Power Allocation and Link Selection for Multicell Cooperative NOMA Hybrid VLC/RF Systems

Mohanad Obeed, Hayssam Dahrouj, *Senior Member, IEEE,* Anas M. Salhab, *Senior Member, IEEE,* Anas Chaaban, *Senior Member, IEEE,* Salam A. Zummo, *Senior Member, IEEE,* and Mohamed-Slim Alouini, *Fellow, IEEE*

***Abstract*—This paper proposes and optimizes a cooperative non-orthogonal multiple-access (Co-NOMA) scheme in the context of multicell visible light communications (VLC) networks to mitigate inter-cell interference. Consider a network where each access-point (AP) serves two users. In each cell, the weak user (cell-edge user) can be served either directly by the VLC AP, or through the strong user that decodes the weak user message and forwards it through the radio-frequency (RF) link. The paper then considers the problem of maximizing the sum-rate under quality-of-service constraints by allocating the powers of the messages and APs, and determining the links serving each weak user. The paper solves this non-convex problem by first finding closed-form solutions of the users' powers and link selection for fixed APs powers. The APs powers are then iteratively solved in an outer loop. Simulation results show that the proposed scheme improves the sum-rate and fairness as compared to non-orthogonal multiple-access (NOMA) scheme.**

***Index Terms*—Cooperative non-orthogonal multiple-access, hybrid visible light communication/radio-frequency networks.**

I. Introduction

The recent escalating need for high data rates and the increasing number of connected devices has necessitated a thorough examination of the vast, unregulated, and free visible light spectrum through visible light communications (VLC). The performance of multicell VLC systems is, however, limited by interference, as the transmitters lamps are often mounted close to each other to achieve sufficient illumination levels. This paper provides a solution for VLC systems that significantly helps in reducing the interference and improves the system sum-rate.

Different papers in the literature consider the problem of interference management in VLC systems [2], [3]. The authors in [2] show that supporting VLC networks by RF APs would mitigate the effect of interference. Reference [3] use the joint transmission and user-centric design to cancel or decrease the interference levels. Moreover, similar to the non-orthogonal multiple-access (NOMA) scheme applied in classical RF networks [4], recent works [5], [6] apply the NOMA principle to VLC networks and show that NOMA scheme outperforms orthogonal multiple-access (OMA) schemes [5], [6]. Cooperative NOMA (Co-NOMA) has been recently proposed to strengthen the received signal-to-noise-ratio (SNR) at the weak receivers in RF networks [7], and in VLC systems [8]–[11]. The authors of [8]–[11] focus only on a single-cell case with two users, where the potential inter-cell interference is absent, unlike our paper that considers a multi-cell VLC system scenario. In addition, the problem of optimizing the power and the link selection are not considered in [9], [11].

The paper proposes the use of Co-NOMA, energy harvesting, and hybrid VLC/RF techniques to mitigate the interference in a multi-cell VLC system. These techniques are used to provide two options for the edge users to be served either directly from VLC AP or through the channels of strong users with the help of RF link. The paper then formulates the problem of maximizing the sum-rate under quality-of-service (QoS) and APs' peak power constraints to allocate the power and optimize link selection vector. The paper tackles such difficult non-convex optimization problem iteratively by first finding closed-form solutions of the users' powers and link selection vector problem, under fixed AP power scenario. It then finds a solution for the total AP transmit power in an iterative outer loop method. Simulation results show that the proposed solution and scheme outperform the NOMA scheme in terms of sum-rate and fairness.

II. System Model and Problem Formulation

A. System Model

The paper considers a system model that consists of N APs, where each AP serves two users as shown in Fig. 1. We assume that each user is served by the closest AP. In each cell, the two users are distributed in a way that one of them (strong user) is around the cell center (within a circle whose center is the center of the cell) and the other (weak user) is located near the cell edge (outside a square closer to the cell-edge). We define a parameter α as the distance between the strong user circumference circle and the weak user square, and this parameter indicates the average interference received by the weak users. Increasing α with

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M. Obeed and A. Chabaan are with the School of Engineering, University of British Columbia, Kelowna V1Y 1V7, BC, Canada (email: mohanad.obeed@ubc.ca, anas.chabaan@ubc.ca).

H. Dahrouj and M.-S. Alouini are with the Computer, Electrical, and Mathematical Siences & Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal, Makkah Province, Saudi Arabia (email: hayssam.dahrouj@gmail.com, (email: slim.alouini@kaust.edu.sa))

A. M. Salhab, and S. A. Zummo are with the Department Electrical Engineering, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran, Eastern Province, Saudi Arabia (email: salhab@kfupm.edu.sa, zummo@kfupm.edu.sa).

A more detailed version of this paper is available on arXiv [1].

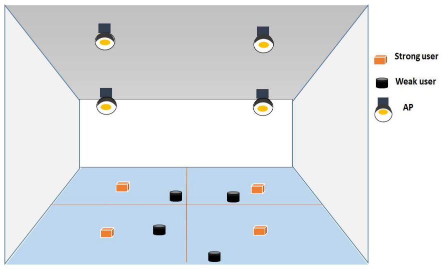

Fig. 1. An example of system model with 4 cells.

fixing the strong user circle shrinks the distribution area of the weak users to be closer to the cell edge. All the VLC APs in the system share the whole available VLC bandwidth, which leads to inter-cell interference. The strong user can also act as a relay, which can decode the weak user's message, harvest the energy through the received light intensity, and then use this energy to forward the decoded message to the weak user using the RF link. The system, therefore, can serve the weak users either by the VLC AP directly, or by the paired strong user through the hybrid VLC/RF link. The transmitted electrical signal from the AP k is $y_k = \sqrt{P_{k,s_k}}x_{k,s_k}+\sqrt{P_{k,w_k}}x_{k,w_k}+b_k$, where the subscripts s_k and w_k indicate the strong and weak users associated to the cell k, respectively, P_{k,s_k} and P_{k,w_k} are the powers assigned to the strong and weak users' symbols x_{k,s_k} and x_{k,w_k}, respectively, and b_k is the direct-current (DC), where $|x_{k,s_k}| \leq 1$ and $|x_{k,w_k}| \leq 1$. To guarantee that y_k is non-negative, real, and falls within the LED's linear operational range, y_k must satisfy $0 \leq \sqrt{P_{k,s_k}}x_{k,s_k} + \sqrt{P_{k,w_k}}x_{k,w_k} + b_k \leq I_H$, where I_H is the maximum current that the LED allows to operate in the linear region. To fully benefit from the available power, we choose $b_k = b = \frac{I_H}{2}, \forall k$ [12]. Hence, the peak power of the input messages must satisfy $\sqrt{P_{k,s_k}} + \sqrt{P_{k,w_k}} \leq I_H - b$.

After removing the DC-bias, the received signal at the strong user associated to the AP k from all APs is given by

$$z_{s_k} = \rho\nu h_{k,s_k}\sqrt{P_{k,s_k}}x_{k,s_k} + \rho\nu h_{k,s_k}\sqrt{P_{k,w_k}}x_{k,w_k} + \rho\nu \sum_{i=1,i\neq k}^{N} h_{i,s_k}\left(\sqrt{P_{i,s_i}}x_{i,s_i} + \sqrt{P_{i,w_i}}x_{i,w_i}\right) + n, \quad (1)$$

where ρ and ν are the optical-to-electrical and electric-to-optical conversion factors, respectively, h_{i,s_k} (h_{i,w_k}) is the VLC channel between the AP i and the strong (weak) user in cell k, and n is the noise that can be modelled as real zero-mean additive white Gaussian noise (AWGN) variable with variance $\sigma^2 = N_v B_v$, where N_v is the noise power spectral density and B_v is the modulation bandwidth. Each strong user then decodes the weak user's signal and uses the received DC signal to harvest energy. The harvested energy then can be used to forward the weak user's signal through the RF link [8]. Therefore, the achievable rate of the strong user of the kth cell can be approximated by [13]

$$R_{s_k} = \frac{B_v}{2}\log_2\left(1+\frac{\nu^2\rho^2 h_{k,s_k}^2 P_{k,s_k}}{9B_vN_v+\nu^2\rho^2\sum_{i=1,i\neq k}^{N}(P_{i,s_i}+P_{i,w_i})h_{i,s_k}^2}\right), \quad (2)$$

where $P_{i,s_i}+P_{i,w_i} \leq (\frac{I_H}{2})^2$ must be satisfied. The achievable rate of the weak user, served directly by the AP k, is given by

$$R_{w_k} = \frac{B_v}{2}\log_2\Big(1+ \frac{\nu^2\rho^2 h_{k,w_k}^2 P_{k,w_k}}{9B_vN_v+c\nu^2\rho^2 P_{k,s_k}h_{k,w_k}^2+\nu^2\rho^2\sum_{i=1,i\neq k}^{N}(P_{i,s_i}+P_{i,w_i})h_{i,w_k}^2}\Big), \quad (3)$$

while the achievable data rate of the weak user, served by the kth AP through the hybrid VLC/RF link, is given by

$$R_{w_k}^{HL} = \min\left(R_{w_k\to s_k}, R_{w_k,s_k}^{RF}\right), \quad (4)$$

where

$$R_{w_k\to s_k} = \frac{B_v}{2}\log_2\Big(1 + \frac{\nu^2\rho^2 h_{k,s_k}^2 P_{k,w_k}}{9B_vN_v+\nu^2\rho^2 P_{k,s_k}h_{k,s_k}^2+\nu^2\rho^2\sum_{i=1,i\neq k}^{N}(P_{i,s_i}+P_{i,w_i})h_{i,s_i}^2}\Big) \quad (5)$$

is the achievable data rate of the weak user received at the strong user, and

$$R_{w_k,s_k}^{RF} = B_{RF}\log_2\left(1+\frac{P_{RF,s_k}h_{RF,w_k,s_k}^2}{B_{RF}N_{RF}}\right) \quad (6)$$

is the achievable data rate of the weak user that can be provided by the strong user through the RF link, where P_{RF,s_k} is the harvested power at the strong user in the cell k, which depends on the DC biases at all the APs [12], h_{RF,w_k,s_k} is the RF channel between the strong user and the weak user in cell k, B_{RF} is the RF bandwidth assigned for one user, and N_{RF} is the RF noise power spectral density.

B. Problem Formulation

Our goal in this paper is to maximize the sum-rate of the system under QoS constraints and peak power constraints by finding the powers of the users' messages and the link selection vector of the weak users. Define $\mathbf{x} = [x_1, x_2, \ldots, x_N]$ as the link selection vector, where $x_k = 1$ means that the weak user in cell k is served by the VLC/RF link, and $x_k = 0$ means that the weak user is served directly by the VLC link from AP k. The problem, then, can be formulated as follows

$$\max_{\mathbf{P},\mathbf{x}} \quad \sum_{k=1}^{N}\left(R_{s_k} + (1-x_k)R_{w_k} + x_k R_{w_k}^{HL}\right) \quad (7a)$$

$$\text{s.t.} \quad R_{s_k} \geq R_{th}, \ k = 1,\ldots,N \quad (7b)$$

$$(1-x_k)R_{w_k} + x_k R_{w_k}^{HL} \geq R_{th}, k = 1,\ldots,N \quad (7c)$$

$$\sqrt{P_{k,w_k}} + \sqrt{P_{k,s_k}} \leq I_H - b, \ k = 1,\ldots,N \quad (7d)$$

$$x_k \in \{0,1\}, \ k = 1,\ldots,N. \quad (7e)$$

The constraint $P_{k,s_k}+P_{k,w_k} \leq (\frac{I_H}{2})^2$ is implied in constraint (7d). Constraints (7b) and (7c) are imposed to guarantee the required QoS for the users. Constraint (7e) is to guarantee that each weak user is either connected directly to the VLC AP, or through the strong user by using the VLC/RF link. Problem (7) is a mixed-integer non-convex optimization problem with a non-concave objective function and non-convex constraint (7d). However, in the following, we propose an efficient solution to tackle the formulated problem. The approach is based on introducing an auxiliary variable that breaks problem (7) into $2N$ inner problems and one outer problem. By defining the auxiliary variable q_k as $q_k = P_{k,s_k} + P_{k,w_k}$, in the inner problems, we can assume that $q_k, \ k = 1,\ldots,N$ are given. Then $q_k,\ k=1,\dots,N$ can be solved in an outer loop. Since $q_k = P_{k,s_k} + P_{k,w_k}$, we hereafter call it the transmit power of AP k. In the following, we first find closed-form solutions for the inner problems, then we provide an iterative algorithm for the outer problem.

III. Inner Problem: Joint Power allocation and Link Selection for a Given q_k

Under the assumption that $q_k,\ k=1,\dots,N$ are given, the inter-cell interference terms in the objective function are given and can be treated as a noise. Therefore, in this section, we will find closed-form solutions for the variables P_{k,s_k}, P_{k,w_k}, and x_k when the budget $P_{k,s_k}+P_{k,w_k}$ is given for all $k=1,\dots,N$. For a fixed vector $\mathbf{q}$, problem (7) can be equivalently divided into N problems, where each problem can be solved at the corresponding AP. Hence, the problem at AP k can be formulated as follows

$$\max_{P_{k,s_k},P_{k,w_k},\mathbf{x}} \quad R_{s_k} + (1-x_k)R_{w_k} + x_k R^{HL}_{w_k} \tag{8a}$$
$$\text{s.t.} \quad R_{s_k} \geq R_{th}, \tag{8b}$$
$$(1-x_k)R_{w_k} + x_k R^{HL}_{w_k} \geq R_{th}, \tag{8c}$$
$$\sqrt{P_{k,w_k}} + \sqrt{P_{k,s_k}} \leq I_H - b, \tag{8d}$$
$$P_{k,w_k} + P_{k,s_k} = q_k, \tag{8e}$$
$$x_k \in \{0,1\}, \tag{8f}$$
$$0 \leq P_{k,s_k} \leq P_{k,w_k}, \tag{8g}$$

where the expression $P_{i,s_i}+P_{i,s_i}$ at the inter-cell interference terms in functions R_{s_k}, R_{w_k}, and $R_{w_k\to s_k}$ are replaced by q_i. Problem (8) is still not convex, because of the binary variables and the interference terms in the expression of R_{w_k}. Constraint (8f) means that problem (8) can be expressed in terms of P_{k,s_k} by plugging $P_{k,w_k} = q_k - P_{k,s_k}$ in (8). Now, we discuss the solution for the two cases $x_k=0$ and $x_k=1$.

A. Case I: x_k=0

In this case, the weak user in cell k is served directly by the VLC AP k. Define the variables Ψ_{s_k} and Ψ_{w_k} as $\Psi_{s_k} = \frac{\nu^2\rho^2 h^2_{k,s_k}}{Z_{s_k}}$, and $\Psi_{w_k} = \frac{\nu^2\rho^2 h^2_{k,w_k}}{Z_{w_k}}$, where $Z_{s_k} = 9B_vN_v + \nu^2\rho^2\sum_{i=1,i\neq k}^{N} q_i h^2_{i,s_k}$ and $Z_{w_k} = 9B_vN_v + \nu^2\rho^2\sum_{i=1,i\neq k}^{N} q_i h^2_{i,w_k}$. Therefore, (8) can be written as

$$\max_{P_{k,s_k}} \quad \frac{B_v}{2}\log_2\left(1+\Psi_{s_k}P_{k,s_k}\right) + \frac{B_v}{2}\log_2\left(1+\frac{q_k-P_{k,s_k}}{\frac{1}{\Psi_{w_k}}+P_{k,s_k}}\right) \tag{9a}$$
$$\text{s.t.} \quad R_{w_k} \geq R_{th}, \tag{9b}$$
$$R_{s_k} \geq R_{th}, \tag{9c}$$
$$\sqrt{q_k - P_{k,s_k}} + \sqrt{P_{k,s_k}} \leq I_H - b, \tag{9d}$$
$$0 \leq P_{k,s_k} \leq \frac{1}{2}q_k. \tag{9e}$$

Since $P_{k,w_k} = q_k - P_{k,w_k}$, constraint (9e) implies that $0 \leq P_{k,s_k} \leq P_{k,w_k}$. Constraint (9d) can be expressed as $\frac{q_k}{2} - \frac{\sqrt{8q_kI_H^2 - I_H^4}}{8} \leq P_{k,s_k} \leq \frac{q_k}{2} + \frac{\sqrt{8q_kI_H^2-I_H^4}}{8}$. The upper bound of such constraint can be ignored since it is achieved by constraint (9e). Hence, constraint (9d) can be replaced by $P_{k,s_k} \geq \frac{q_k}{2} - \frac{\sqrt{8q_kI_H^2-I_H^4}}{8}$. At the outer loop, constraint $q_k \geq \frac{I_H^2}{8}$ must be imposed to guarantee a real value of P_{k,s_k}.

Lemma 1. *Define the variables A_{s_k} and C_{w_k} as $A_{s_k} = \max\left(0, \frac{2^{\frac{2R_{th}}{B_v}}-1}{\Psi_{s_k}}, \frac{q_k}{2} - \frac{\sqrt{8q_kI_H^2-I_H^4}}{8}\right)$ and $C_{w_k} = \min(\frac{1}{2}q_k, \frac{1+\Psi_{w_k}q_k}{\Psi_{w_k}2^{\frac{2R_{th}}{B_v}}} - \frac{1}{\Psi_{w_k}})$, the optimal value of P_{k,s_k}, when $x_k=0$, is given by $P^*_{k,s_k} = P_{s_k,0}$, where*

$$P_{s_k,0} = \begin{cases} A_{s_k}, & \text{if } \Psi_{s_k} < \Psi_{w_k}, \\ C_{w_k}, & \text{otherwise.} \end{cases} \tag{10}$$

Proof. Based on the above definitions of A_{s_k} and C_{w_k}, the constraints in problem (9) can be rewritten as

$$A_{s_k} \leq P_{k,s_k} \leq C_{w_k}. \tag{11}$$

The derivative of the utility function in (9) can be written as:

$$\frac{d}{dP_{k,s_k}}(R_{s_k}+R_{w_k}) = \frac{B_v}{2}\left(\frac{1}{1/\Psi_{s_k}+P_{k,s_k}} - \frac{1}{1/\Psi_{w_k}+P_{k,s_k}}\right). \tag{12}$$

Equation (12) implies that the objective function in (9) is either increasing in P_{k,s_k} if $\Psi_{s_k} > \Psi_{w_k}$, or decreasing if $\Psi_{s_k} < \Psi_{w_k}$. This means that the optimal value of P_{k,s_k} is either the minimum bound or the maximum bound of constraint (11). From the above, we conclude that the optimal value of P_{k,s_k}, when $x_k=0$, is given by $P_{k,s_k} = P_{s_k,0}$, where $P_{s_k,0}$ is given by (10). □

B. Case II: x_k=1

In this case, the weak user in cell k is served by the strong user through the hybrid VLC/RF link. Hence, problem (8) can be written as follows

$$\max_{P_{k,s_k}} \quad R_{s_k} + \min\left(R_{w_k\to s_k}, R^{RF}_{w_k,s_k}\right) \tag{13a}$$
$$\text{s.t.} \quad R_{s_k} \geq R_{th}, \tag{13b}$$
$$\min(R_{w_k\to s_k}, R^{RF}_{w_k,s_k}) \geq R_{th}, \tag{13c}$$
$$\sqrt{q_k - P_{k,s_k}} + \sqrt{P_{k,s_k}} \leq I_H - b, \tag{13d}$$
$$0 \leq P_{k,s_k} \leq \frac{1}{2}q_k. \tag{13e}$$

Lemma 2. *Define the variables $\bar{A}_{s_k}$ and B_{s_k} as $\bar{A}_{s_k} = \max(A_{s_k}, \frac{1+\Psi_{s_k}q_k - 2^{R^{RF}_{w_k,s_k}/B_v}}{\Psi_{s_k}2^{R^{RF}_{w_k,s_k}/B_v}})$, and $B_{s_k} = \min(\frac{1}{2}q_k, \frac{1+\Psi_{s_k}q_k}{\Psi_{s_k}2^{\frac{2R_{th}}{B_v}}} - \frac{1}{\Psi_{s_k}})$, the optimal power allocation of problem (13) is $P^*_{k,s_k} = P_{s_k,1}$, where $P_{s_k,1}$ is any value within the interval $(\bar{A}_{s_k}, B_{s_k})$ (i.e., $\bar{A}_{s_k} \leq P_{s_k,1} \leq B_{s_k}$).*

Proof. In problem (13), it can be seen that $R^{RF}_{w_k,s_k}$ is a fixed function of P_{k,s_k}. It can also be observed that $R_{w_k\to s_k}$ is a decreasing function of P_{k,s_k}, and that R_{s_k} is an increasing function of P_{k,s_k}. This means that the optimal P_{k,s_k} must satisfy $R_{w_k\to s_k} \leq R^{RF}_{w_k,s_k}$ since, otherwise, we can increase P_{k,s_k}, which increases the objective function without violating the constraints. Hence, we replace the term $\min\left(R_{w_k\to s_k}, R^{RF}_{w_k,s_k}\right)$ by $R_{w_k\to s_k}$ in problem (13), and add a constraint $R_{w_k\to s_k} \leq R^{RF}_{w_k,s_k}$ instead. Thus, problem (13) can be rewritten as:

$$\max_{P_{k,s_k}} \quad R_{s_k} + R_{w_k\to s_k} \tag{14a}$$
$$\text{s.t.} \quad \text{(13b), (13d), (13e)} \tag{14b}$$
$$R_{w_k\to s_k} \geq R_{th}, \tag{14c}$$
$$R_{w_k\to s_k} \leq R^{RF}_{w_k,s_k}. \tag{14d}$$

Take the derivative of the utility in (14), we get:

$$\frac{d}{dP_{k,s_k}}(R_{s_k}+R_{w_k\to s_k})=\frac{B_v}{2}\left(\frac{1}{\frac{1}{\Psi_{s_k}}+P_{k,s_k}}-\frac{1}{\frac{1}{\Psi_{s_k}}+P_{k,s_k}}\right). \quad (15)$$

It can be readily seen that equation (15) is equal to zero, which implies that the objective function in (14) is constant with respect to P_{k,s_k}. Any feasible P_{k,s_k} can, therefore, be conveniently chosen, i.e., such a choice does not affect the optimal solution of (14). Constraints (14b)-(14d) can be rewritten as $\bar{A}_{s_k}\leq P_{k,s_k}\leq B_{s_k}$. Thus, the optimal solution of problem (14) is given by $P_{k,s_k}=P_{s_k,1}$, where $P_{s_k,1}$ can be chosen conveniently from the feasible set: $\bar{A}_{s_k}\leq P_{s_k,1}\leq B_{s_k}$. □

In our simulation results, we choose to set $P_{s_k,1}$ to jointly achieve the constraints and maximize the system fairness simultaneously. Hence, $P_{s_k,1}$ is expressed as follows

$$P_{s_k,1}=\begin{cases}\bar{A}_{s_k}, & \text{if } \eta_{s_k}<A_{s_k},\\ \eta_{s_k}, & \text{if } A_{s_k}\leq\eta_{s_k}\leq B_{s_k}\\ B_{s_k}, & \text{if } \eta_{s_k}>B_{s_k},\end{cases} \quad (16)$$

where $\eta_{s_k}=\frac{\sqrt{1+\Psi_{s_k}q_k}-1}{\Psi_{s_k}}$ is the value that achieves equal rate for both the strong and weak users at the cell k At this stage, we are capable of finding closed-form solutions for the joint users' power and link selection problems for every cell k, both for the cases when $x_k=0$ or $x_k=1$. The chosen solution of every cell k is then the pair P_{k,s_k} and x_k that maximizes the utility function in (8)). Algorithm 1 summarizes these procedures.

Algorithm 1: Find the vectors $\mathbf{x}$ and $\mathbf{P}$, given $\mathbf{q}$

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for *for* $k=1:N$ **do**
  Find $P_{s_k,0}$ and $P_{s_k,1}$, using (10) and (16), respectively, i.e., when $x_k=0$ and $x_k=1$;
  Choose the pair P_{k,s_k} and x_k that maximizes the objective function in (8);
end

C. Outer Problem: Optimizing the AP Transmit Powers q_k

Recall that the above per AP formulation (8) of the original problem (7) only holds for a fixed AP q_k. The papers now solves for the vector $\mathbf{q}$ that maximizes problem (7). The proposed solution is iterative in nature, as each AP shares its instantaneous transmit power and users' channels with other APs. The idea is that the AP k uses the shared information of the users' channels and the AP transmit powers to calculate the objective function in (7) in order to find a local optimal q_k, using the golden section method. We define the minimum transmit power that can achieve constraints (8b)-(8g) as $P_{min,k}=\max\left(\frac{I_H^2}{8},\frac{A^2-A}{\Psi_{s_k}}+\frac{A-1}{\Psi_{w_k}}\right)$, where $A=2^{2R_{th}/B_v}$ and $P_{max}=(I_H-b)^2$. Algorithm 2 can be used to find a joint solution of the vectors $\mathbf{P}$, $\mathbf{q}$, and $\mathbf{x}$. Algorithm 2 implements $I\times N$ iterations, where $I\geq1$ is an integer value that specifies how many rounds the algorithm would circulate over the APs to enhance the sum-rate. It is important to note that the proposed scheme and algorithms can be applied when each cell contains more than two users. To show that, assume

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Algorithm 2: Find the vectors $\mathbf{x}$, $\mathbf{P}$, and $\mathbf{q}$

Run Algorithm 1, when $q_k=P_{max}\forall k=1,\dots N$;
for *for* $k=1:I\times N$ **do**
  Assign $m=q_k$, $n=P_{min,k}$, $\theta=1.618$;
  while *while* $m-n\leq\epsilon$ **do**
    Implement Algorithm 1, when $q_k=a$, where $a=(\theta-1)n+(2-\theta)m$ and set the resulted objective function in (7) as R_a;
    Implement Algorithm 1, when $q_k=b$, where $b=(2-\theta)n+(\theta-1)m$ and set the resulted objective function in (7) as R_b;
    if $R_a>R_b$ **then**
      set $m=a$;
    else
      set $n=a$;
    end
  end
  Set $q_k=(m+n)/2$
end

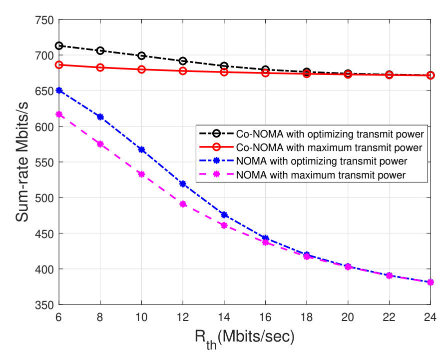

Fig. 2. The effect of R_{th} on sum-rate.

each cell contains an even number of users M, so the proposed scheme and solutions can be applied if we first pair the users into $M/2$ pairs. Under a given pairing scheme, the proposed algorithms and solutions can be applied. For space limitations, we choose to only include the convergence and complexity of Algorithm 2 in the detailed version of this paper available on archive [1].

IV. Simulation Results

In this section, we assess the performance of the proposed algorithms in a Co-NOMA hybrid VLC/RF system. We illustrate how changing the required QoS and increasing the average interference would affect the sum-rate and fairness. Note that Jain's fairness index is used to measure the system fairness [14]. The number of the APs in the ceiling is set to 16, the separation distance between them is set to 2.5 m, and the maximum allowed input current I_H is 1000 mA. The rest of simulation parameters related to the channel values and transmit powers are chosen similar to Table II in reference [8]. We evaluate the proposed solutions through Mote-Carlo simulations, where each point in the following figures is the average of 500 different users' distributions within the restrictions illustrated in the System Model Section. Fig.

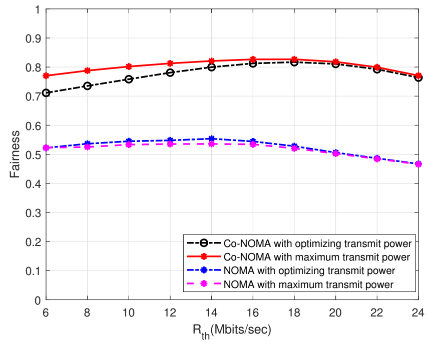

Fig. 3. The effect of R_{th} on fairness.

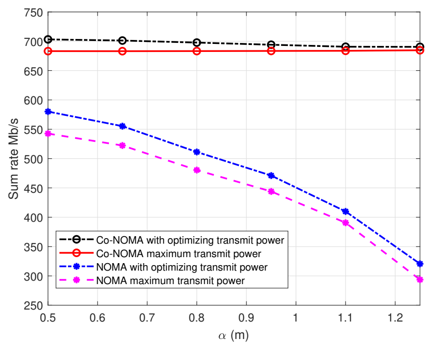

Fig. 4. The effect of increasing the interference at weak users on sum-rate.

2 plots the sum-rate versus the target data rate R_{th} at all users. The figure shows that increasing the R_{th} decreases the sum-rate, especially under the NOMA scheme. This is the case because increasing R_{th} at the weak user decreases the strong user power, which decreases the overall sum-rate. Fig. 2 particularly shows that the Co-NOMA scheme outperforms the NOMA scheme in terms of sum-rate, both with maximum or optimized transmit power. The significant improvement in the performance in Co-NOMA comes from the fact that each weak user can select between the hybrid RF/VLC and the direct VLC links, while in NOMA scheme, each weak user can only be served through the direct VLC link.

To illustrate the system fairness, Fig. 3 plots Jain's index versus the target data rate R_{th}. The figure shows that the fairness of Co-NOMA is much better than the fairness of NOMA systems. This is particularly the case because the weak users in NOMA suffer from inter-cell interference, while the edge users in Co-NOMA can be served through the strong users, which are in relatively good channel conditions. We can see that optimizing the total power of APs has no effect on the fairness because the fairness depends on the required QoS constraint that is achieved in either way. Finally, Fig. 4 shows how increasing the average received interference at weak users affects the system's sum-rate. This is achieved by increasing the value of α (explained at the System Model Section), while keeping the area of the strong user fixed.

Fig. 4 shows that increasing the interference at the weak users does not significantly affect the sum-rate in Co-NOMA, but decreases the performance of the NOMA significantly. This is due to that when the interference increases, the weak users in Co-NOMA migrate from being served through the interfered VLC links to being served through the VLC/RF links, where both the strong and weak users are served using the same VLC channel (the channel of the strong user), and the RF link does not interfere with the VLC links.

V. Conclusion

VLC are expected to play a major role in meeting the ambitious metrics of future wireless systems. This paper applies the Co-NOMA scheme in a multicell VLC network, and maximizes the sum-rate by determining the power and link selection vectors under power and QoS constraints. The paper solves such a non-convex problem by first finding closed form solutions of the joint users' powers and link selection, for a fixed AP power. The APs' transmit powers are then solved in an outer loop using the golden section method. Simulation results show how the proposed scheme outperforms non-cooperative NOMA scheme in terms of sum-rate and fairness.

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