





Efficient Subchannel and Power Allocation in Multi-cell Indoor VLC Systems

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Abstract. Visible light communication (VLC) is seen as a promising technology to improve the performance of indoor communication systems. However, the issues of inter-cell interference (ICI) and blockage effects are seen as crucial problems that could result in performance deterioration for VLC systems. This paper investigates the joint sub-channel allocation (SA) and power allocation (PA) optimization problem to overcome ICI and blockage effects in the downlink of an orthogonal frequency-division multiple access based multi-cell VLC system. This is a non-convex problem, and no efficient algorithm exists to obtain the globally optimal solution. To obtain an efficient solution, the original problem is first separated into the SA and PA problems. A simple yet efficient SA procedure based on the quality of the channel conditions is proposed. Then, the quadratic transform approach is exploited to develop a PA algorithm. Finally, simulation results are used to demonstrate the effectiveness of the proposed solution in terms of its fast convergence and overall performance.

Keywords: Subchannel allocation · Power allocation · Inter-cell interference · Visible light communication · Quadratic transform

1 Introduction

The last decade has witnessed a continuous emergence of high data rate services and bandwidth-hungry applications. This has contributed to the massive growth in the demand for higher capacity cellular networks. At the same time, the radio frequency (RF) spectrum for cellular communications has become oversaturated, requiring network operators to find alternatives to meet this data demand. Visible light communication (VLC) has attracted extensive research interest as a key enabling technology for the next generation of wireless communication networks due to the vast and unregulated bandwidth in the visible light spectrum

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[1]. Recent studies have investigated the resource allocation problem with various objectives for VLC systems. In [2], a spectral efficiency (SE) optimization problem was considered for a time division multiple access (TDMA)-based VLC system. In [3], the energy efficiency (EE) and SE performances of a three-tier heterogeneous network (HetNet), consisting of a macro base station (BS), multiple pico BSs, and many indoor VLC access points (APs), were investigated. The joint problem of AP assignment and power allocation (PA) for a hybrid RF/VLC HetNet was studied in [4]. The issue of subchannel allocation (SA) and PA for an orthogonal frequency division multiple access (OFDMA) based RF/VLC HetNet was explored in [5,6]. The PA problem to maximize the EE was studied for an aggregated RF/VLC system in [7].

The above-mentioned works (i.e., [2–4,6,7]) focused on multi-user VLC systems with one light-emitting diode (LED) array (i.e., single-cell VLC system). However, a single light source is typically not able to provide sufficient illumination in large indoor environments (e.g., conference rooms), and as a consequence, has limited coverage capability. Moreover, VLC relies heavily on line-of-sight (LoS) communication links as the non-LoS (i.e., reflected) signals are usually much weaker than the LoS signals and thus can be neglected. In single-cell indoor VLC systems, blocking effects resulting from the LoS light paths encountering obstructions will compromise the performance of the VLC system. Note that multiple LED arrays, with overlapping illumination regions, are typically deployed in indoor environments to guarantee uniform illumination and overcome blockage effects. As a result, a multi-cell structure is naturally obtained in VLC systems. Although [5] considered a multi-cell VLC system, the authors assumed that the multiple LED arrays (i.e., APs) transmit the same signal simultaneously. Consequently, the proposed approaches in [2–7] are not appropriate for indoor environments with the multi-cell structure, where any resulting interference needs to be considered and mitigated.

Few research works have considered resource allocation problems for multi-cell VLC systems [8–11]. A fuzzy-logic based AP assignment scheme was proposed in [8] for a hybrid light-fidelity (LiFi) and wireless-fidelity network. In [9,10], the optimization problem of AP assignment and time slot resource allocation was proposed for a TDMA-based hybrid RF/Li-Fi indoor network. In [11], a multi-user VLC system based on OFDMA, where a multi-cell structure is used to support a high density of users, was investigated. In multi-cell VLC systems, users residing in different cells may experience inter-cell interference (ICI) since the same subchannel sets are typically reused across the cells. This can have a significant impact on the achievable data rate of users in the VLC system. To the best of the authors' knowledge, the joint optimization of PA and SA for an OFDMA-based indoor VLC system has not appeared in many studies. This paper investigates this resource allocation problem for multi-cell indoor VLC systems bringing the following major contributions:

- We consider the downlink of a multi-user multi-cell OFDMA-based indoor VLC system and investigate the SA and PA optimization problem to maximize the sum-rate.
- The initial joint problem is a combinatorial optimization problem. Hence, we optimize the SA and PA problems separately to reduce the overall computational complexity. The separate SA and PA optimization problems are both non-convex.
- A simple yet efficient algorithm that assigns subchannels to users according to the quality of the channel condition is first proposed. Given the SA solution, the quadratic transform approach is exploited to recast the original non-convex PA problem into a series of convex problems that can be efficiently solved in an iterative manner to obtain at least a stationary point.
- We demonstrate that the proposed SA and PA solution outperforms the considered benchmark scheme and evaluate the impact of varying key system parameters such as the transmit power on the performance of the proposed scheme.

The rest of the paper is organized as follows. Section 2 discusses the system and channel models. Section 3 formulates the optimization problem and Sect. 4 details the proposed solution approach. Simulation results are presented in Sect. 5, followed by conclusion in Sect. 6.

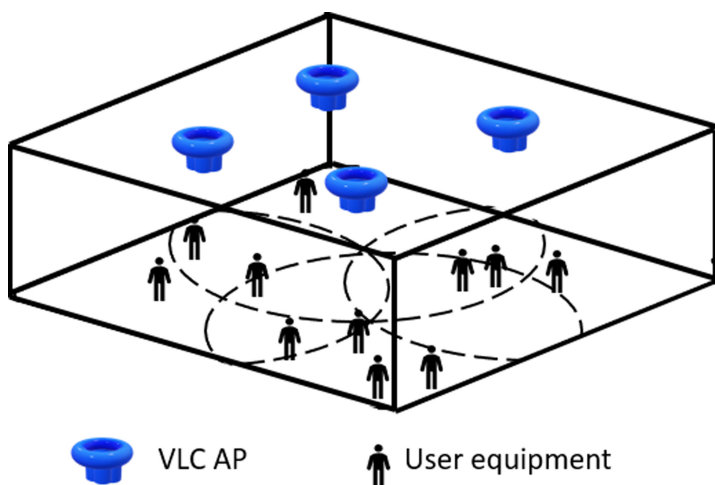


Fig. 1. Multi-user indoor VLC system consisting of multiple APs with overlapping coverage areas.

2 System Model

2.1 VLC Network

An indoor VLC system that consists of multiple APs and serves many user devices equipped with photodetectors (PD) is considered. As shown in Fig. 1, each AP is composed of five LED arrays and its coverage area (i.e., cell) is defined by the illumination region of the LED arrays of that AP. To better serve the users, the illumination regions of the APs are overlapping. The number of APs and users in the indoor environment are represented by the sets $\mathcal{A} = \{1, 2, \dots, a, \dots, |\mathcal{A}|\}$ and $\mathcal{U} = \{1, 2, \dots, u, \dots, |\mathcal{U}|\}$, respectively. Any AP a in the VLC system is assigned a predefined number of OFDMA subchannels which is represented by the set $\mathcal{S}_a = \{1, 2, \dots, s, \dots, |\mathcal{S}_a|\}$. Any user u can be served by a single AP according to the strongest channel gain rule. All the APs in the indoor environment are connected to a central control unit via backhaul links.

2.2 VLC Channel Model

By focusing on the LoS paths, the channel gain between AP a and user u on the subchannel s is given by [5]

$$G_{s,u}^a = \rho_{u,s} \frac{A_{\text{PD}}(m+1)}{2\pi d_{a,u}^2} \cos^m(\Phi_{a,u}) T(\Psi_{a,u}) G(\Psi_{a,u}) \cos(\Psi_{a,u}), \quad (1)$$

where $\rho_{u,s}$ indicates the probability of having a LoS path on subchannel s for user u , A_{PD} is the physical area of the PD, m is the Lambertian emission order which can be calculated as

$$m = -\log_2 \left(\cos \left(\phi_{\frac{1}{2}} \right) \right)^{-1}, \quad (2)$$

with $\phi_{\frac{1}{2}}$ as the LED's semi-angle at half power, $d_{a,u}$ is the distance between the AP a and user u , $\Phi_{a,u}$ is the angle of irradiance, $\Psi_{a,u}$ is the angle of incidence, $T(\Psi_{a,u})$ is the optical filter gain, $G(\Psi_{a,u}) = \frac{f^2}{\sin^2 \Psi_{\text{FoV}}}$, $0 \leq \Psi_{a,u} \leq \Psi_{\text{FoV}}$, is the gain of the non-imaging concentrator, with f being the ratio of the speed of light in vacuum to the velocity of light in the optical material.

The signal-to-interference-plus-noise ratio (SINR) of user u on subchannel s of AP a is given as

$$\text{SINR}_{s,u}^a = \frac{p_{s,u}^a (R_{\text{PD}} G_{s,u}^a)^2}{\sum_{u' \neq u} \left(\sum_{a' \neq a} p_{s,u'}^{a'} (R_{\text{PD}} G_{s,u'}^{a'})^2 \right) + \sigma^2}, \quad (3)$$

where $p_{s,u}^a (R_{\text{PD}} G_{s,u}^a)^2$ is the total electrical power received by the PD of user u on subchannel s from the AP a with $p_{s,u}^a$ being the electrical transmit power on subchannel s of AP a for user u , a is the serving AP and a' denotes other APs that reuse the subchannel s , R_{PD} is the responsivity of the PD, u' represents users other than user u that employ subchannel s , a' denotes other APs reusing

subchannel s , and σ^2 is the electrical additive white Gaussian noise power. The corresponding achievable data rate for user u on subchannel s of AP a can be computed by [12].

$$R_{u,s}^a = \rho_{u,s} B \log_2 \left(1 + \frac{\exp(1)}{2\pi} \text{SINR}_{s,u}^a \right), \quad (4)$$

where B is the bandwidth of a subchannel.

3 Sum-Rate Optimization

The joint optimization of PA and SA to maximize the sum-rate for the considered indoor multi-cell VLC system is formulated as follows:

$$\begin{aligned} & \max_{\mathbf{x}, \mathbf{p}} \sum_{a \in \mathcal{A}} \sum_{u \in \mathcal{U}} \sum_{s \in \mathcal{S}_a} R_{u,s}^a \\ & \text{s.t.} \\ & C1: \sum_{s \in \mathcal{S}_a} R_{u,s}^a \geq R_{\min}, \forall u \in \mathcal{U} \\ & C2: p_{s,u}^a \leq x_{s,u}^a P_a^{\max}, \forall u \in \mathcal{U}, \forall s \in \mathcal{S}_a, \forall a \in \mathcal{A}, \\ & C3: \sum_{u \in \mathcal{U}} \sum_{s \in \mathcal{S}_a} p_{s,u}^a \leq P_a^{\max}, \forall a \in \mathcal{A} \\ & C4: \sum_{u \in \mathcal{U}} x_{s,u}^a \leq 1, \forall s \in \mathcal{S}_a, \forall a \in \mathcal{A} \\ & C5: x_{s,u}^a \in \{0, 1\}, \forall u \in \mathcal{U}, \forall s \in \mathcal{S}_a \\ & C6: p_{s,u}^a \geq 0, \forall u \in \mathcal{U}, \forall s \in \mathcal{S}_a, \forall a \in \mathcal{A} \end{aligned} \quad (5)$$

where \mathbf{x} and \mathbf{p} are the vectors of optimization variables for SA and PA, respectively, and R_{\min} is the required minimum rate. The physical interpretation of the sets of constraints for the optimization problem in (5) is as follows. $C1$ is the quality-of-service (QoS) requirement. $C2$ limits the transmit power on any subchannel to the available maximum power P_v^{\max} of any AP v . $C3$ represents the power budgets for the APs. $C4$ ensures each subchannel of any AP is allocated to at most one user. $C5$ denotes the fact that the SA variables are binary and $C6$ indicates that the PA variables are non-negative.

4 Proposed Sum-Rate Optimization Solution

The optimization problem in (5) is NP-hard due to the presence of both binary variables \mathbf{x} and continuous variables \mathbf{p} . It is challenging to obtain the globally optimal solution within polynomial time. To find a tractable solution, problem (5) is decomposed into two separate problems (i.e., SA problem under fixed PA and PA problem under fixed SA). The SA problem is solved by allocating subchannels to users according to the quality of the channel condition. For a given SA, the quadratic transform approach is exploited to solve the PA problem to obtain at least a stationary point solution. Note that this solution method is a centralized scheme, where all computations and decisions are made by a central control unit. The control unit then broadcasts the solution to the joint problem

to all the APs via backhaul links dedicated for control signals. The VLC APs and the control unit require a complete knowledge of the downlink channel state information and it is assumed that this information can be reliably obtained.

4.1 Subchannel Allocation (SA) Procedure

The SA subproblem is solved for a given PA. Note that the equal PA (EPA) policy, for which each AP equally shares the total available power to all of its subchannels, can be employed at this stage. The main idea of the SA procedure is that each subchannel of an AP should be allocated to the user with the highest power gain. This idea can be mathematically expressed as

$$x_{s^*,u^*}^a = \begin{cases} 1, & (s^*, u^*) = \arg \max_{s,u} G_{s,u}^a \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

Although this SA procedure can lead to instances whereby not every user is assigned subchannel(s) because of the channel condition experienced on all the available subchannels, this is beneficial to the network performance as resources are only allocated to users such that the network performance is maximized. Allocating resources to users with bad channels will lead to their inefficient usage. The admission control scheme will deny such users access to the network, and they can try again later.

4.2 Power Allocation (PA) by the Quadratic Transform Approach

Given the solution to the SA optimization problem, the PA optimization problem can be formulated as

$$\begin{aligned} & \max_{\mathbf{P}} \sum_{a \in \mathcal{A}} \sum_{u \in \mathcal{U}} \sum_{s \in \mathcal{S}_a} R_{u,s}^a \\ & \text{s.t.} \\ & C1 : \sum_{s \in \mathcal{S}_a} R_{u,s}^a \geq R_{\min}, \forall u \in \mathcal{U} \\ & C2 : p_{s,u}^a \leq x_{s,u}^a P_a^{\max}, \forall u \in \mathcal{U}, \forall s \in \mathcal{S}_a, \forall a \in \mathcal{A}, \\ & C3 : \sum_{u \in \mathcal{U}} \sum_{s \in \mathcal{S}_a} p_{s,u}^a \leq P_a^{\max}, \forall a \in \mathcal{A} \\ & C6 : p_{s,u}^a \geq 0, \forall u \in \mathcal{U}, \forall s \in \mathcal{S}_a, \forall a \in \mathcal{A}. \end{aligned} \quad (7)$$

The problem in (7) is still a non-convex optimization problem due to the SINR term in the objective function and the constraint set C1. The quadratic transform approach, introduced in [13] for solving fractional programming problems, is exploited to transform the non-convex problem in (7) into series of convex optimization problems.

In order to solve (7) using the quadratic transform approach, the auxiliary variable λ is first introduced. Then, according to this approach, each SINR in (7) can be replaced by the quadratic term

$$\text{SINR}_{s,u}^{a*} = 2\lambda_{s,u} \sqrt{p_{s,u}^a (R_{\text{PD}} G_{s,u}^a)^2} - \lambda_{s,u}^2 \left(\sum_{u' \neq u} \left(\sum_{a' \neq a} p_{s,u'}^{a'} (R_{\text{PD}} G_{s,u'}^{a'})^2 \right) + \sigma^2 \right), \quad (8)$$

and the corresponding achievable data rate for user u on subchannel s of AP a can be computed by

$$R_{u,s}^{a*} = \rho_{u,s} B \log_2 \left(1 + \frac{\exp(1)}{2\pi} \text{SINR}_{s,u}^{a*} \right). \quad (9)$$

An equivalent optimization problem for (7) can be expressed as

$$\begin{aligned} & \max_{\mathbf{p}, \boldsymbol{\lambda}} \sum_{a \in \mathcal{A}} \sum_{u \in \mathcal{U}} \sum_{s \in \mathcal{S}_a} R_{u,s}^{a*} \\ & \text{s.t.} \\ & C1 : \sum_{s \in \mathcal{S}_a} R_{u,s}^{a*} \geq R_{\min}, \forall u \in \mathcal{U} \\ & C2, C3, \text{ and } C6, \end{aligned} \quad (10)$$

where $\lambda_{s,u}$ is an auxiliary variable introduced by the application of the quadratic transform to the SINR of each user and subchannel. The proof of the equivalence of (7) and (10) can be obtained by following the approach in [13]. Problem (10) is non-convex when $\boldsymbol{\lambda}$ and \mathbf{p} are jointly considered. However, for a fixed $\boldsymbol{\lambda}$, the optimization problem in (10) becomes convex and can be solved to obtain the optimal solution. For a fixed $p_{s,u}^a$, the optimal $\lambda_{s,u}$ can be obtained by setting $\partial \text{SINR}_{s,u}^* / \partial \lambda_{s,u}$ to zero, and is given by

$$\lambda_{s,u}^* = \frac{\sqrt{p_{s,u}^a (R_{\text{PD}} G_{s,u}^a)^2}}{\sum_{u' \neq u} \left(\sum_{a' \neq a} p_{s,u'}^{a'} (R_{\text{PD}} G_{s,u'}^{a'})^2 \right) + \sigma^2}. \quad (11)$$

Then, the optimal \mathbf{p} for fixed $\boldsymbol{\lambda}$ can be found by solving the resulting convex problem in (10). The variables $\boldsymbol{\lambda}$ and \mathbf{p} are optimized iteratively. This PA method is summarized in Algorithm 1.

Algorithm 1. The PA algorithm.

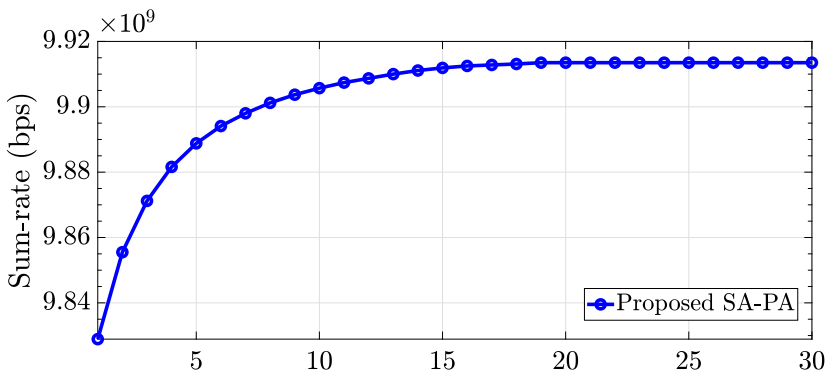
1. \mathbf{p} is initialized to any feasible value;
 - while** *no convergence* **do**
 2. Update the auxiliary variable $\boldsymbol{\lambda}$ according (11);
 3. Update \mathbf{p} by solving (10) for the given $\boldsymbol{\lambda}$.
 - end while**
-

Table 1. Simulation parameters.

Parameter	Value
Maximum transmit power per AP, P_a^{\max}	4 W
Height of VLC APs	2.5 m
Noise power spectral density, σ^2	10^{-21} A ² /Hz
Photodetector responsivity, R_{PD}	0.53 A/W
LED semi-angle at half-power, $\phi_{\frac{1}{2}}$	60°
Gain of the optical filter, T	1
Refractive index, f	1.5
FOV of a photodetector, Ψ_{fov}	70°
Physical area of the photodetector, A_{PD}	1 cm ²

5 Simulation Results and Discussions

In this section, the performance of the proposed SA and PA solution method is investigated for the system model in Fig. 1. A practical room dimension of $15 \times 15 \times 3$ m³ with 4×4 uniformly distributed APs is considered. The users are randomly distributed in the indoor environment according to a uniform distribution. Each user device is fitted with a PD and an assumption is made that it is vertically facing upwards. Each AP has been allocated 25 subchannels and this same set of subchannels is reused by all the APs. A system bandwidth of 1 GHz is used. The QoS requirement is set as 50 Mbps. Unless otherwise noted, the related parameters used to obtain the results are summarized in Table 1. For comparison purposes, EPA is considered as a benchmark scheme.

**Fig. 2.** Sum-rate versus number of iterations.

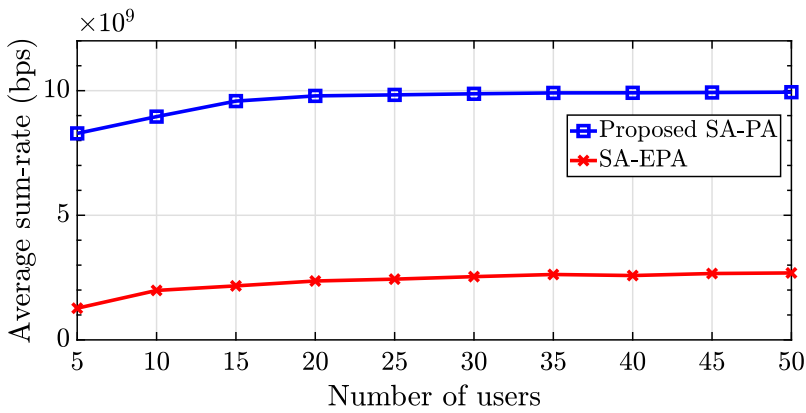


Fig. 3. Average sum-rate versus different number of users.

Figure 2 depicts the convergence rate of the proposed SA-PA solution for a total of 40 users. It can be observed from this figure that the proposed solution has reached convergence after iteration number 19. Hence, it has a fast convergence rate and is suitable for practical implementation.

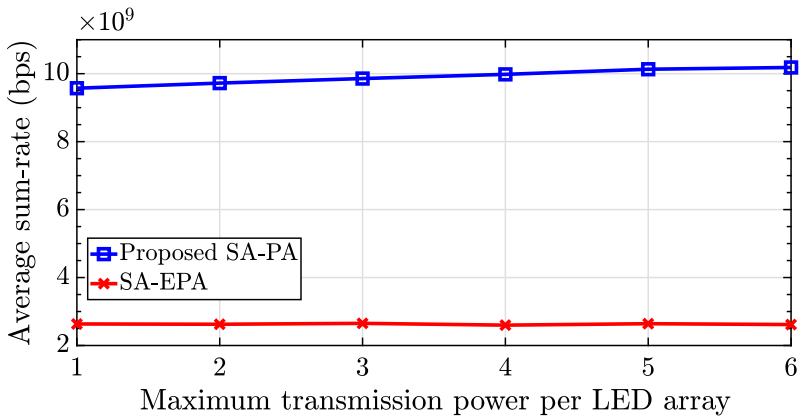


Fig. 4. Average sum-rate versus maximum transmitting power.

Figure 3 illustrates the sum-rate performance of the proposed SA-PA solution and the SA-EPA benchmark scheme for different number of users. It can be observed that the sum-rate performances for both schemes increase with increasing number of users. The reason is that with more users, each subchannel has more candidates to choose from. Hence, the subchannel resources are efficiently utilized. The proposed scheme achieves superior sum-rate performance (i.e., a gain of around 325%) than the SA-EPA, highlighting the importance of performing PA in VLC systems. This is because the proposed PA algorithm effectively

manages any ICI at overlapping regions and any resulting blocking effects. The EPA scheme does not perform any of these operations.

Finally, Fig. 4 compares the sum-rate performance of the proposed SA-PA scheme and the benchmark SA-EPA scheme for different values of the maximum transmit power. This is done for 40 users. It can be observed that increasing the maximum transmit power leads to an increase in the sum-rate performance for the proposed scheme. However, this is not the case for the SA-EPA scheme since augmenting the maximum AP transmit power results in an increase in the available power per subchannel (according to the EPA scheme) which can lead to higher ICI effects in overlapping regions.

6 Conclusion

In this paper, the downlink of a multi-user multi-cell OFDMA-based indoor VLC network was studied. The joint optimization problem of SA and PA to maximize the sum-rate while considering ICI and blockage effects has been formulated and an efficient solution has been proposed. In particular, the initial joint problem was separated into two subproblems to reduce the complexity of solving this mixed integer nonconvex problem. A SA solution based on the quality of the channel condition has been proposed. By exploiting the quadratic transform approach, a PA algorithm has been developed. The effectiveness of the proposed scheme, in terms of sum-rate performance and convergence rate, has been verified via simulation results. This paper has revealed that effective SA-PA is crucial in overcoming ICI and blockage effects in multi-cell VLC systems.

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