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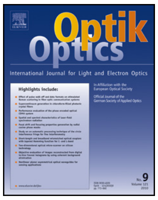

Original research article

A novel strategy for LED re-utilization for visible light communications

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ABSTRACT

A resource allocation optimization model for downlink indoor Optical Wireless Communications networks (OWC) is proposed in this paper. The optimization problem is formulated as a mixed integer binary problem. A centralized smart coordinator solves the problem in order to assign efficiently Visible Light Communications (VLC) channels to users. The optimization problem is solved with two different approaches based on Cuckoo Search algorithm (CS). The first one solves the complete network problem considering all users and access points simultaneously with a random initialization procedure. Whilst the second approach is a CS based decomposition procedure, which obtains feasible solutions with the help of a spatial reuse aided algorithm. Both procedures were tested for different receivers Fields of View (FOV), e.g., $FOV = 30^\circ$ and 60° which are placed randomly on the coverage area and for different transmitter's power levels. Results show that the solutions obtained with spatial reuse aided procedure outperforms the first approach in terms of total network throughput for different power levels, i.e., 1 and 10 W, and different number of users. Finally, results obtained with the second approach allow the usage of a wider FOV.

1. Introduction

Nowadays, wireless communication technology plays a key role on information transmission since many mobile devices such as Notebooks, Mobile Phones, Body Sensor Networks, RFID, among others, are connected to the backbone network through a wireless link [1]. Information provided to wireless devices is transmitted in a dynamic way and strongly depends on the availability of a connection link. Radio Frequency (RF) based systems, in particular, mobile phone networks and Wi-Fi [2] have been the main actors for wireless data transmission. RF technology has been widely used in many fields. Some of wireless RF applications are: identification and positioning information [3], pervasive health applications [4,5], smart city and smart village [2], pervasive agriculture [6] and earth sciences [7] just to name a few. Although the application of RF based systems is massive, the RF spectrum provides a limited bandwidth and due to this, RF based systems will not be able to cope with the ever increasing bandwidth demand. To face the bandwidth problem, Optical Wireless Communication (OWC)

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has emerged as a suitable future technology. Optical Wireless Communications comprises communication provided by infrared, visible light and ultra violet lights. Visible Light Communications (VLC) technology has taken advantage to provide wireless downlink. VLC uses the already deployed infraestructure to provide both, illumination and high data rate wireless communication simultaneously. This, because LED lights' ability to be pulsed at a very high speed without noticeable effect [8].

The VLC technology has also been proposed as a complementary or alternative solution in many apllications where Radio Frequency (RF) based systems are widely used such as Internet data transmition Li-fi [9,10] and indoor positioning and tracking [11–13] among others.

VLC has many advantages which can be exploited to replace or to complement RF systems. VLC systems does not affect other systems due to the electromagnetic interference [14] and it has a higher bandwidth which makes possible the allocation of many low interfering channels (the visible spectrum is in the range of 400–800 THz while RF is in the range of 3 kHz to 300 GHz). Because of this, VLC technology has been proposed as a possible solution to decongest the RF spectrum in indoor environments [15].

Most proposed solutions for RF communication systems have been extended for VLC based systems. Due to the Intensity Modulation Direct Detection (IM/DD) nature of VLC some modifications have to be performed to adapt RF solutions to this technology. In particular, when using single-carrier modulation such as M-ary Pulse Amplitude Modulation (M-PAM), On-Off Keying (OOK) and Pulse Width Modulation (PWM), an additional multiple access technique is required. The most commonly used multiple access techniques for this type of modulation scheme are Frequency Division Multiple Access (FDMA), time division multiple access (TDMA) and/or code division multiple access (CDMA) [15,16].

Another important characteristic of VLC based systems is the spatial reuse. Spatial reuse enables a highly directional communication making possible the coexistence of many non-interfering links in close proximity [8]. Spatial reuse strongly depends on receiver's Field of View (FOV) characteristics and LED lights coverage.

VLC based networking is a topic under study. In particular, the usage of multiple small cellular stations called "optical attocells" was proposed for high speed wireless networking in [17]. These optical attocells are analogous to femtocells used in RF communications. These small cells are used to improve the spectral efficiency. The main problem of using a large amount of optical attocells is the interference [18] since LED lights are commonly placed close to each other [19]. The optimisation of VLC networks has been mainly based on resource allocation, transmission scheduling and access management. These techniques try to avoid inter-celll interference while increasing data rates. In [20], the authors proposed a downlink optimization for orthogonal frequency division multiplexing access based visible light personal area network. In addition to this, the proposal was extended and used for a VLC based Wireless Sensor Network respectively in [21]. The proposed mathematical model for both applications tries to satisfies quality of service requirements and to maximize the channel capacity by means of an intelligent interference coordinator. It reduces the inter-cell interference while increases the network throughput. Another alternative to maximize the whole system performance of VLC networks was proposed in [22]. In this work the fairness of the system was taking into account. The proposed link scheduling was a maximum weighted independent set problem which takes the advantage of spatial reuse property of VLC systems for solving the optimization problem. Besides, in [23] a resource allocation was performed using the spatial reuse. The proposed system is used for Multiple Access (MA) Discrete Multi-Tone (DMT) communication. The aim of the proposal is to maximize the network bit-rate. MA-DMT shows and improvement compared to conventional DMT. Nevertheless, the work did not consider time diversity scheme in the problem formulation.

In this paper, a resource allocation optimization model for downlink indoor Optical Wireless Communications networks (OWC) is proposed. The optimization problem is formulated as a mixed integer binary problem. A centralized smart coordinator solves the problem in order to assign efficiently VLC channels to users. The coordinator allocates each transmitter to a particular user at each time slot maximizing the network thwoughput. The optimization problem is solved by the coordinator with two different approaches based on Cuckoo Search algorithm (CS). The first one solves the complete network problem considering all users and access points simultaneously with a random initialization procedure. Whilst the second approach is a CS based decomposition procedure, which obtains feasible solutions with the help of a spatial reuse aided algorithm. Both procedures were tested for different receiver's Fields of View (FOV), e.g., $FOV = 30^\circ$ and 60° which are placed randomly on the coverage area and for different transmitter's power levels. LEDs will be placed in a grid shape and a circular shaped deployment. The resorce allocation will be compared for both LED deployments. In addition to this, as it was previously proposed in [24], the smart coordinator will switch off the LED access point if it is not being used by any user in the considered time slot.

The paper is structured as follows. In Section 2, the system description is presented. Then, in Section 3 we present two mathematical formulations of the problem as well as the proposed methods for solving them. In Section 4, the numerical results are presented and discussed. Finally, in Section 5 the main conclusions of the paper are outlined.

2. System description

In this paper, the downlink optimization of a single carrier multiple user VLC network for indoor environment is proposed. Notice that the system considered has many applications, for example, in hotel halls or shopping centres where a high number of users and transmitters are required. We consider an square room of 10×10(m). In the ceiling, a total number of K low power LED lights are connected to a smart coordinator. Each LED light handles a single carrier c, $c \in C = \{1, b, \ldots, K\}$. Users u, $u \in U = \{1, 2, \ldots, M\}$, are randomly located in the room. Users receive information from LED lights which are physically

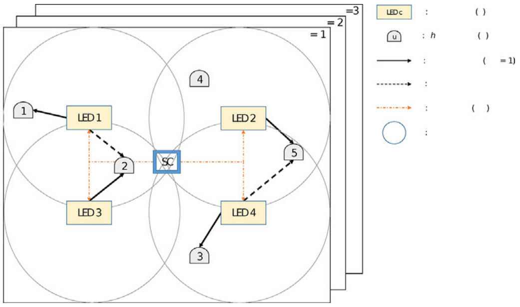

Fig. 1. Smart coordinator decision using 4 LEDs as access points to the network and 5 users.

deployed in the ceiling. The smart coordinator turns on and off each light at unnoticeable speed to human eye's. Each receiver device has access to the network using an assigned channel in different time slots t, $t \in T = \{1, 2, \ldots, N\}$.

In a single optical link, power received by user u from transmitter c is expressed as

$$P_{uc} = R_{PD} h_{uc} P_c \tag{1}$$

where R_{PD} is the responsivity of the photo detector (PD), h_{uc} is the optical channel gain of link (u, c) and P_c is the power of the signal transmitted by the LED light. The channel gain, h_{uc}, is independent from the carrier frequency since most of the VLC systems uses intensity modulation with direct detection (IM/DD) scheme to perform the communication. Channel gain h_{uc} depends on the relative positions of each transmitter–receiver pair. We assume that there is Line of Sight (LOS) between them. The channel gain with LOS can be expressed as

$$h_{uc} = \begin{cases} \dfrac{(m_l + 1)A}{2\pi d_{uc}^2} \cos^{m_l}(\varphi_{uc}) T_s(\psi_{uc}) g(\psi_{uc}) \cos(\psi_{uc}) & 0 \leq \psi_{uc} \leq \Psi_l \\ 0 & \text{elsewhere} \end{cases} \tag{2}$$

where m_l is the Lambertian order transmission of the LED light, A is the effective area of the PD, d_{uc}, φ_{uc}, ψ_{uc}, $T_s(\psi_{uc})$ and $g(\psi_{uc})$, are the distance, angle of irradiance, angle of incidence of the signal, gain of the optical filter and gain of the optical concentrator between transmitter c and receiver u, respectively. Finally, Ψ_l is the field of view (FOV). The signal received by the PD from an assigned source can be interfered by the signal emitted from a different transmitter placed nearby the receiver. The total Inter Channel Interference I_{uc} affecting receiver u in channel c is given by

$$I_{uc} = \sum_{j \neq c, j=1}^{K} (R_{PD} h_{uj} P_j)^2 \tag{3}$$

Signal to Interference Noise Ratio (SINR) is a metric used to measure the received signal quality. The SINR for each receiver u assigned to channel c in time slot t can be calculated as

$$SINR_{uc}^t = \frac{P_{uc}^t}{I_{uc}^t + \sigma_u^t} = \frac{(R_{PD} h_{uc}^t P_c)^2}{\sum_{j \neq c, j=1}^{K} (R_{PD} h_{uj} P_j)^2 + \sigma_u^t} \tag{4}$$

where σ_u^t is the sum of shot and thermal noise power at time slot t. The channel capacity for each user can be determined by using the Shannon–Hartley theorem. It uses the SINR and the bandwidth channel capacity. Thus, the channel capacity of user u can be computed as

$$R_u = \sum_{c=1}^{K} B_c \log_2(1 + SINR_{u,c}) \tag{5}$$

where B_c is the bandwidth of the channel c in Hertz. Since the overall system is subject to interference we use a binary transmitter allocation variable x_{uc}^t which is defined as

$$x_{u,c}^t = \begin{cases} 1 & \text{Access allowed} \\ 0 & \text{Access denied} \end{cases} \tag{6}$$

more precisely, $x_{u,c}^t = 1$ if user u uses channel c at time t, and $x_{u,c}^t = 0$ otherwise.

Fig. 1 shows the general scheme where the Smart Coordinator (SC) takes the decision to allow or deny the connection of different users. As it can be seen from Fig. 1 the smart coordinator sends the decision to each LED light. LED transmitters allows the connection of one user at a time.

Users positioned near to a different light from the one that they receive access are affected by interference. Considering Fig. 1 as a practical example for $M = 5$ PDs, $K = 4$ LEDs and $N = 1$ slot. The SC decision matrix **X**, is defined as

$$\mathbf{X} = \begin{bmatrix} x_{11}^1 & x_{12}^1 & x_{13}^1 & x_{14}^1 \\ x_{21}^1 & x_{22}^1 & x_{23}^1 & x_{24}^1 \\ x_{31}^1 & x_{32}^1 & x_{33}^1 & x_{34}^1 \\ x_{41}^1 & x_{42}^1 & x_{43}^1 & x_{44}^1 \\ x_{51}^1 & x_{52}^1 & x_{53}^1 & x_{54}^1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

As it can be observed, receiver 4 has not been assigned to any communication link, i.e., $\sum_{c=1}^{K} x_{4c}^1 = 0$. User 1 has been allowed to access to the network by LED 1. Similarly, user 2 is connected to the network by means of LED 3. However, due to its proximity user 2 is being interfered by LED 1. Formally, it can be expressed as $user_2 \in \{O_{LED1} \cap O_{LED2}\}$ where $O_{LED\,c}$, $c \in C$ is the coverage area of the LED transmitter c. User 3 is connected to the network by LED 4 and finally, user 5 is connected to LED 2 and interfered by LED 4. Moreover, it can observed that each link is assigned at most 1 user at a time, i.e.,$\sum_{u=1}^{M} x_{u,c}^t \leq 1$ $\forall\, c \in C$. The channel matrix **H** of the above mentioned example is

$$\mathbf{H} = \begin{bmatrix} h_{11}^1 & 0 & 0 & 0 \\ h_{21}^1 & 0 & h_{23}^1 & 0 \\ 0 & 0 & 0 & h_{34}^1 \\ 0 & h_{42}^1 & 0 & 0 \\ 0 & h_{52}^1 & 0 & h_{54}^1 \end{bmatrix}$$

Due to the highly directional link provided by VLC based Networks, the coverage area for each LED transmitter is confined to a small area O_c. Consequently, the value of the decision variable x_{uc}^t can be neglected or assumed to be equal to 0 when some previous information about the channel gain matrix **H** exists. From Eq. (4), if $h_{ij}^t = 0 \rightarrow SINR_{ij}^t = 0$ for each $i \in U$ and $j \in C$. Therefore, the decision variable $x_{ij}^t = 0$ since this value does not affect the contribution of link ij on the overall channel capacity of user i in Eq. (5).

3. Methods

3.1. Binary Cuckoo search

Cuckoo Search is a metaheuristic optimization algorithm. Its development has been inspired by using the way in which some species of cuckoo birds lay their eggs in different species nests [25]. The optimization procedure is initialized with a fix number of initial population of nests n_d. Each solution for the optimization problem is represented as a nest. The initial solution is the same for all the nests and it is chosen randomly most of the time. Nevertheless, using the spatial reuse property of VLC networks we will generate a feasible initial solution in order to improve the result of the optimization procedure. Once the initial solution is determined, the new nest $\mathbf{x}_i$, $i \in \{1, 2, \ldots, n_d\}$ is generated by

$$\mathrm{x_i}^{t+1} = \mathrm{x_i}^{t} + \alpha \oplus Levy(\lambda) \tag{7}$$

where α is the step size $\alpha > 0$, $Levy(\lambda)$ is a random number from a levy distribution, $\oplus$ is the element-wise add operator. Levy flight represents a variation of commonly used random walk. The step length is determined by the Levy distribution.

$$Levy{\sim}u = t^{-\lambda},\ 1 \leq \lambda \leq 3 \tag{8}$$

In Binary cuckoo search [26] a threshold function is used to obtain a discrete feasible solution space $\mathbf{x}_i$

$$x_j = \begin{cases} 1 & \text{if}\, x_j > V \\ 0 & \text{if}\, x_j \leq V \end{cases} \tag{9}$$

where $x_j \in \mathbf{x}_i, j \in \{1, 2, \ldots, Z\}$, Z is the number of decision variables of the optimization problem.

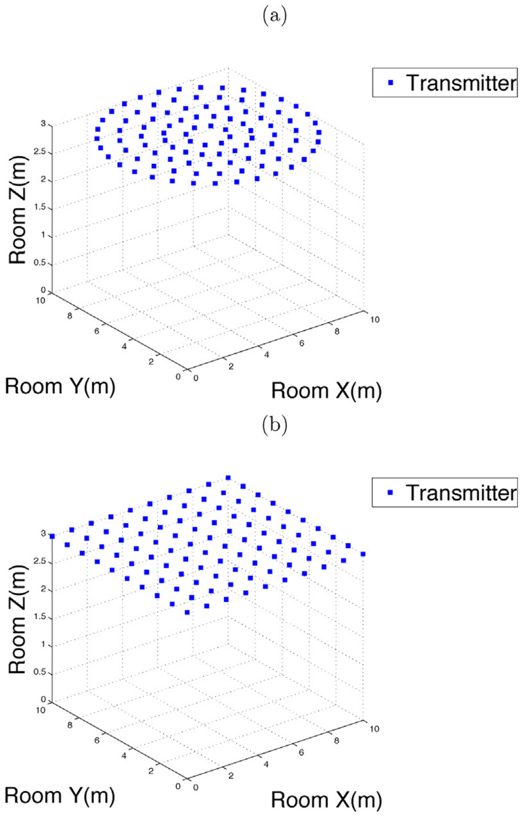

Fig. 2. Proposed VLC networks deployments: (a) circular LED deployment and (b) grid LED deployment.

3.2. Problem formulation

We consider the following optimization problem

$$\begin{aligned} \underset{X}{\text{maximize}} \quad & R = \sum_{t\in T}\sum_{u\in U}\sum_{c\in C} x^t_{u,c} B_c \log_2\left(1 + \frac{(R_{PD} h^t_{u,c} P_c)^2}{\sum_{\substack{j\neq c\\ j=1}}^{K} \left(R_{PD} h^t_{uj} \left(\sum_{\substack{i\neq u\\ i=1}}^{M} x^t_{ij}\right) P_j\right)^2 + \sigma^t_u}\right) \\ \text{subject to} \quad & \sum_{u\in U} x^t_{uc} \leq 1,\ \forall c \in C \text{ and } t \in T \\ & \sum_{t\in T}\sum_{c\in C} x_{uc} \geq 1,\ \forall u \in U \\ & x_{uc} \in \{0, 1\} \end{aligned} \tag{10}$$

where **X** is a $M \times K \times N$ matrix which contains all the x^t_{uc} elements. Each decision variable $x^t_{uc} \in \{0, 1\}$ enables or disables the transmission of LED light c to user u at time t. The objective function in model (10) maximizes the overall network throughput. The first set of constraints allow the connection of 1 user at most in each channel within each time slot. In addition to this, the second set of constraints ensure the fairness of the network by assigning one channel to each user in at least one time slot. The LED c is switched off in time slot t when $\sum_{u=1}^{M} x^t_{uc} = 0$ which is an energy savin scheme proposed in [24]. Notice that the problem (10) is formulated as a mixed integer non-linear programming problem which is hard to solve in general [27].

Thus we propose CS metaheuristic procedures to find good solutions in reasonable CPU time. In order to ensure the system fairness, we use a spatial-time diversity scheme. A VLC network with a high number of LED lights is considered. In this paper two different optimization procedures are proposed. The first one solves the complete network problem considering all users and access points simultaneously with a random initialization procedure. Whilst the second approach is a CS based

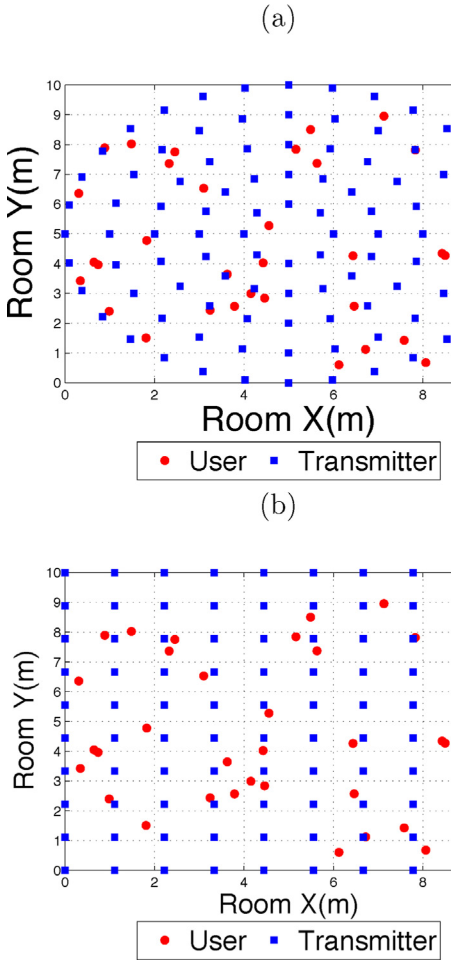

Fig. 3. Transmitters and receivers: (a) circular deployment with 32 users and (b) grid deployment with 32 users.

decomposition procedure, which obtains feasible solutions with the help of a spatial reuse aided algorithm. For this purpose, the network is clustered into L subsets, each subset has a joint coverage area $O^l = O_{LED_1} \cap O_{LED_2} \cap \ldots \cap O_{LED_n}$ where n is the number of LED lights considered in the cluster. Each covered area is optimized independently and the solution provided by this initialization procedure is used as the initial solution for the optimization of the overall network capacity.

Fig. 2 shows two different spatial LED lights deployments. Notice that the transmitters set C is divided into L subsets. Each subset $O^l \subseteq C$ has a visibility of U^l possible users,$U^l \subseteq U$. LED sets are grouped considering K/L overlapped transmitters on each subset. The decomposed spatially-reuse aided procedure first maximizes each subset throughput O^l as shown bellow

$$\begin{aligned}
\underset{X^{(l)}}{\text{maximize}} \quad & R = \sum_{t \in T} \sum_{u \in U^l} \sum_{c \in O^l} x_{u,c}^t B_c \log_2 \left(1 + \frac{(R_{PD} h_{u,c}^t P_c)^2}{\sum_{\substack{j \neq c \\ j=1}}^{K} \left(R_{PD} h_{uj}^t \left(\sum_{\substack{i \neq u \\ i=1}}^{M} x_{ij}^t\right) P_j\right)^2 + \sigma_u^t} \right) \\
\text{subject to} \quad & \sum_{u \in U^l} x_{uc}^t \leq 1, \ \forall c \in O^l \text{ and } t \in T \\
& \sum_{t \in T} \sum_{c \in O^l} x_{uc} \geq 1, \ \forall u \in U^l \\
& x_{uc} \in \{0, 1\}
\end{aligned} \tag{11}$$

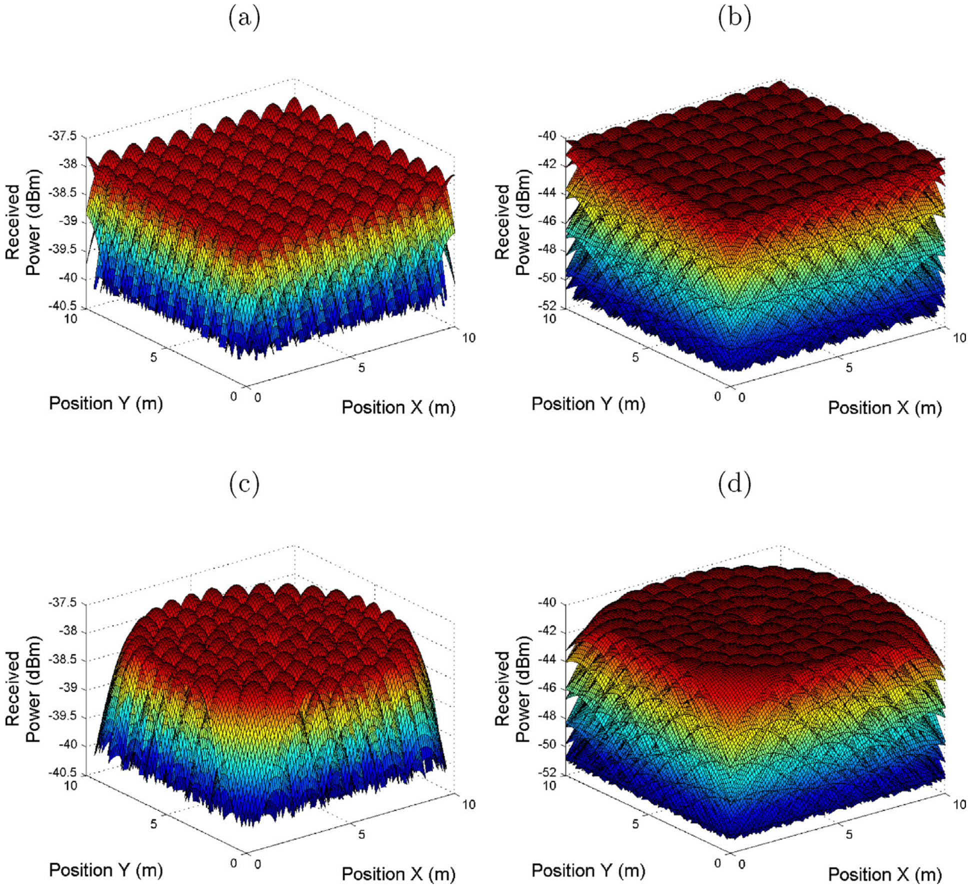

Fig. 4. Received power distribution: (a) grid deployment $FOV = 30^{\circ}$, (b) grid deployment $FOV = 60^{\circ}$, (c) circular deployment $FOV = 30^{\circ}$ and (d) circular deployment $FOV = 60^{\circ}$.

Table 1
Simulation parameters.

Parameter	Symbol	Value	Parameter	Symbol	Value
Number of clusters	L	4	PD responsivity	R_{PD}	1 A/W
PD area	A	1256 cm^2	Semi-angle of the half power	$\Phi_{1/2}$	70°
LED power	P_c	10 W	Refractive index	n	1.5
Channel bandwidth	B_c	2 MHz	Receiver field of view	FOV	30° and 60°
Time slots	N	5	Users	M	[8, 16, 32, 64]
Gain of the optical filter	T_s	1	Number of LED lights	K	100

The first set of constraints ensures that each channel $c \in O^l$ can be used at most by one user at a time. Additionally, the system provides not less than one channel $c \in O^l$ to every user $u \in U^l$ for at least one time slot $t \in T$. The results of the above optimization, $\mathbf{X}^1$, $\mathbf{X}^2$, $\mathbf{X}^3$ and $\mathbf{X}^4$ are merged into a single $M \times K \times N$ matrix denoted as $\mathbf{X}^0 = \mathbf{X}^1 + \mathbf{X}^2 + \mathbf{X}^3 + \mathbf{X}^4$ where + is the logical element-wise OR operator. Subsequently, the matrix is used as the initial solution for the CS algorithm in order to solve the complete maximization problem described in Eq. (10).

4. Numerical results

Both methods were implemented in MATLAB. Four different scenarios were considered. A total of 100 LED lights placed in the ceiling using two different deployments as shown in Fig. 2 were used as transmitters, i.e., grid deployment and circular deployment. The number of users was varied from 8 to 64 users as detailed in Table 1. The stopping criteria of the optimization algorithms was a minimum change on the fitness value after 200 iterations. The value for the stopping criteria is set to 10^{-3}.

The CS parameters are given as follows. The threshold value $V = 0.9$, step size and lambda values were set to $\alpha = 0.01$ and $\lambda = 3/2$, respectively. As shown in Table 1 different number of users were considered. Users were randomly distributed inside the room as depicted in Fig. 3. Fig. 4 shows the power distribution for the proposed scenarios. More precisely, Fig. 4(a) and (b)

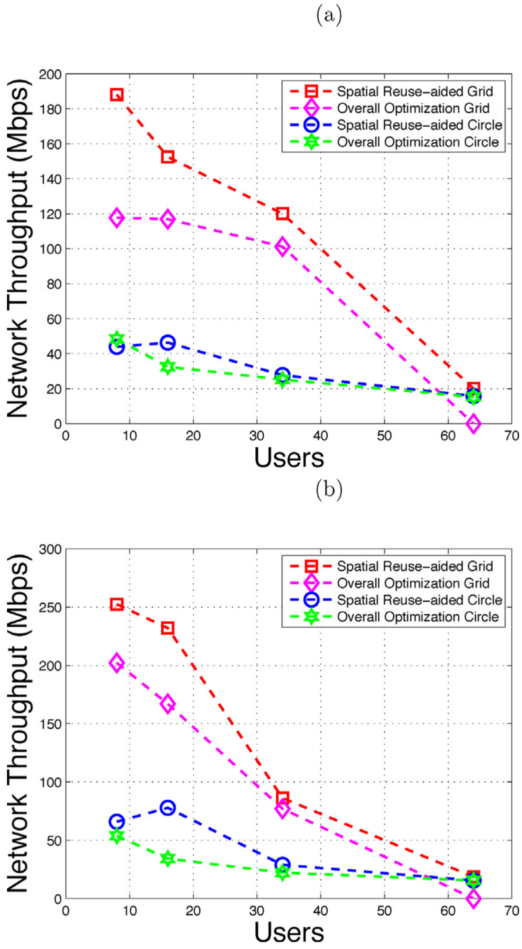

Fig. 5. (a) Network throughput for $FOV = 30^\circ$ using overall and spatial reuse-aided optimization procedures and (b) network throughput for $FOV = 60^\circ$ using overall and spatial reuse-aided optimization procedures.

shows the power distribution using grid LED deployment for $FOV = 30^\circ$ and 60° respectively. Whereas Fig. 4(c) and (d) show the power distribution of circular LED deployment for $FOV = 30^\circ$ and 60° respectively. The transmitter power is set as 10 W for each LED light. Notice from Fig. 4 that the interference produced when there is a large number of LED lights increases when the FOV on the receiver has a wider angle. On the opposite, a narrow FOV angle leads to a higher spatial reuse. Due to the large number of VLC transmitters, the entire room surface is covered by transmitters using both FOV angles, i.e., $FOV = 30$ and $FOV = 60$ and both LED deployments.

Simulations for different scenarios have been performed for 100 samples for fixed receivers' positions as shown in Fig. 3 in order to obtain a mean value of the network throughput taking the average.

Fig. 5(a) and (b) shows the network throughput for circular and grid deployment using the overall and the spatial reuse-aided procedure. Each LED light has a power of $P_c = 10\,\text{W}$. Simulations were performed with different number of users as detailed in Table 1. For both LED deployments the decomposition procedure obtains higher network capacity values. Furthermore, it achieves higher performance for $FOV = 30^\circ$ and $FOV = 60^\circ$. We also see that for a larger FOV the network capacities are even higher although, using a $FOV = 60^\circ$ increases the inter-cell interference as shown in Fig. 4. This can be explained because a wider FOV allows receivers to perceive signals from a larger number of sources. Consequently, a higher number of LED devices placed in the ceiling combined with a large FOV on the receiver increases the network throughput. Moreover, grid LED deployment overcomes the circular deployment in terms of network throughput.

The optimization procedure performs a switching operation on the LEDs that are not being used. In Fig. 6, the switching operation is shown with different colors for $M = 16$. Blue color indicates that LED light has been switched off, whereas green color indicates that the LED is transmitting.

Notice from Fig. 6 that most of LED lights placed far from users positions are turned off. Similarly, when users are closer LED lights placed between both users' positions are also turned off. This can be explained because LED lights placed between users will produce more interference and as a result, the network throughput will decrease.

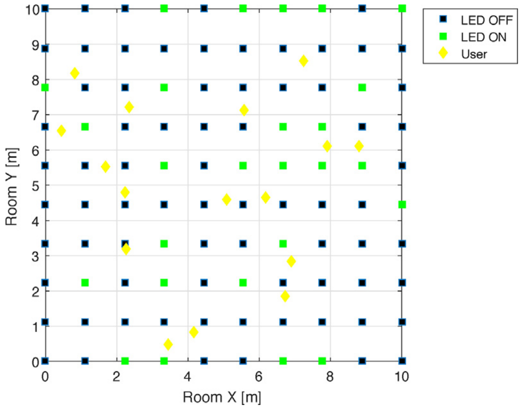

Fig. 6. LED lights turned on for 16 users inside the room using spatial reuse aided procedure.

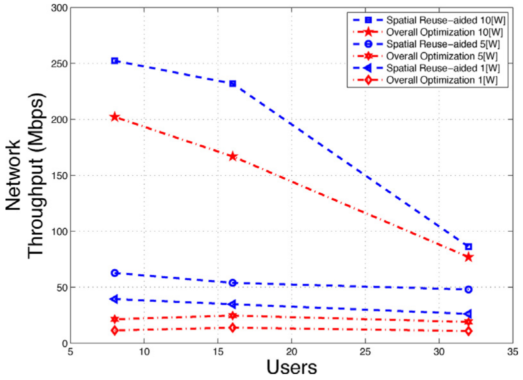

Fig. 7. Network capacities using LED powers of P_c=1, 5 and 10 W for $FOV = 60^\circ$.

In Fig. 7, we compare both procedures using $P_c = 1$ W, $P_c = 5$ W and $P_c = 10$ W for grid LED deployment. From this figure, we mainly observe that the proposed spatial reuse procedure obtains better solutions. Moreover, LED power can be increased without a detrimental effect on network capacity.

Both approaches used in this paper are based on CS metaheuristic. It is well known that there are still many issues to be addressed by the research community regarding complexity analysis of meta-heuristics [28]. In general, all meta-heuristics have polynomial complexity in time and space. Therefore, the complexity of our proposed algorithms is polynomial. However, there is no formal theoretical approach in the literature so far to compute exact bounds [29]. This can be explained by the intrinsic randomness of meta-heuristics. In particular, CS has proved to be highly efficient when solving combinatorial optimization problems [30,31].

5. Conclusions and future work

Two procedures were used for solving the resource allocation problem in a Single Carrier Multi User (SC-MU) VLC network. Two different LED deployments were proposed, i.e., circular and grid. Optimization results show that grid LED deployment achieves better results in terms of network throughput disregarding receivers' FOV.

In addition to this, our numerical results show that spatial reuse aided procedure has a significant effect when computing feasible solutions for the optimization problem outperforming the complete approach. We conclude that the spatial reuse characteristics of VLC networks can be used in order to reduce the problem complexity leading to significantly better results for both fields of view, e.g., $FOV = 30^\circ$ and $FOV = 60^\circ$. Disregarding power levels, the decomposition approach obtains higher network capacities. The throughput of the network decreases when the number of users increases due to the inter-channel interference. Finally, it is not necessary that all LED lights be active for all time slots in order to guarantee a high network capacity.

As future work, new clustering strategies could be plausible. Also, stochastic formulations of the problem to deal with the inherent uncertainty of wireless channels will be considered.

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