

Conflict Graph-based Downlink Resource Allocation and Scheduling for Indoor Visible Light Communications

Huanlin Liu^{1*}, Hongyue Dai¹, Yong Chen², and Peijie Xia¹

¹Key Laboratory of Optical Communications and Networks, Chongqing University of Posts and Telecommunications, Chongqing 400065, China

²School of Automation, Chongqing University of Posts and Telecommunications, Chongqing 400065, China

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Visible Light Communication (VLC) using Light Emitting Diodes (LEDs) within the existing lighting infrastructure can reduce the implementation cost and may gain higher throughput than radio frequency (RF) or Infrared (IR) based wireless systems. Current indoor VLC systems may suffer from poor downlink resource allocation problems and small system throughput. To address these two issues, we propose an algorithm called a conflict graph scheduling (CGS) algorithm, including a conflict graph and a scheme that is based on the conflict graph. The conflict graph can ensure that users are able to transmit data without interference. The scheme considers the user fairness and system throughput, so that they both can get optimum values. Simulation results show that the proposed algorithm can guarantee significant improvement of system throughput under the premise of fairness.

Keywords : Visible light communications, Downlink resource allocation, Conflict graph scheduling, User scheduling, Throughput

OCIS codes : (060.4510) Optical Communications; (060.5625) Radio frequency photonics; (060.4256) Networks, network optimization

I. INTRODUCTION

As a new high-capacity short-range wireless technology, visible light communications can meet the needs for lighting and communications [1-3]. In order to meet the needs of communication, multiple transmitters need to be installed on the ceiling. Because of the channel characteristics of visible light, transmitter coverage and reception range of a receiver are usually limited. In multi-user scenario, several transmitters are necessary in order to cover the whole communication area, which may cause severe inter-user interference. Therefore, a proper scheduling algorithm is needed to address this problem. Other problems we are concerned with are user "fairness" and system throughput. A proper scheduling of users depends on the balance of them. One cannot always choose the user with the highest rate, because the users with lower rates would be starved. However, if the users with the lowest rate are chosen, the throughput would drop. The question is how to schedule the resource fairly. Fair scheduling

would lower the throughput over the maximum possible, but it would provide more acceptable levels to low-rate users.

The research in the topic is scarce, since the study of scheduling on multi-user scenarios for indoor visible light communications is in an initial stage. Targeting at higher system throughput, a novel full-duplex self-adaptive minimum contention window (SACW) MAC protocol was designed for an indoor VLC star topology network system [4]. This protocol allowed concurrent sending and receiving of data frames between the central node and terminal nodes. It could achieve higher downlink throughput compared with half-duplex operation. A fairness tuning parameter might help balance user fairness and throughput. This goal was achieved through initiatively tuning the parameter in [5]. Ojemba Babatundi *et al.* [6, 7] proposed a proportional fair sharing algorithm. They took the user rate and average user rate into consideration, which made them capable of achieving a balance between user fairness and throughput. In [8],

*Corresponding author: liuhl2@sina.com

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researchers presented a signaling scheme for user access and service setup. They proposed three lamp selection schemes distance-prior (DP), service aggregation (SA) and bandwidth-based (BB). These three schemes realized flexible user access and efficient resource allocation. The interference graph model was used to choose as many users as possible without interference in [9]. The model avoided interference but lost the advantage of transmitting diversity because all users were dealt with independently. Researchers [10, 11] proposed a greedy weight minimum (GWMIN) algorithm. It considered the fairness and throughput. However, because the greedy algorithm converges locally, the obtained solution might not be globally optimal. A light fidelity access point (AP) provided high throughput while wireless fidelity offered basic coverage. In [12], researchers proposed a scheme for dynamic allocation of resources to users. They proved that there was a tradeoff between the aggregate throughput and user fairness. Li *et al.* [13] investigated various VLC cell formation schemes. To solve the load balance problem, they invoked a centralized and distributed algorithms.

In order to solve the problems we mentioned above, a conflict graph-based scheduling (CGS) algorithm is proposed in this paper. The algorithm consists of two parts. Based on the coverage of each AP, the conflict graph that is also employed to select user sets of non-interference is obtained. Using the conflict graph and the user sets, we design a scheduling scheme to choose the users to schedule for each time slot.

The rest of the paper is organized as follows. In Section 2, we give an overview of indoor VLC system and the problem formulation. We introduce the CGS algorithm in Section 3. The simulation and results are given in Section 4. Finally, we draw the conclusions in Section 5.

II. INDOOR VLC SYSTEM MODEL

According to [14], compared with the direct received average power of the line of sight (LOS) path, the NLOS-power may be negligible. Therefore only LOS-power is considered as the desired received power for the reason of simplicity. There are several users in the room, their position is randomly distributed. Many APs are mounted on the ceiling, each one of them consists of many LED chips for the purpose of signal enhancement and illumination. A photon detector (PD) serves as a receiver to receive downlink signals. The sensitivity of the PD determines the received signal intensity. The light source is assumed to be Lambert pattern [15]. A typical indoor VLC system model is depicted as follows.

For a given transmitted optical power P_t of each VLC AP, the optical power P_r received by PD is given as [14]:

$$P_r = P_t \frac{(m+1)E}{2\pi D_d^2} \cos^m(\phi) T_s(\psi) g(\psi) \cos(\psi) \quad (1)$$

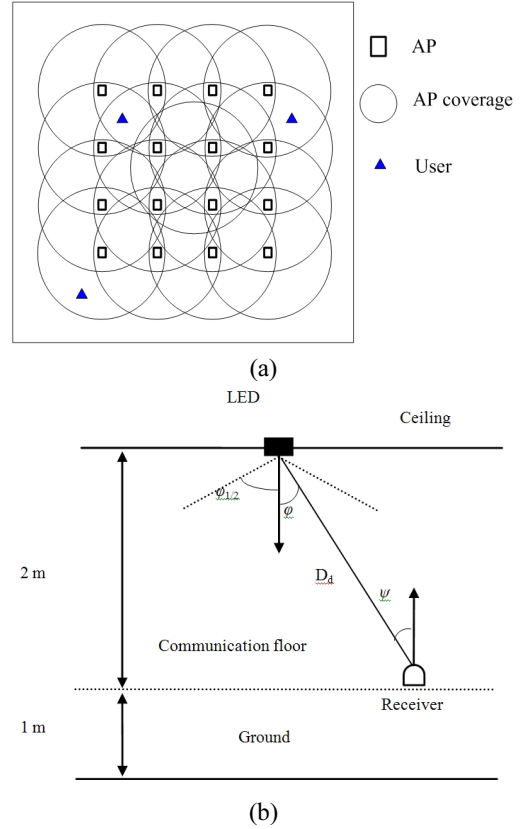


FIG. 1. Indoor VLC system model. (a) Layout of APs, (b) Light downlink transmission sketch.

where D_d is the distance between transmitter and receiver, E is the physical area of the detector in a VLC receiver, $T_s(\psi)$ denotes the gain of the optical filter, $g(\psi)$ is the gain of an optical concentrator, ϕ is the angle of irradiance, and ψ is the angle of incidence. Parameter m , the order of Lambertian emission is given by the semi-angle at half illumination of an LED $\phi_{1/2}$ as: $m = -\ln 2 / \ln(\cos(\phi_{1/2}))$. In a common scenario, the $m=1$, $T_s(\psi)=T_{s0}$, $g(\psi)=g_0$, which are constant. Hence, if the sensitivity of the receiver P_{sens} is given, the coverage of each AP can be obtained. Its definition is given as:

$$D_m^2 = h \sqrt{\frac{P_t E T_{s0} g_0}{\pi P_{sens}}} - h^2 \quad (2)$$

where h denotes the vertical distance between the receiver and AP. For an AP L_i and its coordinate denotes as (x_i, y_i) , we know whether a user $U_j(x_j, y_j)$ is within its coverage. Let S_i denote the user set that L_i covers then it should satisfy the following conditions:

$$S_i = \{U_j | (x_i - x_j)^2 + (y_i - y_j)^2 < D_m^2\} \quad (3)$$

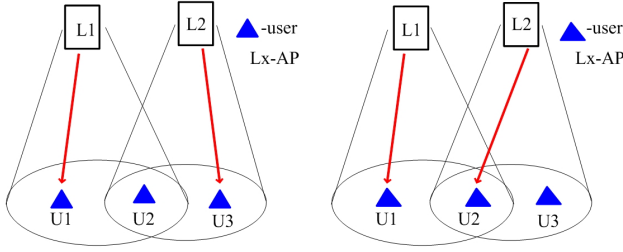


FIG. 2. Demonstration of interferences between users.

There are N APs and M users within the VLC system. Time is divided into small scheduling intervals (called slots). In each interval several of the N users are chosen to transmit to its destination by a central scheduler [8]. Because of the inherent nature of visible light channels, it is appropriate to consider the inter-user interferences as depicted in Fig. 2.

The L_x represents an AP and U_x denotes a user in Fig. 2. For a given time slot as shown in Fig. 2 on the left, assuming that L_1 is assigned to user U_1 for data transmission, L_2 is assigned to user U_3 for data transmission. Because U_1 and U_3 are in different coverage, there is no interference in this scenario. However, the scenario depicted in Fig. 2 the right shows the interference case. U_1 chooses L_1 for data transmission and U_2 chooses L_2 for data transmission. Since there are two users in the coverage of L_1 , the interference occurs. U_2 would suffer severe inter-user interference. Apparently, for a given time slot there can only be one user within a given coverage for the purpose of interference avoidance. Therefore we can formulate the problem as follows. Let $\Theta = \{U_i \mid 1, 2, \dots, N\}$ be the user set and $T = \{L_i \mid i = 1, 2, \dots, M\}$ be the AP set. The user set that L_i covers is denoted as S_i as shown in Eq. (3). In order to avoid interference, for each AP L_i we have:

$$\sum_{\{j \mid U_j \in S_i, S_i \neq \emptyset\}} b_{j,i}^{(k)} = 1 \quad (4)$$

where $b_{j,i}^{(k)} = 1$ if user U_i is chosen at time slot k and is zero otherwise.

Our goal is to maximize the throughput of the system as well as take into consideration the quality of service (the user fairness), hence the problem formulation can be given as:

$$\begin{aligned} \max_{R \in \mathfrak{R}} \sum_j F_j(\bar{R}_j) \\ \text{s.t.} \quad \sum_{\{j \mid U_j \in S_i, S_i \neq \emptyset\}} b_{j,i}^{(k)} = 1 \end{aligned} \quad (5)$$

where \mathfrak{R} is the rate region and R and \bar{R}_j are the rate vector of all users and the average rate vector of user U_j , respectively. Each $F_j(x)$ is an increasing concave continuously differentiable function defined for $x \geq 0$. More discussions

of this function can be found in [6, 7]. If the scheduler always chooses the users with the highest rate, it is the maximum rate (MR) scheduling. It takes no consideration of interference or fairness. As a result, the user fairness may become very low and throughput very high.

III. CONFLICT GRAPH SCHEDULING DOWNLINK RESOURCE

From the previous analysis, we can draw the conclusion that there are three problems that we need to solve. They are interference between users, throughput and user fairness. A conflict graph is employed to solve the first problem—interference. The scheduling scheme is used to achieve the balance between fairness and throughput.

First, let us define the conflict graph. As shown in Fig. 3, there are several users within an AP coverage. They are not allowed to choose the same AP to transmit at the same time slot. Therefore, a dotted line is drawn between them, which means there is interference between them. When all the users are dealt with the same operation, the conflict graph is achieved. Obviously, if there is no dotted line between users, they can choose the same time slot to transmit without interference. Hence the conflict graph can be given as $G = \langle V, E, \varphi \rangle$ where $V = \{U_1, U_2, \dots, U_M\}$, $E = \{e_1, e_2, \dots\}$, e_x denotes the edge between users in the conflict graph. And M -order matrix $A = (a_{ij})$ is called user interference matrix where a_{ij} is the number of edges whose starting point is U_i and ending point is U_j . According to Eq. (3), the definition of a_{ij} is given as:

$$a_{ij} = \begin{cases} 1, & \exists U_i \in S_k \quad \text{and} \quad U_j \in S_k, k = 1, 2, \dots, M \\ 0, & \text{else} \end{cases} \quad (6)$$

After the conflict graph is obtained, the next step is to determine the users who are selected to transmit data at the current slot. However this is not an easy task. In order to solve it, the problem is divided into two phases: finding the user sets and choosing one from them.

Phase 1: find the users (we define these users as non-interference user set) who are able to transmit data without causing interferences and more than one set may be found.

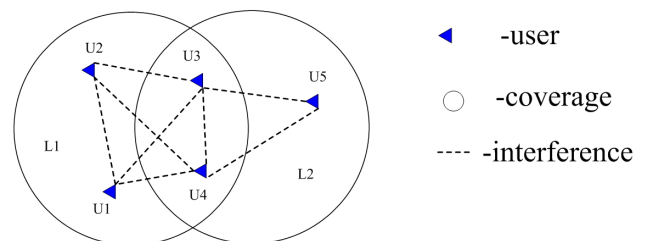


FIG. 3. Demonstration of conflict graph.

TABLE 1. Process of finding non-interference user sets

Algorithm : selection of non-interference user sets	
1	Initialize the user vertex array $v_x = x, x = 1, 2, \dots, M, M$ is the number of user.
2	Initialize the non-interference user set $H = \{\emptyset\}$.
3	for $i \leftarrow 1$ to M^2
3	Initialize an user set $Q = \{\emptyset\}$.
4	Random shuffle array v .
5	$Q = Q \cup v_1$.
6	for $j \leftarrow 2$ to M
7	Initialize Boolean variable $f = 0$.
8	for each user $k \in Q$
9	In matrix A , if $a_{jk} = 1$, then let $f = 1$, go to row 6.
10	if $f = 0$, then $Q = Q \sim v_j$.
11	if $Q \notin H$, then $H = Q \sim H$.

The goal of this phase is to find all the non-interference user sets. This operation is equal to finding all the maximal independent sets in graph G . It is a non-deterministic polynomial problem. In order to solve this problem, a non-interference user sets selection algorithm is proposed and its fake code is given in Table 1.

In Table 1, Q represents the users set of non-interference, and each Q consists of several users with no interference between them. H stands for the set of Q . We can use Fig. 3 to illustrate the algorithm. In Fig. 3, $Q_1 = \{U_3\}$, $Q_2 = \{U_4\}$, $Q_3 = \{U_2, U_5\}$, $Q_4 = \{U_1, U_5\}$, therefore $H = \{Q_1, Q_2, Q_3, Q_4\}$.

Phase 2: in this phase, we focus on selecting a user set from H so that the central scheduler can decide which users are allowed to transmit data at the current slot. In other words, we can use H to calculate the users who have access to the APs at the current slot. Assuming that the end of each time slot is represented as k , and at time k for each user the possible rate for the next time slot is known as $R_{i,k+1}$. $I_{i,k+1}$ indicates that the user U_i is selected for data transmission at the time slot $k+1$, the average rate of user U_i before slot k is given as:

$$\bar{R}_{i,k} = \sum_{l=1}^k \frac{R_{i,l} I_{i,l}}{k} \quad (7)$$

For each $Q_j \in H$, calculate the weight as W_j :

$$W_j = \sum_i \frac{R_{i,k+1}}{\bar{R}_{i,k}} \quad (8)$$

where $R_{i,k+1}$ is the rate at time slot $k+1$, when we decide the users who have the access to AP in time slot k , the users that satisfy the following condition is our preference:

$$\{U \mid W_j = \max \{W_1, W_2, \dots, W_\Gamma\}, U \in Q_j\} \quad (9)$$

where Γ is the element number in \mathcal{W} . After the users are derived, we decide which APs provide service for the users. From Eq. (1), we know that the received power is inversely proportional to the square of distance between the user and the AP. For the purpose of maximizing the received power, the nearest AP is chosen, that is, the AP that serves the user satisfies the following condition:

$$\{L \mid D(U, L) = \min \{D(U, L_1), D(U, L_2), \dots, D(U, L_N)\} \quad (10)$$

where $D(U, L)$ is the Euclidean distance between user U and AP L , it can be calculated by the coordinates of user and AP.

IV. SIMULATION AND ANALYSIS

We evaluate the performance of the proposed CGS algorithm from the perspective of the throughput and the user fairness. The scenario is based on a room of size $10 \text{ m} \times 10 \text{ m} \times 3 \text{ m}$. The APs in the room are uniformly distributed as 4×4 arrays. Their heights are 3 meters above the floor. All the APs transmit identical power. The height of the receiver is 1 meter. Detailed parameters are shown in Table 2.

Two parameters are simulated, the throughput and the SFI (Service Fairness Index) which represents the user fairness [16]. The SFI is defined as:

$$SFI = \max_{i,j} \left| \bar{r}_i - \bar{r}_j \right| / \left(\frac{1}{k} \sum_{l=1}^k \bar{r}_l \right) \quad (11)$$

TABLE 2. Default parameters used in simulation

Symbol	Quantity	Value
-	Room size	10×10×3 m
-	Height of communication plane	1 m
-	AP number	4×4
P_t	Transmitted power	50 mW
T_{s0}	Gain of optical filter	1.0
g_0	Gain of optical concentrator	1.0
E	Physical area of the detector	1.0 cm ²
-	O/E conversion efficiency	0.53 A/W
-	Bandwidth of the lamp	100 Mb/s
P_{sens}	Sensitivity of PD	0.52 mW

where \bar{r}_i is the average throughput of U_i . The smaller the SFI is, the higher the fairness is. On the contrary, the bigger the SFI is, the lower the fairness becomes. When SFI = 0, all the users have the same average throughput, which means absolute fairness is achieved. The SFI under different numbers of users is shown in Fig. 4.

MR algorithm always chooses the maximum rate users without interference. This feature makes its throughput the highest of all algorithms, however its user fairness is the lowest. The meaning of the algorithm is that it reveals the maximum possible throughput. Algorithm1 [9] always chooses the most users without interference. Because this algorithm takes neither throughput nor fairness into consideration, its fairness and throughput are the worst of all algorithms. GWMIN [11] stands for the minimum weight greedy algorithm. Because the greedy algorithm converges locally, the throughput and fairness may not reach its limitation.

From Fig. 4 and Fig. 5 we can see that proposed CGS has the highest user fairness and better throughput, because in phase 1 the conflict graph ensures that users can transmit data without interference, and in phase 2 the scheduling scheme takes the user rate and average user rate into account, which makes sure of the balance between throughput and user fairness. From Eq. (7) and Eq. (8), when the user rate increases or average user rate decreases, the weight of this user set increases, which makes the possibility of choosing this user set increase. As a result, throughput and user fairness increase; On the contrary, when the user rate decreases or average user rate increases, the weight of this user set decreases, which makes the possibility of choosing this user set decrease. As a result, throughput and user fairness increase. Doing these two operations repeatedly, the balance between the throughput and fairness is achieved.

In order to prove the robustness of the proposed algorithm, we would like to increase the number of APs and enlarge the room size. In this configuration, the system environment deployed is an empty room with dimensions 10 m × 18 m × 3 m and there are 4×8 APs installed equidistantly on the ceiling. The vertical view of the layout is shown in Fig. 6. Again

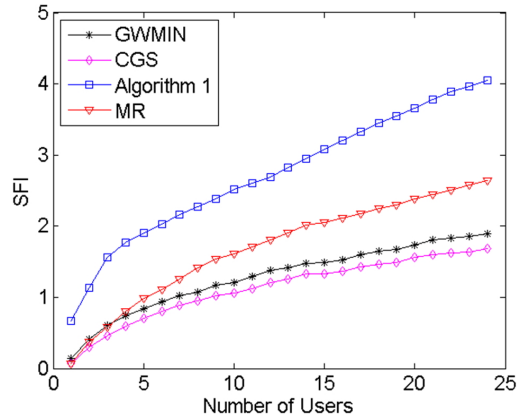


FIG. 4. SFI by using different algorithms.

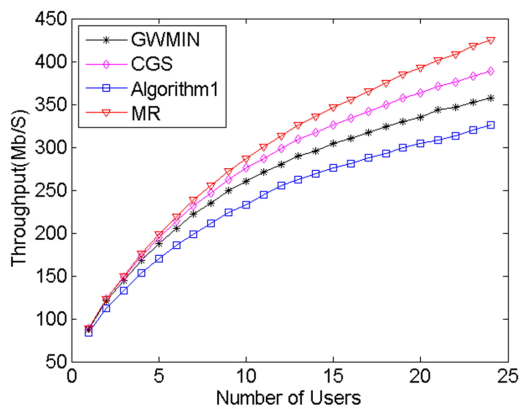


FIG. 5. Throughput by using different algorithms.

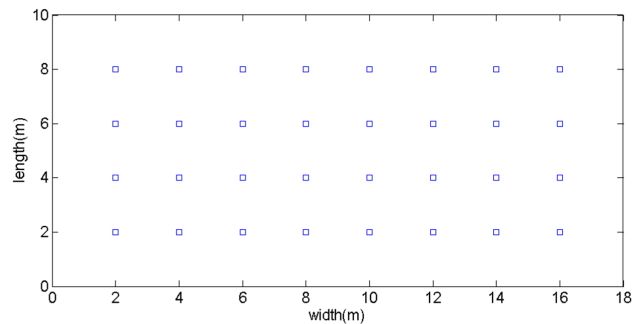


FIG. 6. Vertical view of second AP arrangement.

we compare the performance of our proposed algorithm with the other three algorithms mentioned earlier. The simulation results are depicted in Fig. 7 and Fig. 8.

Similar to the results in the first configuration, our proposed algorithm has the highest user fairness and better throughput. Moreover, the advantages of our scheme are more obvious with more APs and larger room size. With these numerical results, we would like to demonstrate that the application of our scheme is not limited by the AP number or room size. Our scheduling algorithm is robust to arbitrary AP number or room size.

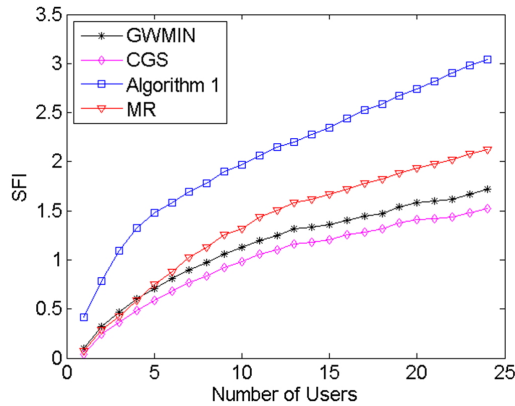


FIG. 7. SFI with different algorithms under the second configuration.

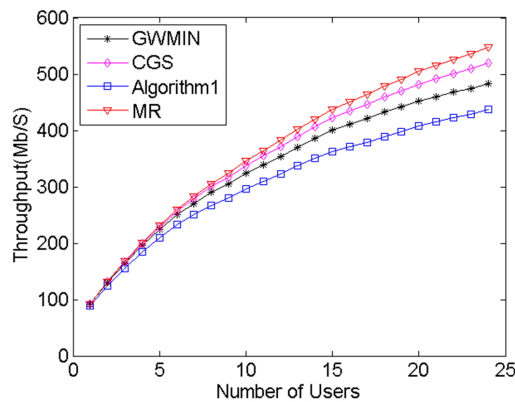


FIG. 8. Throughput with different algorithms under the second configuration.

V. CONCLUSION

In this paper, we first give an overview of indoor VLC channel characteristics and the problem formulation. Under the principle of fairness scheduling, a conflict graph-based scheduling algorithm is proposed to improve the performance of downlink resource allocation. Simulations and results demonstrate that our algorithm can achieve the balance between the throughput and user fairness. And time division multiplexing is used to ensure that the algorithm can be applied for a variety of modulation methods.

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