. 3. The coverage area of each AP is divided into two regions, namely Zone 0 (Non-CCI Area) and Zone 1(CCI area). The users located in Zone 0 are assumed to be private users, whereas the users of Zone 1 are referred as shared ones. We define the Zone 0 and Zone 1 in terms of both the geographical area and the number of users served by that region. To that end, the radius of the entire coverage area related to the LiFi AP is denoted as

$$r_{1,li} = d_v tan(\phi) \tag{24}$$

where d_v is the distance between AP and receiver planes and ϕ is the LED half intensity angle. Notice that the radius of Zone 0, which is denoted as $r_{0,li}$, depends directly on the distance between two LiFi APs. In this work we assumed the distance between two LiFi APs $r_{0,li} = r_{1,li} - q$. It follows that Zone 1(CCl area) is defined as a two-dimensional ring whose width is q as shown in Fig.2.

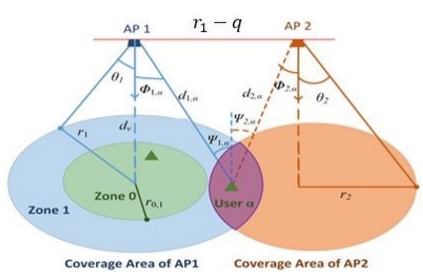

Fig. 3: General System model of a partially connected VLC scenario comprised by two LiFi AP and multiple users

Depending on the radius of zone Z with $(Z = [0,1])$, the number of users can be expressed as

$$U_{Z,li} = \pi \varepsilon r_{Z,li}^2, \tag{25}$$

where ε is the user density and $r_{Z,li}^2$ is the radius of zone Z.

In this work and because of use of BIA in the LiFi tier, we have assumed am upper limit to the number of private users in LiFi cell depending on the radius of Zone 0 and the user density ε denoted as $U_{0,li}$. Therefore, the vertical handover from the LiFi tier to the Wi-Fi tier os considered just in Non-CCI area when the number of a private users exceed defined value $U_{0,li}$. Similarly the vertical handover in CCI area occurs when the number of shared users exceeds $U_{1,li}$. Notice that the handover process of Zone 0 is independent on the handover process of Zone 1.Thus a balance between Wi-Fi and LiFi can be achieved.

TABLE I: Simulation Parameters

Parameter	Value
Number of LED transmitters per cell	2
Bandwidth for each LiFi 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 LiFi AP	$10^{-22} A^2/Hz$
OFDM sub-carrier number	64
Transmitted power for Wi-Fi AP	10 dBm
Bandwidth for Wi-Fi AP	10 MHz
Noise spectral density for Wi-Fi	$-75 dBm/MHz$

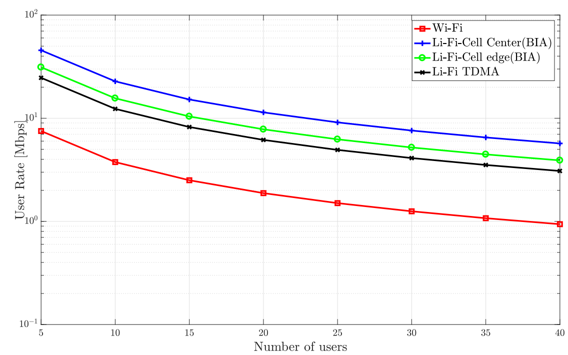

Fig. 4: Comparison of the data rate achieved by Wi-Fi tier and LiFi tier.

V. Simulations Results

A 10 m×10 m×3 m room model is considered, which is only covered by a VLC system including 2 Optical APs at a height of 3 m and the distance between them less than the radius of a LiFi cell by $q = 1$ m. The users are randomly distributed over the plane $h = 2.15$ m from ceiling. In order to provide uniform illumination the optical power of each LED lamp is within the range (-4,16) dBW. If it is not specified, an optical power of 10 dBW is considered. Additionally, the room is entirely covered by a Wi-Fi AP. The other parameters are summarized in Table I.

As shown in Fig. 4 the data user rate achieved in the center or edge of a LiFi cell outperforms the data rate of Wi-Fi for the same number of users, which certainly means the users located in the center or the edge of a LiFi cell are preferably served by LiFi tier. Depending on the distance between two LiFi APs, the radius of a Non-CCI area is $r_{0,1} = r_1 - q$ and the size of the CCI area equals q. Therefore, assuming a user density $\varepsilon[users/m^2]$ it results straightforward to calculate the maximum number of users served by both the Non-CCI area and the CCI area.

For Non-CCI area, it can be seen in Fig. 5 that the proposed BIA scheme provides a user rate above 15 Mbps in most of the areas of the scenario when the number of private users per one LiFi cell is $k_p = 30$. After the handover process the