User Association in User-Centric Hybrid VLC/RF Cell-Free Massive MIMO Systems

Ahmed Almehdhar, Mohanad Obeed, Anas Chaaban, Senior Member, IEEE, and Salam A. Zummo, Senior Member, IEEE

Abstract—A continuous goal in all communication systems is to enhance the users experience and provide them with the highest possible data rates. Recently, the concept of cell-free massive MIMO (CF-mMIMO) systems has been considered to enhance the performance of systems that operate merely with Radio Frequency (RF) or visible light communication (VLC) technologies. In this paper, a hybrid VLC/RF cell-free massive MIMO system is proposed where an RF cell-free network and a VLC cell-free network coexist to serve users. The idea is to utilize the benefits of each network and balance the load aiming at maximizing the system’s sum-rate. The system is evaluated using zero-forcing (ZF) precoding scheme. Two user association algorithms are proposed to assign users to either the VLC or the RF networks. In addition, two user-centric clustering approaches are proposed and evaluated. Simulation results show that the proposed association algorithms significantly outperform a random network association of users in terms of sum-rate. Results also show great potential for the proposed system compared to standalone cell-free networks.

Index Terms—Hybrid visible light communication/radio-frequency systems, cell-Free massive MIMO, user association, user clustering, Gibbs sampling.

I. INTRODUCTION

ADVANCEMENTS in communication technologies are driven by the unprecedented requirements of data rates to satisfy the expected future growth of data that is caused by advancements in other fields and technologies.Proposing advanced communication technologies is one way to meet the requirements of providing high energy efficiency, high spectral efficiency, massive device connectivity, more robust security, and an ultra-low latency [2], [3], [4], [5]. To enhance the wireless communications experience, researchers started exploring other frequency ranges in the electromagnetic spectrum such as the visible light spectrum [6]. Visible light communication (VLC) is a wireless communications technology that uses the visible light spectrum to transmit data between two points [7]. Moreover, the invention of energy-efficient light emitting diodes (LEDs) and their spread as the main source of lighting have pushed the focus in research towards using visible light spectrum to transmit data. VLC has proven to provide data rates much higher than the radio-frequency (RF) [2], [8].

Nonetheless, VLC systems inherently suffer from short range of coverage and their signals do not propagate through non-transparent objects (requiring a line-of-sight (LoS) links) [9], [10]. A common solution to overcome the aforementioned problems is to support the standalone VLC system with RF APs as they have larger coverage and better operation in non-LoS environments. In addition, users served by one network (RF or VLC) do not receive interference from the other network, which leads to mitigating the total received interference [11]. Such systems are called hybrid VLC/RF systems and they are suitable for areas with multiple blockages [12], [13].

Recently, the cell-free massive MIMO (CF-mMIMO) concept was introduced in [14], [15], where all access points (APs) in such systems serve all users simultaneously using the same time and frequency resources. In these systems, the boundaries between cells are removed, hence the name ‘cell-free’. CF-mMIMO systems have demonstrated better performance than small cells in terms of fairness and per-user throughput [16]. In addition, they reduce the signal-to-noise ratio (SNR) fluctuation that is caused by variations in channel conditions [16]. CF-mMIMO systems using RF have been studied in the literature with multiple channel models and multiple combining schemes in the uplink and precoding schemes in the downlink [14], [17], [18].

Even though the idea of CF-mMIMO systems is appealing, it has two main problems; 1) all users, no matter how bad their channel links are, would be served by all APs, which means that each AP allocates resources to all users even if they do not receive a good service. This prevents other users with a good channel quality from utilizing these ‘wasted’ resources [19]; 2) the unscalability of CF-mMIMO systems [20]. To address these challenges, S. Buzzi et al. in [19] proposed a modification on the original CF-mMIMO idea, where they proposed a user-centric (UC) approach where each AP only serves a certain number of users that have the strongest channel links. This forms the basis to solve the scalability issue in the original CF-mMIMO systems since the required backhaul capacity for each AP is reduced significantly. The authors of [20] proposed a scalable CF-mMIMO where they grouped the APs into N pre-determined cell-clusters. They applied a UC approach to see what APs are best to serve a specific user. Those best serving APs, along with all the other APs in their clusters, jointly serve that user. Björnson and Sanguinetti, in [21] and [22], studied the scalability issue in the CF-mMIMO...
system and provided a systematic procedure for determining whether a process/technique is scalable or not. Furthermore, they proposed a new framework for scalable CF-mMIMO and provided an algorithm for joint initial access, pilot assignment, and cluster formation.

Due to the dense nature of LED deployment, a VLC-based CF system has been introduced in [23]. It was further studied in [24], where the power was allocated to manage the interference. Although the CF-mMIMO concept has been investigated in RF and VLC networks, there is no paper (up to our knowledge) that studied the CF in hybrid VLC/RF systems.

In this paper, motivated by the advantages of CF systems, we introduce a hybrid VLC/RF CF-mMIMO system where both networks adopt the CF concept and each user is served by either the VLC or the RF network. Moreover, the provided derivations include user clustering into our analysis. A mathematical joint optimization problem of user clustering and user association is formulated. Two approaches are proposed to solve the optimization problem where users are assigned to either the VLC or RF networks aiming at maximizing the sum-rate. We evaluate the hybrid CF-mMIMO system and show that the proposed system performs better than the VLC or RF standalone CF systems. We also show that the proposed algorithms outperform a random user association scheme. The main contributions of this paper are listed here:

- We propose and evaluate a hybrid VLC/RF CF-mMIMO system; concept and derivations.
- We mathematically formulate a joint optimization problem for the user association and user clustering. This problem turns out to be a non-convex integer problem and it is not easy to tackle. The problem is then converted into two separate sub-problems: a user association sub-problem and a user clustering sub-problem.
- We propose two approaches for the user association sub-problem, a heuristic approach with low complexity, and a Gibb sampling-based approach.
- We evaluate the system for two different user clustering techniques and show that the original CF structure is a special case of our general derivations.
- We compare the results of the proposed system and algorithms with standalone VLC and RF CF systems and a hybrid system with random user association. The results of this comparison convey the significant lead of the proposed system and the proposed algorithms over the other systems.
- The analysis is built around a general clustering matrix and an arbitrary precoding scheme. Thus, it is valid for any clustering approach and precoding technique.

The rest of this paper is organized as follows. Section II describes the system and channel models. In Section III, we provide detailed analysis and derivations for the expressions of the achievable data rates in both the VLC and the RF networks. Section IV formulates a joint optimization problem for both user association and user clustering and proposes different solutions for the formulated problem. Simulation results are presented in Section V. Finally, Section VI concludes the paper.

**Notations**: Vectors are denoted by boldface lowercase letters, whereas matrices are denoted by boldface uppercase letters. The transpose, Hermitian, and inverse operators are represented by $(\cdot)^T$, $(\cdot)^H$, and $(\cdot)^{-1}$, respectively. The operator $\odot$ is the Hadamard product or element-wise product of matrices. The function $\text{diag}(\cdot)$ outputs a diagonal square matrix with the diagonal elements being the elements of the input vector. In addition, the function $\text{max}(\cdot)$ returns the maximum value of its input with respect to the variable $i$. The symbols $\mathbb{R}$, $\mathbb{R}^N$, and $\mathbb{R}^{N \times M}$ represent the set of real numbers, set of $N$-dimensional vectors of real numbers, and the set of $N \times M$ matrices of real numbers, respectively. The superscript $(\cdot)^{(v)}$ indicates that the quantity inside the parentheses is a VLC quantity, while $(\cdot)^{(r)}$ means that it is an RF quantity.

II. System and Channel Models

In this paper, a centralized hybrid VLC/RF CF-mMIMO system is examined for indoor communications. As shown in Fig. 1, we assume a room of size $M \times M \times \text{height}$ that contains $N_{\text{VAP}}$ VLC APs and $N_{\text{RAP}}$ RF APs, both are uniformly deployed on the ceiling of the room. Intensity modulation (IM) is assumed to be used by each VLC AP to transmit optical signals to the associated users. Each user equipment is assumed to be equipped with a photo detector (PD) to directly detect the light intensity and a regular antenna to receive RF signals. Moreover, it is assumed that the room contains a total of $N_u$ users that are randomly distributed over the floor according to the uniform distribution. We denote the number of users served by VLC APs and RF APs by $N_{u,v}$ and $N_{u,r}$, respectively. Furthermore, we assume that the channel coefficients remain constant during the transmission of one block of data.

In this system, we consider the idea of a centralized hybrid VLC/RF CF system where multiple VLC (or RF) APs cooperate to serve each user. As implied by the word ‘centralized’, all APs are assumed to be connected to a central processing unit (CPU) that processes users’ signals and coordinates their interactions.
connections. To eliminate confusion, the word ‘network’ is used only to indicate a network of only VLC APs or a network of only RF APs, and thus our system consists of two disjoint networks. In this system, a user would be served by a subset of the APs in one network (either VLC network or RF network). In other words, different users are served by different subsets of APs, and those subsets are not necessarily mutually exclusive, i.e. they could be overlapping. Moreover, all VLC (or RF) APs use the same bandwidth to serve their associated users.

A. VLC Channel

It has been shown in [25] that the LoS component of the VLC channel link between user \( j \) and VLC AP \( i \), denoted by \( h_{j,i}^{(v)} \), is given by

\[
h_{j,i}^{(v)} = \frac{(m + 1)A_p}{2\pi d_{j,i}^2} \cos^m(\phi)G_{of}f(\theta)\cos(\theta),
\]

where \( m = -\left(\log_2\left(\cos\left(\frac{\theta}{2}\right)\right)\right)^{-1} \) is the Lambertian index, \( \theta/2 \) is the half-intensity radiation angle, \( A_p \) is the physical area of the PD at the receiver side, \( d_{j,i} \) is the Euclidean distance from user \( j \) to AP \( i \), \( G_{of} \) is the gain of the optical filter, \( \phi \) is the angle of radiation from the AP, \( \theta \) is the angle of incidence at the PD and \( f(\theta) \) is the optical concentrator gain and is given by

\[
f(\theta) = \begin{cases} \frac{n^2}{\sin^2(\theta)}, & 0 \leq \theta \leq \Theta; \\ 0, & \theta > \Theta, \end{cases}
\]

where \( n \) is the refractive index of the PD and \( \Theta \) is the semi-angle of the Field-of-View (FoV) of the PD.

B. RF Channel

Similar to the VLC, the RF APs in the CF system cooperate to serve their users. The RF channel link between user \( j \) and RF AP \( i \), denoted by \( h_{j,i}^{(r)} \), is given as in [26] by

\[
h_{j,i}^{(r)} = \sqrt{10^{-\frac{L(d)}{10}} \left(\frac{K}{K + 1} h_d + \frac{1}{K + 1} h_s\right)},
\]

where \( K = 10 \) dB is the Rician factor for indoor 60 GHz mmWave links, \( h_d = \sqrt{0.5(1 + j)} \) is the LoS path fading channel, \( h_s \sim CN(0, 1) \) is the scattered path fading channel, and \( L(d) \) is the corresponding path loss in dB at a distance \( d \) from the transmitter and is given by

\[
L(d) = L(d_0) + 10v\log_{10}\left(\frac{d}{d_0}\right) + X,
\]

where \( L(d_0) = 68 \) dB is the reference path loss at a reference distance of \( d_0 = 1 \) m, \( v = 1.6 \) is the path loss exponent, and \( X \) is the random variable representing the shadowing effect which is assumed to have a log-normal distribution of zero mean and a standard deviation of 1.8 dB.

III. NETWORKS’ ACHIEVABLE SUM-RATE

In this section, we analyze the received signal at the receiver side and provide an expression for the achievable sum-rate. Let \( U_i^{(v)} \) be the set of users served by VLC AP \( i \), and \( U_i^{(r)} \) be the set of users served by RF AP \( i \). Moreover, let \( A_i^{(v)} \) be the set of VLC APs serving an arbitrary user \( j \) and let \( A_j^{(r)} \) be the set of RF APs serving an arbitrary user \( j \). Note that the two sets \( A_j^{(v)} \) and \( A_j^{(r)} \) are mutually exclusive. In fact, for a specific user \( j \) one of the two sets will be the empty set \( \emptyset \), which means that a user can only be served by either the VLC network or the RF network but not both. Furthermore, the two sets \( U_i^{(v)} \) and \( U_i^{(r)} \) are mutually exclusive because a user cannot be served by both networks simultaneously. We can see that \( \bigcup_{i=1}^{N_u} U_i^{(v)} = N_{u,v} \leq N_u \), \( \bigcup_{i=1}^{N_u} U_i^{(r)} = N_{u,r} \leq N_u \), and \( \bigcup_{m \in \{v,r\}} \bigcup_{i=1}^{N_{m,ap}} U_i^{(m)} = N_u \). In addition, we define a matrix \( A^{(v)} \in \mathbb{R}^{N_u \times N_{vap}} \) of length \( N_u \times N_{vap} \) that represents the user clustering in the VLC network as

\[
A^{(v)} = \begin{bmatrix}
a_{1,1}^{(v)} & a_{1,2}^{(v)} & \cdots & a_{1,N_{vap}}^{(v)} \\
a_{2,1}^{(v)} & a_{2,2}^{(v)} & \cdots & a_{2,N_{vap}}^{(v)} \\
\vdots & \vdots & \ddots & \vdots \\
a_{N_u,1}^{(v)} & a_{N_u,2}^{(v)} & \cdots & a_{N_u,N_{vap}}^{(v)}
\end{bmatrix},
\]

where the element \( a_{j,i}^{(v)} \) is a clustering factor between user \( j \) and VLC AP \( i \), and is given by

\[
a_{j,i}^{(v)} = \begin{cases} 1, & \text{if VLC AP } i \text{ serves user } j; \\ 0, & \text{if VLC AP } i \text{ does not serve user } j. \end{cases}
\]

A similar matrix for RF user clustering \( A^{(r)} \in \mathbb{R}^{N_u \times N_{rap}} \) is also defined as

\[
A^{(r)} = \begin{bmatrix}
a_{1,1}^{(r)} & a_{1,2}^{(r)} & \cdots & a_{1,N_{rap}}^{(r)} \\
a_{2,1}^{(r)} & a_{2,2}^{(r)} & \cdots & a_{2,N_{rap}}^{(r)} \\
\vdots & \vdots & \ddots & \vdots \\
a_{N_u,1}^{(r)} & a_{N_u,2}^{(r)} & \cdots & a_{N_u,N_{rap}}^{(r)}
\end{bmatrix},
\]

where the element \( a_{j,i}^{(r)} \) is a clustering factor between user \( j \) and RF AP \( i \), and is given by

\[
a_{j,i}^{(r)} = \begin{cases} 1, & \text{if RF AP } i \text{ chooses to serve user } j; \\ 0, & \text{if RF AP } i \text{ chooses not to serve user } j. \end{cases}
\]

Finally, we define a vector \( b \) of length \( N_u \) that indicates the users’ connection to either the VLC network or the RF network, which can be written as

\[
b = [b_1 \ b_2 \ \cdots \ b_{N_u}]^T,
\]

where \( b_j \in \{0,1\} \). Setting \( b_j = 0 \) means that user \( j \) is connected to the RF network, while \( b_j = 1 \) indicates that user \( j \) is connected to the VLC network. Vector \( b \) guarantees that a single user cannot be served simultaneously by both networks.
A. VLC Achievable Rate

Here, we provide an achievable rate expression for the users that are served by the VLC network. We denote the transmitted vector of VLC APs by \( \mathbf{x}^{(v)} = [x_1^{(v)} \; x_2^{(v)} \; \ldots \; x_{N_{\text{vap}}}^{(v)}]^T \), where the \( i^{th} \) AP transmits the \( i^{th} \) entry that is given by

\[
x_i^{(v)} = \sqrt{\rho_i^{(v)}} \sum_{j \in U_i^{(v)}} w_{i,j}^{(v)} \sqrt{P_j^{(v)}} s_j
\]

(10a)

\[
= \sqrt{\rho_j^{(v)}} \sum_{j \in U_i^{(v)}} b_j a_{i,j}^{(v)} w_{i,j}^{(v)} \sqrt{P_j^{(v)}} s_j,
\]

(10b)

where \( s_j \) is the message intended for user \( j \), \( \rho_j^{(v)} \) is the total available power at each VLC AP, \( P_j^{(v)} \) is the power allocated to the messages of user \( j \) in the VLC network, and \( w_{i,j}^{(v)} \) is the weight assigned to symbol \( s_j \) that is transmitted by VLC AP \( i \). We define \( \mathbf{W}^{(v)} \in \mathbb{R}^{N_{\text{vap}} \times N_u} \) to be the precoding matrix, where its \((i,j)^{th}\) entry is given by \( w_{i,j}^{(v)} \). Therefore, we can write the received signal at the VLC user \( j \) as

\[
y_j^{(v)} = \rho_j^{(v)} \sum_{i=1}^{N_{\text{vap}}} h_{j,i}^{(v)} x_i^{(v)} + n_j^{(v)},
\]

(11a)

\[
= \rho_j^{(v)} \sum_{i=1}^{N_{\text{vap}}} h_{j,i}^{(v)} \left( \sqrt{\rho_j^{(v)}} \sum_{l=1}^{N_u} b_l a_{l,i}^{(v)} w_{l,i}^{(v)} \sqrt{P_l^{(v)}} s_l \right) + n_j^{(v)},
\]

(11b)

\[
= \rho_j^{(v)} \sum_{i=1}^{N_{\text{vap}}} h_{j,i}^{(v)} \left( \sum_{l=1}^{N_u} b_l a_{l,i}^{(v)} w_{l,i}^{(v)} \sqrt{P_l^{(v)}} s_l \right) + n_j^{(v)},
\]

(11c)

where \( \rho_j^{(v)} \) is the total available power at each VLC AP, \( P_l^{(v)} \) is the power allocated to the messages of user \( j \) in the VLC network, and \( w_{l,i}^{(v)} \) is the weight assigned to symbol \( s_l \) transmitted by the \( i^{th} \) VLC AP and is given by

\[
x_l^{(v)} = \sqrt{\rho_j^{(v)}} \sum_{j \in U_i^{(v)}} w_{i,j}^{(v)} \sqrt{P_j^{(v)}} s_j
\]

(16a)

\[
= \sqrt{\rho_j^{(v)}} \sum_{j \in U_i^{(v)}} (1 - b_j) a_{j,i}^{(v)} w_{j,i}^{(v)} \sqrt{P_j^{(v)}} s_j.
\]

(16b)

where \( \rho_j^{(v)} \) is defined as the equivalent conversion factor, \( \rho_{oo} \) and \( \rho_{eo} \) are the optical-to-electrical and the electrical-to-optical conversion factors, respectively, \( \mathbf{H}_v = [h_1^{(v)} \; h_2^{(v)} \; \ldots \; h_{N_u}^{(v)}]^T \) is the VLC channel matrix, where \( h_j^{(v)} = [h_{j,1}^{(v)} \; h_{j,2}^{(v)} \; \ldots \; h_{j,N_{\text{vap}}}^{(v)}]^T \) is the channel vector of all VLC APs to the \( j^{th} \) user, \( w_{l,i}^{(v)} \) is the \( l^{th} \) column vector of \( \mathbf{W}^{(v)} \), and \( \mathbf{A}_{d,l}^{(v)} \) is a diagonal matrix with the diagonal elements being the elements in the \( l^{th} \) row of \( \mathbf{A}^{(v)} \), and is mathematically written as

\[
\mathbf{A}_{d,l}^{(v)} = \text{diag} \left( \mathbf{a}_{l,:}^{(v)} \right).
\]

(12)

where \( \mathbf{a}_{l,:}^{(v)} \) is the symbol used to indicate the \( l^{th} \) row vector of \( \mathbf{A}^{(v)} \). Equation (11c) is further decomposed in equation (13) at the top of the next page where the desired signal at the receiver of VLC user \( j \), the interference, and noise are separated. An achievable rate at user \( j \) connected to the VLC network is given by

\[
R_j^{(v)} = \frac{B^{(v)}}{2} \log_2 \left( 1 + \gamma_j^{(v)} \right)
\]

(14)

where \( B^{(v)} \) is the total VLC bandwidth and \( \gamma_j^{(v)} \) is given by

\[
\gamma_j^{(v)} = \frac{\rho_j^{(v)} \sum_{i=1}^{N_{\text{vap}}} \left( h_{j,i}^{(v)} \right)^T \mathbf{A}_{d,l}^{(v)} w_{l,i}^{(v)} \sqrt{P_l^{(v)}} \right) \gamma_j^{(v)} = \frac{\rho_j^{(v)} \sum_{i=1}^{N_{\text{vap}}} \left( h_{j,i}^{(v)} \right)^T \mathbf{A}_{d,l}^{(v)} w_{l,i}^{(v)} \sqrt{P_l^{(v)}} \right)^2}{\sum_{i=1}^{N_{\text{vap}}} \left( h_{j,i}^{(v)} \right)^T \mathbf{A}_{d,l}^{(v)} w_{l,i}^{(v)} \sqrt{P_l^{(v)}} \right)^2} + 9 \sigma_v^2
\]

(15)

B. RF Achievable Rate

Here, we provide an expression for the achievable rate at the users that are served by the RF network. The vector \( \mathbf{x}^{(r)} = [x_1^{(r)} \; x_2^{(r)} \; \ldots \; x_{N_{\text{rap}}}^{(r)}]^T \) represents the transmitted signals from RF APs, where \( x_i^{(r)} \) is the transmitted signal from the \( i^{th} \) RF AP and is given by

\[
x_i^{(r)} = \sqrt{\rho_i^{(r)}} \sum_{j \in U_i^{(r)}} w_{i,j}^{(r)} \sqrt{P_j^{(r)}} s_j
\]

(16a)

\[
= \sqrt{\rho_i^{(r)}} \sum_{j \in U_i^{(r)}} (1 - b_j) a_{j,i}^{(r)} w_{j,i}^{(r)} \sqrt{P_j^{(r)}} s_j.
\]

(16b)

where \( \rho_j^{(r)} \) is the total available power at each RF AP, \( P_j^{(r)} \) is the power allocated to the messages of user \( j \) in the RF network, and \( w_{i,j}^{(r)} \) is the weight assigned to symbol \( s_j \) transmitted by the \( i^{th} \) RF AP. Let \( \mathbf{W}^{(r)} \in \mathbb{R}^{N_{\text{rap}} \times N_u} \) be the precoding matrix, where its \((i,j)^{th}\) entry is given by \( w_{i,j}^{(r)} \). The received signal by user \( j \) can then be written as

\[
y_j^{(r)} = \sum_{i=1}^{N_{\text{rap}}} h_{j,i}^{(r)} x_i^{(r)} + y_j^{(r)},
\]

(17a)

\[
= \sum_{i=1}^{N_{\text{rap}}} h_{j,i}^{(r)} \left( \sqrt{\rho_j^{(r)}} \sum_{l=1}^{N_u} (1 - b_l) a_{l,i}^{(r)} w_{l,i}^{(r)} \sqrt{P_l^{(r)}} s_l \right) + n_j^{(r)},
\]

(17b)

\[
= \sqrt{\rho_j^{(r)}} \sum_{l=1}^{N_u} (1 - b_l) \left( h_{j,r}^{(r)} \right)^T \mathbf{A}_{d,l}^{(r)} w_{l,i}^{(r)} \sqrt{P_l^{(r)}} s_l + n_j^{(r)},
\]

(17c)

where \( w_{l,i}^{(r)} \) is the \( l^{th} \) column vector of \( \mathbf{W}^{(r)} \), and \( h_{j,r}^{(r)} = [h_{j,1}^{(r)} \; h_{j,2}^{(r)} \; \ldots \; h_{j,N_{\text{rap}}}^{(r)}]^T \) is the channel vector of all RF APs to the \( j^{th} \) user, and the RF channel matrix is given as \( \mathbf{H}_r = [h_1^{(r)} \; h_2^{(r)} \; \ldots \; h_{N_u}^{(r)}]^T \), and \( n_j^{(r)} \sim \mathcal{CN}(0, \sigma_v^2) \) is the additive white gaussian noise at the antenna of user \( j \).

Equation (17c) is further decomposed in equation (18) at the top of the next page where the desired signal, the interference, and noise are separated. An achievable rate at user \( j \) that is connected to the RF network is given by Shannon’s formula as

\[
R_j^{(r)} = B^{(r)} \log_2 \left( 1 + \gamma_j^{(r)} \right)
\]

(19)
where $B^{(r)}$ is the total available RF bandwidth and $\gamma_j^{(r)}$ is given by

$$
\gamma_j^{(r)} = \frac{\sqrt{\rho_j^{(r)} (1 - b_j)} \left( \mathbf{h}_j^{(r)} \right)^T \mathbf{A}_d^{(r)} \mathbf{w}_j^{(r)} \sqrt{P_j^{(r)}}}{\sum_{i=1\atop i \neq j}^{N_u} \sqrt{\rho_i^{(r)} (1 - b_i)} \left( \mathbf{h}_i^{(r)} \right)^T \mathbf{A}_d^{(r)} \mathbf{w}_i^{(r)} \sqrt{P_i^{(r)}}} + \sigma^2. $$

(20)

IV. PROBLEM FORMULATION AND SOLUTION

In this section, we are interested in associating users to the two networks and clustering the users within each network, aiming at maximizing the system’s sum-rate. In other words, we are trying here to find out what are the best selections of the vector $\mathbf{b}$ and the matrices $\mathbf{A}^{(v)}$ and $\mathbf{A}^{(r)}$ that maximize the sum-rate. Since the user association and clustering problems are interlinked, we first formulate a joint optimization problem for both user association and user clustering. The joint optimization problem is then simplified into two independent sub-problems, where each is handled separately.

A. Problem Formulation

Given that the association variable $b_j \in \{0, 1\}, \forall j$, we can express the achievable rate at user $j$ as follows

$$ R_j = R_j^{(v)} + R_j^{(r)}, $$

(21)

where $R_j^{(v)}$ and $R_j^{(r)}$ are defined in (14) and (19), respectively. Expression (21) implies that $R_j = R_j^{(v)}$ if $b_j = 1$ (user $j$ is connected to VLC network), and $R_j = R_j^{(r)}$ if $b_j = 0$ (user $j$ is connected to RF network). This emphasizes the fact that only one network, either VLC or RF, would serve user $j$ at a time. Therefore, we can formulate our joint optimization problem as

$$ \max_{\mathbf{A}^{(v)}, \mathbf{A}^{(r)}, \mathbf{b}} \sum_j R_j $$

s.t. $b_j \in \{0, 1\}, \forall j,$ (22a)

$ a_{j,i}^{(v)} \in \{0, 1\}, \forall i, j,$ (22b)

$ a_{j,i}^{(r)} \in \{0, 1\}, \forall i, j,$ (22c)

$$ \sum_{j=1}^{N_u} \left( w_{i,j}^{(v)} \right)^2 P_j^{(v)} \leq 1, \forall i,$$ (22d)

$$ \sum_{j=1}^{N_u} \left( w_{i,j}^{(r)} \right)^2 P_j^{(r)} \leq 1, \forall i.$$ (22e)

Constraint (22b) guarantees that each user is served by only one network at a time. Constraints (22c) and (22d) are responsible for clustering the users in each network. Constraints (22c) and (22d) are imposed to make sure that the transmit power from the AP $i$ is not greater than $\rho_f$ (the total available power). Problem (22) is not an easy problem to tackle since it is a non-convex nonlinear integer problem. In our work, we first simplify problem (22) by discarding the link between the three interlinked optimization variables ($\mathbf{b}, \mathbf{A}^{(v)}, \mathbf{A}^{(r)}$). Then, we select a sub-optimal clustering scheme and solve the problem in terms of $\mathbf{b}$, under the given $\mathbf{A}^{(v)}$ and $\mathbf{A}^{(r)}$, thereafter. Thus, we can formulate a users association sub-problem as

$$ \max_{\mathbf{b}} \sum_j R_j $$

s.t. $b_j \in \{0, 1\}, \forall j,$ (23a)

$$ \sum_{j=1}^{N_u} \left( w_{i,j}^{(v)} \right)^2 P_j^{(v)} \leq 1, \forall i,$$ (23b)

$$ \sum_{j=1}^{N_u} \left( w_{i,j}^{(r)} \right)^2 P_j^{(r)} \leq 1, \forall i.$$ (23c)

This is a non-convex nonlinear integer problem which is still not easy to tackle. The optimal solution can be attained by using exhaustive search approach, where we try every possible choice of the vector $\mathbf{b}$ and select the vector that maximizes the objective function given in (23a). However, this approach is not practical since increasing the number of users in the
Algorithm 1 Gibbs Sampling-Based User Association

Input: \( N_u, T_{\text{max}}, \beta, H_u, H_r, W^{(v)}, W^{(r)}, \rho_f^{(u)}, \rho_f^{(r)}, B^{(v)}, B^{(r)}, \rho_e, \rho_o, \sigma_v, \sigma_r. \)

Output: \( b \)

Initialize: Sample \( b \) according to DUD from \( \{0, 1\} \)
1: Convergence \( \leftarrow \) False
2: \( b_{\text{old}} \leftarrow b \)
3: while \( t \leq T_{\text{max}} \) AND Convergence \( \neq \) True do
4: Generate the set \( B^{t-1} = (b_m^{t-1})_{m=0}^{N_u} \) \( \triangleright \) Containing \( N_u + 1 \) vectors
5: for each \( b'_t \in B^{t-1} \) do
6: From \( H_u \) and \( H_r \), Obtain \( A_u \) and \( A_r \), respectively
7: Calculate \( R_s \leftarrow \sum_j R_j \) using (14), (19) and (21)
8: end for
9: \( \bar{R}_s \leftarrow [R_s] \in \mathbb{R}^{N_u+1} \) \( \triangleright \) i.e. concatenate values of \( R_s \)
10: Normalize the vector \( \bar{R}_s \) to be in \( [0, 1] \)
11: Divide the elements of \( \bar{R}_s \) by \( \sum R_s \)
12: Square all the elements of \( \bar{R}_s \)
13: \( \triangleright \) To distinguish the values in \( \bar{R}_s \)
14: Sample \( b'_t \) from the distribution in (27)
15: if \( b'_t = b_{\text{old}} \) then
16: Convergence \( \leftarrow \) True
17: else
18: \( b_{\text{old}} \leftarrow b'_t \)
19: end if
20: end while

This modification in the problem formulation enables us to make use of Gibbs sampling with some other modifications.

A Gibbs-sampling based algorithm for user association is developed (similar to [29] but for a different setup). At the beginning of each iteration \( t \), we have the value of \( b_t^{t-1} \), which is the result of the previous iteration. We define the set \( B^{t-1} \) that contains all the vectors \( b_m^{t-1} \) that are different by only the \( m^{th} \) element from \( b_0^{t-1} \) and the vector \( b_t^{t-1} \) itself. For mathematical convenience \( b_0^{t-1} = b_t^{t-1} \). Hence, the probability distribution function becomes:

\[
\Lambda_t(b'_t) = \frac{\exp\left(-\beta U(b'_t)\right)}{\sum_{b'_t \in B^{t-1}} \exp\left(-\beta U(b'_t)\right)},
\]

(27a)

\[
= \frac{\exp\left(-\sum_{j=1}^{N_u} P_j^{(v)}\right)}{\sum_{b'_t \in B^{t-1}} \exp\left(-\sum_{j=1}^{N_u} P_j^{(r)}\right)}.
\]

(27b)

The algorithm is presented in details in Algorithm 1. Note that at the beginning of the Algorithm 1 we initialize the elements of the vector \( b \) from the set \( \{0, 1\} \) according to the discrete uniform distribution (DUD). The power constrains in the problem are satisfied as will be shown in Section IV-E.

C. Proposed Approach 2: Iterative Approach

Aside from the complications and statistics in the approach proposed in Section IV-B, one simple and efficient way to approach this problem is by iteratively considering the impact of switching each user from its current network to the other network. This starts by first sorting the users’ rates in an ascending order then start switching the users with minimum rates first. If changing the user’s network increases the backhaul rate, the approach keeps that user in its new network; otherwise, brings it back to its previous network. This continues until convergence. This approach is presented in details in Algorithm 2. The users’ rates sorting in line 6 of the algorithm is beneficial because starting with users who receive the poorest service gets us to the maximum faster than if we started randomly.

D. User Clustering

User clustering has several advantages that include limiting backhaul transmission as well as enabling the scalability of the CF-mMIMO system. The goal here is to determine which
APs in each network should serve each of the users in that network. Under a given user association (i.e., given $b$), we can reformulate problem (22) in any network $m \in \{v, r\}$ as

$$\max_{\mathbf{A}} \sum_{j} R_{j} \quad (28a)$$

s.t. $a_{j,i} \in \{0, 1\}, \quad \forall i, j, \quad (28b)$

$$\sum_{j=1}^{N_{u}} (w_{i,j})^{2} P_{j} \leq 1, \quad \forall i. \quad (28c)$$

Note that the superscripts are omitted since the problem is applied for both networks. Problem (28) is also a non-convex nonlinear integer problem and not easy to tackle. Therefore, without loss of generality, we propose to use two distinct suboptimal clustering techniques, namely $\mathbf{A}_1$ and $\mathbf{A}_2$, to help evaluate the system. These clustering techniques certainly do not guarantee the optimal solution but are justified selections in our problem as discussed in the following.

The first clustering technique, $\mathbf{A}_1 = [a_{1,j,i}]$, is given by

$$a_{1,j,i} = \begin{cases} 1, & d_{j,i} \leq d_{\text{max}}; \\ 0, & d_{j,i} > d_{\text{max}}. \end{cases} \quad (29)$$

where $d_{j,i}$ denotes the distance between user $j$ and AP $i$, and $d_{\text{max}}$ is a network design parameter that represents the maximum distance between an AP and a user under which the user is served by that AP. Fig. 2 shows this clustering technique in action. Changing $d_{\text{max}}$ affects the volume of surrounding space served by each AP. Increasing $d_{\text{max}}$ increases the average number of users served by each AP. On the other hand, decreasing $d_{\text{max}}$ means fewer users will be served by each AP. Note that setting $d_{\text{max}}$ to be larger than $M$ (the room dimension), ensures that all APs serve all users. Increasing $d_{\text{max}}$ increases the amount of exchanged data between the CPU and the APs. This might cause the date rate received by an AP to exceed the backhaul capacity of that AP. In particular, $d_{\text{max}}$ must be selected to guarantee that the received rate at the associated users is not greater than the received rate at the AP from the CPU. However, in this paper, we assume that $d_{\text{max}}$ is given for each AP.

The second clustering technique, $\mathbf{A}_2 = [a_{2,j,i}]$, is based on the maximum number of served users per AP. In other words, we assume that the number of users that can be served by an AP is limited by $N_{\text{max}}$, where $N_{\text{max}}$ is a network design parameter. Those users are chosen based on their distance form the associated users is not greater than the received rate at the AP from the CPU. However, in this paper, we assume that $d_{\text{max}}$ is given for each AP.

$$a_{2,j,i} = \begin{cases} 1, & j \in \mathcal{D}_i; \\ 0, & \text{otherwise}. \end{cases} \quad (30)$$

This clustering technique limits the number of users served by each AP. Hence, exceeding the backhaul capacity of each AP is less probable compared to using $\mathbf{A}_1$ clustering. However, without a reasonable selection of this variable, the performance of the system will degrade. Fig. 3 shows a simple scenario where this clustering is implemented with $N_{\text{max}} = 3$.

Now, to provide a solution to the problem in (22), we first select a clustering technique to adopt, either $\mathbf{A}_1$ or $\mathbf{A}_2$. Then, users are associated to the VLC network or the RF network according to Algorithms 1 or Algorithm 2.
This guarantees that each AP transmits signal within its power budget.

This guarantees that each AP transmits signal within its power budget.

Fig. 3. Illustration of $A_2$ clustering.

E. Constraints Satisfaction

In this subsection, we present the precoding scheme used in this paper. In addition, we provide the methodology that we follow to satisfy the constraints in (22c) and (22d) which are the same as those in (23c), (23d), (26c), (26d), and the general one in (28c).

The precoding matrix $W$ can be selected in multiple ways. However, we choose to use the zero-forcing (ZF) precoding scheme. This precoding scheme is meant to suppress the intranetwork interference. The ZF precoding that incorporates the clustering is denoted by $W_{ZF} = [w_1 \ w_2 \ \cdots \ w_{N_u}]$, where $w_j$ is given by [30]

$$w_j = \left(\sum_{i \in S_j} A_{d,j} h_i (A_{d,j} h_i)^H\right)^{-1} A_{d,j} h_j, \quad (31)$$

where $S_j$ represents the set of users that are served by partially the same APs as user $j$. Hence, this precoding scheme is usually referred to as partial ZF. Moreover, this set is given as $S_j = \{i : A_{d,i} A_{d,j} \neq 0\}$, where $0$ is the zero matrix [30].

To meet the power constraints in our problem/sub-problems we need to allocate powers to the users. The transmitted power from AP $i$ in any network can be given in term of both users’ powers and the elements of the precoding matrix as

$$p_i = \sum_{j=1}^{N_u} (w_{i,j})^2 P_j, \quad (32)$$

where $p_i$ is the power transmitted by AP $i$. To satisfy the constraints of our problem, we choose to allocate equal power to all users. Hence, users’ powers are given by

$$P_j = \frac{1}{\max_i \left(\sum_{j=1}^{N_u} (w_{i,j})^2\right)}. \quad (33)$$

This guarantees that each AP transmits signal within its power budget.

V. SIMULATION RESULTS

In this section, the performance of the proposed system along with the two proposed user association algorithms are evaluated by showing the effect of changing several parameters on the sum-rate. Unless stated otherwise, the simulation parameters used in our setup to generate all the results are listed in Table I. Monte-Carlo simulation has been implemented to obtain more accurate and generic results, where every displayed point is the arithmetic mean of 1000 points resulted from 1000 independent distribution of users. In addition, VLC blockage effect in the VLC systems and the Hybrid systems is considered in all results. The results in this section are divided into two subsections, where in the first subsection we evaluate the system with no clustering, and in the second subsection we evaluate it using the two proposed clustering techniques.

A. Hybrid CF-mMIMO without clustering

It has been established that the clustering matrix $A$ allows for a generalized analysis. This means that it covers all the possible connections between APs and users. Hence, the static (original) CF structure is nothing but a special case. In fact, setting $a_{j,\cdot} = 1, \forall i,j$ leads to having all APs serve all users, which we call a no-clustering scenario. In this subsection, we evaluate this special case of the system.

In Fig. 4 the sum-rate of the proposed hybrid VLC/RF CF-mMIMO system using each of proposed user association algorithms is compared with three systems, a traditional standalone VLC CF-mMIMO, a traditional standalone RF CF-mMIMO, a hybrid VLC/RF CF-mMIMO system but with a random user association. The comparison is held over different numbers of users in the system. To have a fair comparison, the number of APs in each of the standalone systems is set to be equal to the total number of APs in our hybrid system. Nonetheless, using either Algorithm 1 or Algorithm 1 the

| Parameter | Value |
|-----------|-------|
| Room length | 10 m |
| Room width | 10 m |
| Room height | 3 m |
| Electrical-to-optical conversion factor $\rho_{oc}$ | 0.53 A/W |
| Optical-to-electrical conversion factor $\rho_{eo}$ | 10 W/A |
| Bandwidth of the VLC network $B^{(v)}$ | 40 MHz |
| Bandwidth of the RF network $B^{(r)}$ | 15 MHz |
| Noise power spectral density in VLC network $\sigma_N^{(v)}$ | $10^{-22}$ W/Hz |
| Noise power spectral density in RF network $\sigma_N^{(r)}$ | $10^{-19}$ W/Hz |
| Power limit for each VLC AP $p_{v}^{(v)}$ | 5 W |
| Power limit for each RF AP $p_{r}^{(r)}$ | 5 W |
| Number of VLC APs $N_{vap}$ | 16 |
| Number of RF APs $N_{rap}$ | 9 |
| User’s altitude | 0.85 m |
| Physical area of a PD $A_p$ | 1 cm |
| Half-intensity radiation angle $\theta$ | 60° |
| Semi-angle of the FoV of PDs $\Theta$ | 60° |
| Gain of the optical filter $G_{o/f}$ | 1 |
| Refractive index of PDs $n$ | 1.5 |
| Monte-Carlo simulation | 1000 scenarios |
| Blockage rate | $10\%$ of users |

TABLE I

**Simulation Parameters**

| Parameter | Value |
|-----------|-------|
| Room length | 10 m |
| Room width | 10 m |
| Room height | 3 m |
| Electrical-to-optical conversion factor $\rho_{oc}$ | 0.53 A/W |
| Optical-to-electrical conversion factor $\rho_{eo}$ | 10 W/A |
| Bandwidth of the VLC network $B^{(v)}$ | 40 MHz |
| Bandwidth of the RF network $B^{(r)}$ | 15 MHz |
| Noise power spectral density in VLC network $\sigma_N^{(v)}$ | $10^{-22}$ W/Hz |
| Noise power spectral density in RF network $\sigma_N^{(r)}$ | $10^{-19}$ W/Hz |
| Power limit for each VLC AP $p_{v}^{(v)}$ | 5 W |
| Power limit for each RF AP $p_{r}^{(r)}$ | 5 W |
| Number of VLC APs $N_{vap}$ | 16 |
| Number of RF APs $N_{rap}$ | 9 |
| User’s altitude | 0.85 m |
| Physical area of a PD $A_p$ | 1 cm |
| Half-intensity radiation angle $\theta$ | 60° |
| Semi-angle of the FoV of PDs $\Theta$ | 60° |
| Gain of the optical filter $G_{o/f}$ | 1 |
| Refractive index of PDs $n$ | 1.5 |
| Monte-Carlo simulation | 1000 scenarios |
| Blockage rate | $10\%$ of users |
The proposed system shows a slightly better performance than the VLC standalone CF system until a point where it significantly surpasses it. This can be explained by the fact that the RF contribution to the hybrid system increases as the system gets more crowded by alleviating the load off the VLC, which helps improving the sum-rate. In this specific setup, Fig. 4 also shows that Algorithm 2 performs better than Algorithm 1 in terms of the system’s achievable rate. In addition, it can be seen that the proposed system with with either algorithms 1 and 2 dramatically outperforms the system with random user association that performs the worst as the number of users increases, which clearly points out that the system with random user association does not take an advantage of having both networks.

Fig. 5 shows the steady performance of the proposed hybrid system using the proposed algorithms for an increasing number of the total APs in the room with a fixed number of users $N_u = 30$. In this figure, we adapt the room dimensions to accommodate all the APs in the system in order to maintain a reasonable deployment density of the APs. For instance, we preserve the minimum distance between any two adjacent VLC APs to be around 2.5 m. The exact numbers of VLC APs, RF APs, and room dimensions are presented in Table II. It is clear from Fig. 4 and Fig. 5 that the proposed system and algorithms work well with increasing the number of users and the number of APs, respectively.

The FoV of the PDs is an important parameter that affects the VLC channel gain and hence the performance of VLC systems. Fig. 6 shows the effect of changing the FoV of the VLC receivers on the average per-user data rate in both the proposed system (using both Algorithm 1 and Algorithm 2) and a VLC standalone CF system. In the VLC standalone system, we set the number of APs to be equivalent to the total number of (VLC+RF) APs in the proposed hybrid system. This has been carried out over three different choices of number of users in the system. The figure shows that for large values of the FoV, the performance diminishes, which should not be of any surprise since the VLC channel gain drops as the angle of the FoV increases as can be noticed in (2). Moreover, as the FoV decreases, the performance decreases as a result of more users not being able to be in the view of the VLC APs. VLC CF-MIMO systems in general tend to push that limit to a very low FoV value since having more VLC APs to cover more ground area ensures that all users are able to connect. The proposed hybrid system, however, shows more resilience as the value of the FoV drops which is a direct result of having the RF network as a support to the VLC network. Nevertheless, this resiliency is only visible when $N_u$ is small since there could be cases where all VLC APs aren’t in the FoV of any receiver. In addition, it is obvious from the figure that the performance gap between the proposed system and the VLC standalone widens as the number of user in the system increases. It came as surprise that when $N_u = 5$ the standalone VLC CF system performed better than the proposed system with Algorithm 1 which indicates that this algorithm may not always be suitable when the room has a small number of users.

Fig. 7 shows the cumulative distribution function (CDF) of the average per-user rate of the five systems considered in Fig. 4. All the systems are evaluated when $N_u = 10$ and $N_u = 20$. 

---

Fig. 4. Sum-rate versus number of users in the systems.

Fig. 5. Sum-rate versus total number of APs.

Fig. 6. Sum-rate versus FoV.
TABLE II
ROOM DIMENSIONS AND NUMBER OF APs IN FIG. 5

| Total number of APs | 25  | 32  | 45  | 65  | 80  | 97  | 125 |
|---------------------|-----|-----|-----|-----|-----|-----|-----|
| VLC APs             | 16  | 16  | 36  | 49  | 64  | 81  | 100 |
| RF APs              | 9   | 16  | 9   | 16  | 16  | 16  | 25  |
| Room dimensions     | 10×10 | 11×11 | 14×14 | 16×16 | 19×19 | 22×22 | 25×25 |

Fig. 7. CDF of Average Per-user Rate.

Fig. 8. Number of iterations required for convergence versus number of users.

Fig. 9. Sum-rate versus total number of changes.

Fig. 10 shows the CDF of the proposed hybrid CF-mMIMO system utilizing the first clustering technique $A_1$ with three

Table III
PARAMETERS FOR CLUSTERING

| Clustering | $A_1$ | $A_2$ |
|------------|-------|-------|
| Network    |       |       |
| $d_{max}$  | 4 m   | 3 m   |
| $N_{max}$  | 6 m   | 5 m   |
| $d_{min}$  | –     | 5 m   |
| $N_{min}$  | –     | –     |

B. Hybrid CF-mMIMO with clustering

In this subsection, the performance of the proposed system and algorithms along with the proposed clustering techniques are studied. The main advantage of the proposed clustering techniques is that they do not require any complex computation or iterative search. Nonetheless, they perform very well with the right choice of precoding schemes. Clustering parameters are presented in Table III.

Fig. 10 shows the CDF of the proposed hybrid CF-mMIMO system utilizing the first clustering technique $A_1$ with three
user association approaches, namely, Algorithm 1, Algorithm 2 and random user association. Standalone CF systems are evaluated using the same clustering technique for comparison. In this figure, ZF precoding is implemented. We see the clear lead of the proposed hybrid system with both association algorithms over all other systems in the figure. It is worth to notice that Algorithm 2 performs better than Algorithm 1, however, the performance gap between them is almost null when $N_u = 20$. It can be seen that using $A_1$ clustering reduces the sum-rate of all the systems in the figure. The drop in the performance is mostly due to the fact that each AP is limited to serve only users within $d_{\text{max}}$ proximity, which removes the users that could have experienced a decent channel gain but are located outside the AP’s $d_{\text{max}}$ range, hence limiting the data rates.

The performance of the second clustering technique $A_2$ using ZF precoding is shown in Fig. 11. Several things can be concluded from this figure. First, the overall performance of the system using $A_2$ clustering is better than the performance of the system with $A_1$ clustering. Second, by comparing the plots on both figures, we notice that with $A_2$ clustering, less than 30% of the users experience an average rate of 300 Mbits/s or less, while around 85% of the users receive an average rate of less than 300 Mbits/s when $A_1$ is used. Although one might notice that this specific clustering technique ($A_2$) significantly lowers the performance of the VLC standalone CF system and kills the performance of the RF standalone CF system, it does not have such an impact on the hybrid system when using any of the proposed user association algorithms, especially when the number of users is low. However, when the number of users is relatively high, e.g. $N_u = 20$ in this case, two things are noted; first, the performance when using $A_2$ clustering is slightly better than when $A_1$ clustering is used. Second, the performance of the gibbs sampling-based algorithm (Algorithm 1) is superior to that of Algorithm 2. This fact is further studied in Fig. 12 and Fig. 13.

Fig. 12 compares the two proposed algorithms in terms of the achievable sum-rate with different number of users when $A_1$ clustering is used. Fig. 13, on the other hand, presents the same comparison but with $A_2$ clustering instead. Both
figures show that regardless of what clustering technique is used, it is better to adopt Algorithm 2 for user association when low number of users exists in the system. However, things turn around as the number of users increases above a certain number, where Algorithm 1 becomes superior and its performance dominates. These figures suggest that the user association algorithm can be selected according to the expected number of users in a given system/area.

VI. CONCLUSION

A user-centric hybrid VLC/RF cell-free massive MIMO system has been introduced for the first time in this paper. User association and user clustering are two interlinked problems, and thus were formulated into a joint optimization problem that aims at maximizing the sum-rate of the proposed system. The joint optimization problem was then simplified into two independent sub-problems, where each one has been tackled independently. Two sub-optimal algorithms were proposed for the user association sub-problem. Each algorithm showed high potential in certain cases. In particular, the iterative algorithm (Algorithm 2) performed better when clustering is accounted for, specifically in systems with large number of users. Two user clustering techniques were proposed and evaluated as well. The proposed system outperformed other cell-free systems with standalone VLC or RF networks especially at a relatively high number of users.

REFERENCES

[1] Ahmed Almehdhar, Mohanad Obeed, Anas Chaaban, and Salam A. Zummo, “A Hybrid VLC/RF Cell-Free Massive MIMO System,” in IEEE International Conference on Communications (ICC), 2022.
[2] M. Obeed, A. M. Salhab, M. S. Alouini, and S. A. Zummo, “On Optimizing VLC Networks for Downlink Multi-User Transmission: A Survey,” IEEE Commun. Surveys Tuts., vol. 21, no. 3, pp. 2947–2976, 2019.
[3] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, “What Will 5G Be?,” IEEE J. Sel. Areas Commun., vol. 32, no. 6, pp. 1065–1082, 2014.
[4] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tuvelsson, A. Benjebbour, and G. Wunder, “5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice,” IEEE J. Sel. Areas Commun., vol. 35, no. 6, pp. 1201–1221, 2017.
[5] P. Pirinen, “A brief overview of 5G research activities,” in 1st International Conference on 5G for Ubiquitous Connectivity, 2014, pp. 17–22.
[6] Yuichi Tanaka, S. Haruyama, and M. Nakagawa, “Wireless optical transmissions with white colored LED for wireless home links,” 11th IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC. Proceedings (Cat. No.00TH8523), vol. 2, pp. 1325–1329 vol.2, 2000.
[7] Galefong Allycan Mapunda, Reuben Ramogomana, Leatile Marata, Bokamoso Basutli, Amjad Saeed Khan, and Joseph Monamati Chuma, “Indoor Visible Light Communication: A Tutorial and Survey,” Wirel. Commun. Mob. Comput., vol. 2020, pp. 8881305:1–8881305:46, 2020.
[8] Lin Cheng, Wantiane Viriyasitavat, Mate Boban, and Hsin-Mu Tsai, “Comparison of Radio Frequency and Visible Light Propagation Channels for Vehicular Communications,” IEEE Access, vol. 6, pp. 2634–2644, 2018.
[9] Mohanad Obeed, Anas M. Salhab, S. A. Zummo, and M-Slim Alouini, “New Algorithms for Energy-Efficient VLC Networks With User-Centric Cell Formation,” IEEE Trans. Green Commun. Netw., vol. 3, no. 1, pp. 108–121, 2019.
[10] Mohanad Obeed, Anas M. Salhab, Salam A. Zummo, and Mohamed-Slim Alouini, “Joint optimization of power allocation and load balancing for hybrid VLC/RF networks,” J. Opt. Commun. Netw., vol. 10, no. 5, pp. 553–562, 2018.
[11] M. Ayyash, H. Elgala, A. Khreishah, V. Jungnickel, T. Little, S. Shao, M. Rahaim, D. Schulz, J. Hilt, and R. Freund, “Coexistence of WiFi and LiFi toward 5G: concepts, opportunities, and challenges,” IEEE Commun. Mag., vol. 54, no. 2, pp. 64–71, 2016.
[12] Tamer Rakia, Hong-Chuan Yang, Fayeaz Gebali, and Mohamed-Slim Alouini, “Dual-Hop VLC/RF Transmission System with Energy Harvesting Relay under Delays Constraint,” in 2016 IEEE Globecom Workshops (GC Wkshps), 2016, pp. 1–6.
[13] Yue Xiao, Panagiotis D. Diamantoulakis, Zequn Fang, Li Hao, Zheng Ma, and George K. Karagiannidis, “Cooperative hybrid vlc/rf systems with sltp,” IEEE Transactions on Communications, vol. 69, no. 4, pp. 2532–2545, 2021.
[14] E. Neyebi, A. Ashikhmin, T. L. Marzetta, and H. Yang, “Cell-Free Massive MIMO systems,” in 2015 49th Asilomar Conference on Signals and Systems, 2015, pp. 695–699.
[15] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, “Cell-Free Massive MIMO: Uniformly great service for everyone,” in IEEE Workshop Signal Process. Adv. Wirel. Commun. SPAWC, 2015, pp. 201–205.
[16] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, “Cell-Free Massive MIMO Versus Small Cells,” IEEE Trans. Wireless Commun., vol. 16, no. 3, pp. 1834–1850, 2017.
[17] E. Neyebi, A. Ashikhmin, T. L. Marzetta, and B. D. Rao, “Performance of cell-free massive MIMO systems with MMSE and LSFd receivers,” in 2016 50th Asilomar Conference on Signals, Systems and Computers, 2016, pp. 203–207.
[18] S. Buzzi, C. D’Andrea, and C. D’Elia, “User-Centric Cell-Free Massive MIMO with Interference Cancellation and Local ZF Downlink Precoding,” in 2018 15th International Symposium on Wireless Communication Systems (ISWCS), 2018, pp. 1–5.
[19] S. Buzzi and C. D’Andrea, “Cell-Free Massive MIMO: User-Centric Approach,” IEEE Wireless Communications Letters, vol. 6, no. 6, pp. 706–709, 2017.
[20] G. Interdonato, P. Frenger, and E. G. Larsson, “Scalability Aspects of Cell-Free Massive MIMO,” in IEEE International Conference on Communications (ICC), 2019, pp. 1–6.
[21] F. Björnson and L. Sanguinetti, “A New Look at Cell-Free Massive MIMO: Making It Practical With Dynamic Cooperation,” in 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2019, pp. 1–6.
[22] E. Björnson and L. Sanguinetti, “Scalable Cell-Free Massive MIMO Systems,” IEEE Transactions on Communications, vol. 68, no. 7, pp. 4247–4261, 2020.
[23] R. Jiang, Q. Wang, H. Haas, and Z. Wang, “Joint User Association and Power Allocation for Cell-Free Visible Light Communication Networks,” IEEE J. Sel. Areas Commun., vol. 36, no. 1, pp. 136–148, 2018.
[24] J. Chen, Z. Wang, and R. Jiang, “Downlink interference management in cell-free vlc network,” IEEE Trans. Veh. Technol., vol. 68, no. 9, pp. 9009–9017, 2019.
[25] J.M. Kahn and J.R. Barry, “Wireless infrared communications,” Proc. IEEE, vol. 85, no. 2, pp. 265–298, 1997.
[26] Yunlu Wang, Dushyantha A. Basnayaka, and Harald Haas, “Dynamic load balancing for hybrid Li-Fi and RF indoor networks,” in 2015 IEEE International Conference on Communication Workshop (ICCW), 2015, pp. 1422–1427.
[27] Anas Chaaban, Souheir Rezki, and Mohamed-Slim Alouini, “On the Capacity of the Intensity-Modulation Direct-Detection Optical Broadcast Channel,” IEEE Trans. Wireless Commun., vol. 15, no. 5, pp. 3114–3130, 2016.
[28] Li Ping Qian, Ying Jun Angela Zhang, and Mung Chiang, “Distributed Nonconvex Power Control using Gibbs Sampling,” IEEE Transactions on Communications, vol. 60, no. 12, pp. 3886–3898, 2012.
[29] Hang Liu, Xiaojun Yuan, and Ying-Jun Angela Zhang, “Reconfigurable Intelligent Surface Enabled Federated Learning: A Unified Communication-Learning Design Approach,” IEEE Transactions on Wireless Communications, pp. 1–1, 2021.
[30] Özlem Tugfe Demir, Emil Björnson, and Luca Sanguinetti, “Foundations and Trends® in Signal Processing, vol. 14, no. 3-4, pp. 162–472, 2021.
[31] Mohanad Obeed, Hayssam Dahrouj, Anas M. Salhab, Salam A. Zummo, and Mohamed-Slim Alouini, “DC-Bias and Power Allocation in Cooperative VLC Networks for Joint Information and Energy Transfer,” IEEE Trans. Wireless Commun., vol. 18, no. 12, pp. 5486–5499, 2019.