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Improvement of indoor VLC network downlink scheduling and resource allocation

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Abstract: Indoor visible light communications (VLC) combines illumination and communication by utilizing the high-modulation-speed of LEDs. VLC is anticipated to be complementary to radio frequency communications and an important part of next generation heterogeneous networks. In order to make the maximum use of VLC technology in a networking environment, we need to expand existing research from studies of traditional point-to-point links to encompass scheduling and resource allocation related to multi-user scenarios. This work aims to maximize the downlink throughput of an indoor VLC network, while taking both user fairness and time latency into consideration. Inter-user interference is eliminated by appropriately allocating LEDs to users with the aid of graph theory. A three-term priority factor model is derived and is shown to improve the throughput performance of the network scheduling scheme over those previously reported. Simulations of VLC downlink scheduling have been performed under proportional fairness scheduling principles where our newly formulated priority factor model has been applied. The downlink throughput is improved by 19.6% compared to previous two-term priority models, while achieving similar fairness and latency performance. When the number of users grows larger, the three-term priority model indicates an improvement in Fairness performance compared to two-term priority model scheduling.

OCIS codes: (060.4510) Optical communications; (060.4251) Networks, assignment and routing algorithms.

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Optics EXPRESS

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1. Introduction

Ever since Nakagawa and his group proposed the combination of illumination and communication functions based on fast modulated LEDs [1,2], Visible Light Communications (VLC) have been extensively studied for use in next generation wide band wireless communication networks. Point-to-point links with high data rate of about 3 ~4 Gbps have been demonstrated using LEDs [3,4], [6–8]. Generally speaking, although some unsolved problems in the physical Point-to-Point links layer still remain, it is clear that the research focus of VLC is evolving to include studies of networking.

In the scenario of networks where multiple Access Points (APs) serve multiple users, as in Fig. 1, two or more users may try to gain physical access to the same AP resulting in a potential conflict. As conflict between user1 and user2 in there links with LED3. A VLC network scheduling and allocation scheme should properly allocate APs to the conflicting users and guarantee all the users have access (so called fairness). Clearly, quality-of-service (QoS) oriented scheduling and allocation should achieve high capacity and low time latency.

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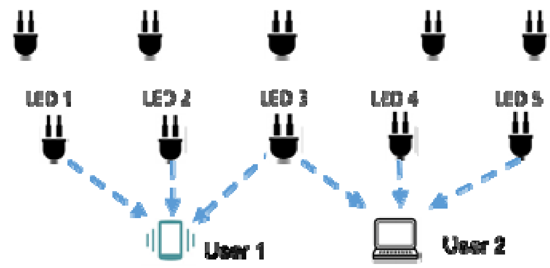

Fig. 1. An indoor UC-VLC network.

This topic has been the subject of several articles [9–12] where frequency reuse and cell formation technology have been studied. Channel selection is made via a joint scheduling and resource allocation scheme in [13] to increase the system throughput of IEEE 802.15.7 WPAN. Higher layer protocol design and configuration issues in VLC settings were studied in [7], where the author proposed a scheduling based on tunable beam-widths and beam-angles. Other work [14], studied transmitter and subcarrier allocation employing discrete multi-tone (DMT) modulation to improve the throughput in multiuser VLC systems. In [15] a scheduling scheme capable of achieving a substantial throughput at a modest complexity was described. Note that most studies endeavor to improve throughput without considering fairness among users and time latencies experienced by users. By taking fairness into account, the authors of [16] proposed a scheduling algorithm based on Proportional Fairness (PF) which achieves a balance between user fairness and network throughput. In [17] an interference graph was introduced to describe the inter-user interference and a carrier scheduling scheme based on a PF principle for a centrally controlled VLC system which outperformed the maximum-rate scheduling policy in terms of balancing the achievable throughput against the fairness experienced by the users.

In this paper, we investigate the downlink scheduling and resource allocation problem of a centrally controlled User Centric VLC (UC-VLC) system with multiple-users. Unlike Base Centric (BC) networks where the cell is formed by the bases, in the downlinks of a UC-VLC system all the APs within one user's field of view (FOV) form a cell and transmit the same signal to a user. Previous research has shown that UC cell formation outperforms the BC cell formation as capacity increases and more users are added [11]. Accordingly, we use the UC cell formation in our study. Because the shape and number of APs in the transmitting cell is elastic and changes with the location and FOV of the user, this type of cell is referred to as a Virtual Cells (VC).

We aim to propose a downlink scheduling scheme for a UC-VLC network which delivers a high QoS. Our scheduling scheme follows the principle of PF and also employs the interference graph proposed by [17]. We establish a new three-term priority factor model, Eq. (2), based on the previous two-term model, Eq. (1), used in [17] for the scheduling scheme.

$$p_{i,k} = f(r_{i,k}) \cdot q(D_{i,k}) \tag{1}$$

$$p_{i,k} = F(r_{i,k}) \cdot G(CIR_{i,k}) \cdot Q(D_{i,k}) \tag{2}$$

where in the two-term model, the $f(\cdot)$ and $q(\cdot)$ functions take the fairness and time latency into consideration [17,18].

In the proposed three-term model we use functions $F(\cdot)$ and $Q(\cdot)$ to replace functions $f(\cdot)$ and $q(\cdot)$, and a third function $G(\cdot)$ is added to make the priority factor sensitive to the wireless channel condition. More details are discussed in Section 3. Simulation shows that the scheduling and allocation algorithm with the three-term model achieves a notable increase in throughput, while maintaining similar fairness and time latency performance compared to

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existing models. The improvement does not need any specific modulation format nor system mechanical settings.

The rest of this paper is organized as follows. The optical and communication model of multi-user multi-APs links is presented in Section 2 along with the problem formulation of multi-user access in a VLC network. In Section 3 the solution by application of an interference graph and Greedy algorithm is discussed and details of our new priority factor model are established. The results of network simulations for the established and proposed models are compared in Section 4. Finally, Section 5 draws the conclusions.

2. VLC system model and problem formulation

Here we define, for the downlink of a UC-VLC network, the sum data rate of all the users in a time slot as the throughput γ which can be denoted as

$$\gamma=\sum_{i=1}^{K} r_i=\sum_{i=1}^{K}\log_2\left[1+\frac{\left(\sum_{j\in VC_i} h_{ij}P_{ot}R\right)^2}{\sigma_t^2+\sigma_s^2+I_i}\right] \tag{3}$$

where σ_s^2 and σ_t^2 denote the shot and thermal noise respectively. I_i is the inter-channel interference (ICI) imposed by neighbor VCs for other users which can be calculated as $I_i=\left(\sum_{j\notin VC_i} h_{ij}P_{ot}R\right)^2$. P_{ot} is the transmitting optical power of the APs. Here the throughput γ is normalized by the channel bandwidth and its unit is bps/Hz. h_{ij} is the optical channel gain for the link of AP j to user i and can be denoted as [19]

$$h_{ij}=\begin{cases}\dfrac{A_i\left(k+1\right)m}{2\pi d_{ij}^2}\cos^k\left(\phi_{ij}\right)\cos\left(\psi_{ij}\right)T_i g_i & (\phi_{ij}\le FOV_i)\\ 0 & (\phi_{ij}>FOV_i)\end{cases} \tag{4}$$

The channel gain describes the optical power attenuation along the optical path. For the sake of simplicity, we only consider LOS (line-of-sight) links in this paper. If there are K users and N APs in the networks, the channel gains for all possible optical links form the channel information matrix **H** (K × N).

The throughput is a measure of the data transmitting ability of the VLC network and is the most important performance metric with regard to both the users' experience and the network management. A good QoS scheduling scheme aims to maximize throughput.

$$Max \quad \gamma=\sum_{i=1}^{K} r_i \tag{5}$$

where r_i is the throughput of user i in a single time slot, and which may change in every time slot. For time slot k we can define the vector in $\boldsymbol{r}_k=[r_{1,k}, r_{2,k}, \ldots, r_{K,k}]^T$. In [17] Tao et al and in [20] Miao et al have explained in detail that this proportional fair throughput vector is a vector that maximizes the network throughput in Eq. (5), and therefore this optimization problem leads to a proportional fairness scheduling (PFS) which will be discussed in section 3.2.

Equation (3) indicates that we could optimize the network throughput in Eq. (5) by either raising the transmitted optical power or by reducing the noise through proper scheduling. If the transmitted optical power is increased, both the numerator and the denominator are increased. This could lead to a decrease in SNR and therefore reduce the throughput. Due to the high emitting power level required for VLCs, the ICI dominates over the other noise sources and varies widely with a user's location. Hypothetically, if the PF scheduling

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algorithm is able to detect the interference between users and only activate the users whose VCs are independent from each other, then the ICI can be mitigated more effectively.

Therefore the problem of optimizing the network throughput can be formed as

$$\begin{gathered} Max \quad \gamma = \sum_{i=1}^{K} r_i \\ VC_i \cap VC_j = \varnothing \quad i, j = 1, \ldots, K, i \neq j \\ \bigcup_{i=1}^{K} VC_i = U \end{gathered} \tag{6}$$

where $\varnothing$ denotes an empty set, U denotes the user set, U = {U_i, i, j = 1,…, K}. In brief, through mitigation of the main noise source in VLC networks we can optimize the throughput of a VLC network.

3. Problem solution

3.1 Graph theory

Graph theory has been extensively used in Wireless Radio Frequency Network Management. In graph theory, network interference relationships are typically represented using edge-based interference graphs [17] or conflict graphs. Conflict graphs have been used in the context of networks with single antenna elements in [21]. In VLC networks there are multi-transmitters for one user. In a conflict graph, the vertex set corresponds to all possible links, and therefore it would be very large in multi-user VLC networks. In this paper we use the interference graph model provided by [17] for the vertex set in an interference graph is fixed and equals to the number of users. As discussed in Section 2, if a scheduling algorithm is able to recognize users without ICI in every time slot and pick them for scheduling and resource allocation, the throughput can be improved. In fact all the users without ICI can be represented by the Maximum Independent Set (MaxIS) of the interference graph. So the scheduling problem has been transformed into finding the MaxIS in graph theory. In the next part of this paper, this problem will be further transformed into a problem of finding the Maximum Weighted Independent Set (MWIS).

3.2 Scheduling algorithm

A practical scheduling algorithm needs to consider the complexity of implementation while paying attention to the impact on system performance indicators, such as fairness, time latency and throughput. In practice throughput matters the most, but the scheduling algorithm still needs to guarantee that other performance criteria are not being compromised. Currently there are three main categories of scheduling algorithm for wireless access networks, namely Round-Robin Scheduling (RRS), Maximum Carrier–to-Interference Ratio Scheduling (Max C/I) and Proportional Fairness Scheduling (PFS) [20]. RRS achieves the highest fairness, and Max C/I achieves the highest throughout, while PFS outperforms them by balancing throughput against both fairness and latency. In this paper we follow the principle of PFS and adjust the model to meet the requirements of VLC downlinks.

PFS is a compromise scheduling policy, trying to balance the competing interests of maximizing total throughput delivered to users and providing at least a minimal level of services [20,22]. Usually PFS is performed at the base station and works within a cell. By taking fairness into consideration, the PFS calculates the priority factor $p_{i,k}$ for user i in slot k by considering the data rate requirements for this slot $r_{i,k}$ against its average data rate $\langle r_{i,k-1} \rangle$ as shown in Eq. (7). In each time slot, PFS chooses the user with the highest $p_{i,k}$ to transfer data.

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$$p_{i,k} = f(r_{i,k}) = \frac{r_{i,k}}{\langle r_{i,k} \rangle} \tag{7}$$

$$\langle r_{i,k} \rangle = \begin{cases} \left(1 - \frac{1}{T_c}\right) \cdot \langle r_{i,k-1} \rangle + \frac{1}{T_c} \cdot r_{i,k-1} \, (scheduled \quad in \quad last \quad slot) \\ \left(1 - \frac{1}{T_c}\right) \cdot \langle r_{i,k-1} \rangle \qquad (else) \end{cases} \tag{8}$$

where T_c is the time window used to perform the trade-off. Function $f(r_{i,k})$ uses a proportional form to realize the fairness among multiple users. In slot k the user with the highest priority is scheduled, which will increase its average data rate $\langle r_{i,k-1} \rangle$. This will then result in its future priority being reduced. Every user therefore gets the chance to use the resource in transmitting/receiving their data. Thus fairness is guaranteed.

While 3G standards did not select a particular opportunistic schedule, PFS was the most popular both in the research community and in industry [22]. Networks may implement modified versions of PFS. In addition to the basic PFS rule, an exponential rule developed by Shakkottai and Stolyar in 2000 is a PF rule that also tries explicitly to equalize the latencies of all the users when their differences become large. In time slot k, the priority factor for user i is calculated in a two-term formation [18].

$$p_{i,k} = f\left(r_{i,k}\right) \cdot q\left(D_{i,k}\right) = \frac{r_{i,k}}{\langle r_{i,k} \rangle} \cdot \exp\left(\frac{D_{i,k} - \langle D'_{i,k} \rangle}{1 + \sqrt{\langle D'_{i,k} \rangle}} \right) \tag{9}$$

where $\langle D'_{i,k} \rangle$ is the average delay of all the users other than user i and it can be denoted as $\langle D'_{i,k} \rangle = \left(\sum_{j=1, j \neq i}^{K} D_{i,k} \right) / (k-1)$.

The exponential form of function $q\left(D_{i,k}\right)$ in Eq. (9) makes the priority factor $p_{i,k}$ sensitive to a large latency variation and results in a user whose latency different from the average being given a modified priority factor. For small latency differences, the exponential term is close to 1 and the policy becomes similar to the basic PFS rule as in Eq. (7).

Combining the principle of PFS and interference graph theory, every user has a priority at each time slot in order to be scheduled and thereafter the interference graph changes to the Weighted Interference Graph (WIG). Under the PFS principle, the scheduling algorithm needs to identify the users with the highest sum of priority at first. At the same time, in order to optimize the throughput, the scheduling scheme needs to identify the users with the lowest ICI. By activating users who satisfy both of these two requirements and allocating APs to them, the throughput of a VLC network will be optimized. In a WIG, the users set with the highest sum of priority and lowest ICI in fact form the Maximum Weighted Independent Set (MWIS) of the graph. This therefore becomes a problem of finding the Maximum Weighted Independent Set (MWIS). Due to its NP-complete character, the MWISP heuristic algorithm is needed to find the solution within an acceptable timeframe. The “Greedy” algorithm is one of the most simple and efficient heuristic algorithms for MWISP and here we adopt the MIN-Greedy algorithm [23] within our scheduling algorithm. The details of implementing the Min-Greedy algorithm to solve the MWISP are listed below.

Note that in step 8, $N(v_i)$ is the neighbor matrix of vertex v_i. $d(v_i)$ is the degree of vertex v_i, which is equal to the number of vertices in $N(v_i)$, and represents the interference

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experienced by user i. The larger $d(v_i)$ is the stronger the inter-user interference experienced by user i is. Dividing $p_{i,k}$ with $[d(v_i)+1]$ in step 6 avoids the situation that the denominator equals to zero when $d(v_i) = 0$. Removing the union sets of the chosen v_i and vertex in its neighbor matrix in step 8 improves the convergence of the algorithm. When vertex v_i is chosen in the MWIS then any vertex (i.e. user) in its neighbor matrix must be de-activated to avoid causing ICI to v_i.

Algorithm 1: the MIN-Greedy algorithm for MWIS searching

1 Input location information of $v_i \in U$
2 **for** each time slot k **do**
3 update $h_{i,k}$, $p_{i,k}$;
4 MWIS=ϕ and V(G)= U;
5 **while** $V(G) \neq \phi$ **do**
6 $Max \quad p_{i,k} / \left[d(v_i) + 1 \right], \quad (v_{i \in} V(G))$;
7 MWIS=MWIS $\cup v_i$;
8 V(G)= V(G) $/ \left[v_i \cup N(v_i) \right]$;
9 **end while**
10 **end for**

3.3 Proposed three-term priority model

In this part, we will discuss how to improve the mathematical form of the priority factor in order to improve the performance of the VLC network.

Wireless resource is scarce and mobile users perceive time-varying and location-dependent channel conditions due to fading and shadowing. This causes the multi-user diversity effect: since many users fade independently, at any given time some subset of users will likely have strong channel conditions. Since instantaneous channel conditions derive the instantaneous data rates of users, in order to achieve higher throughput, the scheduler at the central control station should select a user (or a subset of users) with relatively good channel conditions for data transfer.

Here we introduce a new factor which takes into account the indoor wireless communication channel conditions. Based on knowledge of this factor, we implement channel condition-aware scheduling by giving higher priority to users with better channel conditions under the PFS rule, and so achieve higher throughput. The carrier-to-noise ratio (CNR) is a typical parameter used to reflect the channel condition. As discussed in Section 2, inter-channel interference (ICI) from neighboring VCs used by other users overwhelms all other noise sources. Consequently CNR is equivalent to the carrier-to-interference ratio (CIR) in VLC networks and therefore we use CIR in this paper to reflect the channel conditions of the users.

We insert the function $G(CIR_{i,k})$ to reflect the channel condition. It is important that $G(CIR_{i,k})$ takes the CIR of both the past and the present into consideration, since the network will be changing continuously due to the movement of users. Therefore we calculate the function $G(CIR_{i,k})$ as

$$G(CIR_{i,k}) = 1/T_C \cdot CIR_{i,k-1} + (1 - 1/T_C) \cdot CIR_{i,k} \quad (10)$$

where T_C determines the weighting given to historical values. If the channel is very unstable, the current CIR can be given more weight by choosing a large T_c.

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Channel information such as the SNR is readily available in RF wireless networks. It may be possible to use other performance metrics such as optical signal strength monitoring techniques where the use of the channel information matrix **H** is involved. This requires the cooperation of the indoor positioning technology to provide the precise location of the users. Some techniques for VLC-based positioning have been addressed, differentiating the metric that provides information on positioning (i.e., power or time-based), most using a positioning technique based on triangulation, fingerprinting, and proximity. To use the triangulation technique, it is required to measure the angle or distance between a reference point and a mobile terminal, such as angle of arrival, time of arrival and TDOA [24], and received signal strength intensity [25]. In these simulations, the location of multiple users is randomly generated and $\left(\sum_{j\in VC_i} h_{ij} P_{ot}\right)^2 / I_i$ is used to calculate the CIR.

Secondly, we adjust the weight of each function term to achieve a high throughput without compromising the performance with respect to fairness and average user delay. As an alternative to Eq. (9), functions other than the linear function for the user's data rate and the exponential function for the latency difference may be used for the priority in PFS. By adjusting the weight of the three terms, the priority factor exerts a different influence on system performance indicators, such as the throughput parameter given in Eq. (3) and the Schedule Fairness Index (SFI) defined as follows.

$$SFI = \frac{\underset{i,j}{Max}\left|\langle\rho_i\rangle - \langle\rho_j\rangle\right|}{1/k\sum_{i=1}^{K}\langle\rho_i\rangle} \quad (i, j = 1,...K) \tag{11}$$

where $\langle\rho_i\rangle$ is the average data rate of user *i*. A smaller SFI value means a better fairness among users.

In [26] a stronger nonlinearity for the latency difference term, $q\left(D_{i,k}\right) = 6 \wedge \left[\left(D_{i,k} - \langle D'_{i,k}\rangle\right) / \left(1 + \sqrt{\langle D'_{i,k}\rangle}\right)\right]$, and in [17,26] a higher weight on the data rate term, $f\left(r_{i,k}\right) = \alpha \cdot \left(r_{i,k} / \langle r_{i,k}\rangle\right)^S$, $\left(\alpha \in [1,9], S = 1, 2 \text{ and } 3\right)$,were analyzed but showed no improvements.

By computer simulation, with the inclusion of the $G(CIR_{i,k})$ term, we tested priority models formed by several nonlinearity orders of the latency-aware term and the proportional fair term. The simulations will be discussed in Section 4. Finally the proportional fair term was modified to an exponential form and the latency-aware term was modified to the 8th power of the latency difference. These changes result in the following priority model,

$$p_{i,k} = F(r_{i,k}) \cdot G(CIR_{i,k}) \cdot Q(D_{i,k}) = \exp\left(\frac{r_{i,k}}{\langle r_{i,k}\rangle}\right) \cdot G(CIR_{i,k}) \cdot 8^{\frac{D_{i,k} - \langle D'_{i,k}\rangle}{1+\sqrt{\langle D'_{i,k}\rangle}}} \tag{12}$$

From simulation results, we found that when the base is larger than 8 for the term $\left[\left(D_{i,k} - \langle D'_{i,k}\rangle\right) / \left(1 + \sqrt{\langle D'_{i,k}\rangle}\right)\right]$ or larger than 2.718 for the term $\left(r_{i,k} / \langle r_{i,k}\rangle\right)$, the throughput does not increase further, so these values have been used in the proposed three-term model and the later simulations in Section 4.

4. System simulations and results

Simulations were performed to evaluate our priority model in Eq. (12) and compare it with existing models. The throughput given by Eq. (3), the SFI given by Eq. (11), and the latency performance represented by the average delay, defined as Eq. (13) were all calculated.

$$Ave\_Latency = \frac{\sum_{i=1}^{SIMU}\left[\sum_{i=1}^{K} delay(u_i)/K\right]}{SIMU} \tag{13}$$

where $delay(u_i)$ is the actual delayed time slots for user i in a single scheduling progress, K is the number of users, and $SIMU$ is the cycle number of each simulation runs. The $Ave\_Latency$ is a key parameter and it represents the efficiency of the scheduling scheme.

The scheduling simulation algorithm is listed below.

Algorithm 2: Scheduling simulation algorithm

Input initial system parameter matrix (as in Tab. 1)
for each simulation cycle SIMU **do**
    Randomly generate users' geometry locations
    For each time slot k **do**
        update $h_{i,k}$, $p_{i,k}$;
        build the weighted interference graph WIG (V,E);
        MIN-Greedy algorithm for WMIS searching;
    end for
    Allocate the APs to users in MWIS;
    Allocate the idle Aps;
    Calculate capacity and delayed timeslots for every user;
end for
Calculate network throughput, SFI and $Ave\_Latency$.

In order to make a restricted comparison we used exactly the same conditions as [17]. In the simulations, the 8*8 LEDs are equally separated by distance of 2 meters. For numbers of users from 1 to 32, we carried out scheduling simulations. Each simulation used 5000 cycles and for each cycle the scheduling was performed for 50 time slots. In each cycle the locations of users were generated randomly by Matlab codes to simulate the movement of users. The throughput, SFI and $Ave\_Latency$ were calculated to investigate the performance of the proposed three-term model.

Before each performance comparison, we carried out simulations to test the robustness of our codes based on the previous two-term model using our own implementation. Once the similarity was established with previous results, the scheduling simulation was performed based on the proposed three-term priority model and afterwards to do the comparison.

Figure 2(a) shows results for validating the code's robustness. The dotted line shows the throughput performance versus number of users calculated by our codes applying the 2-term model used in [17], and the solid line is the throughput performance provided by [17]. The two curves show a high similarity and confirm that our simulation codes form a sound basis for later comparison.

Figure 2(b) shows a comparison of throughput performance against different numbers of users. The proposed three-term model shows increased throughput for all numbers of users, with an increase of 19.6% on average over the range of 1 user to 32 users. This improvement is consistent with our expectations of inserting the channel condition function $G(CIR_{i,k})$ into the priority model in Section 3.3. Channel condition fluctuations resulting from multi-pass/ multi-user effects are an important factor limiting the throughput of a wireless networks. However in a multi-user VLC network, we can exploit such fluctuations in scheduling the network to improve throughput. Our three-term model opportunistically exploits the time-varying nature and spatial diversity of the wireless channels to make effective use of the available system bandwidth.

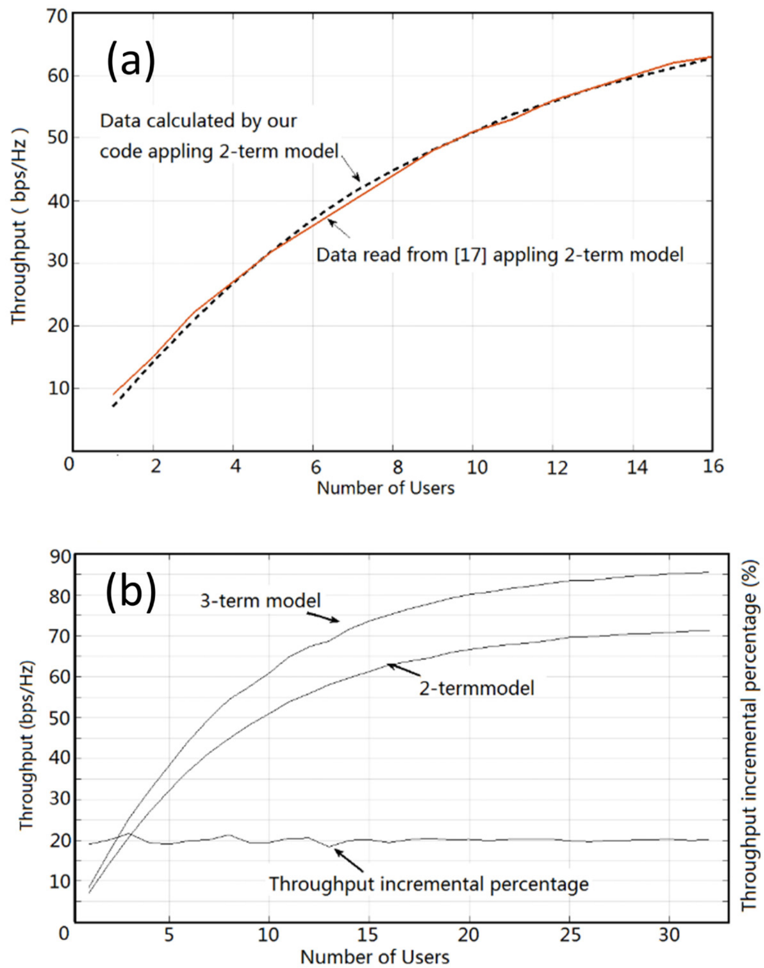

Fig. 2. Throughput performance: (a) robustness of our simulation codes. (b) Throughput performance comparison between 2- and 3-term models as function of number of users.

The two curves in Fig. 3(a) are the normalized SFI data applying the two-term priority model calculated using our simulations and using values from [17] respectively. In each case the curves are normalized to their maximum value. The two curves closely follow each other, which indicates that our simulation code is an appropriate method for later comparison. Later we use similar codes in scheduling simulation using the two-term model used in [17] and for the proposed three-term priority model.

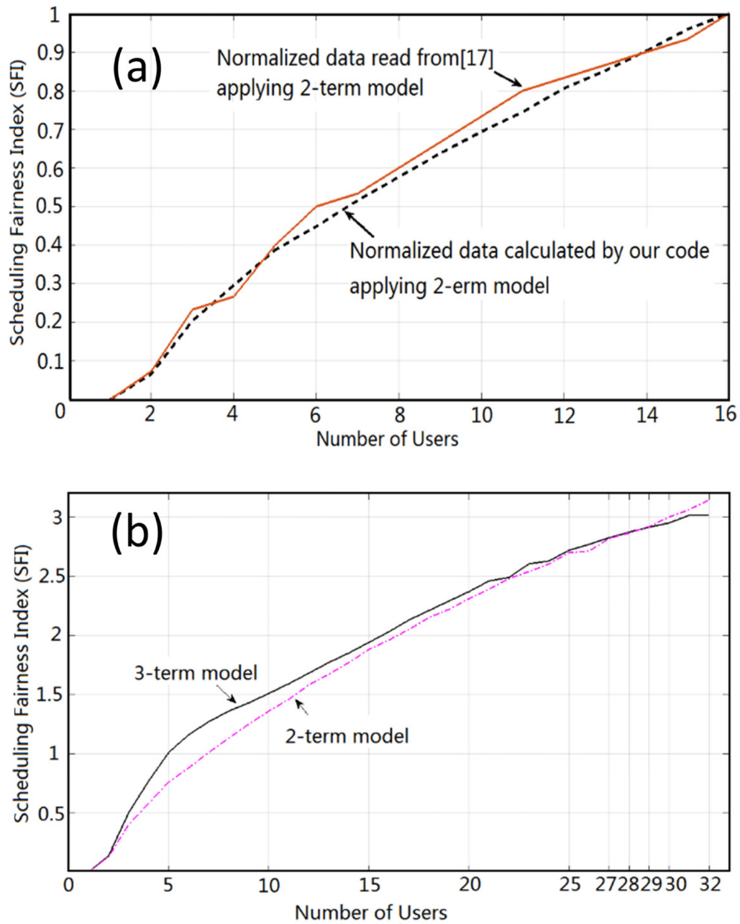

Fig. 3. Fairness performance: (a) robustness of our simulation codes. (b) Fairness performance for 2-term model and 3-term model as function of number of users.

The SFI performance comparison is shown in Fig. 3(b). It is clear that scheduling utilizing the three-term priority model achieves a fairness performance close to that of applying the two-term model in [17]. The larger the SFI value is, the poorer the fairness performance. There is a small degradation around K = 6~8 (K is the number of users) and the maximum degradation is about 22% at K = 6. This degradation may due to the introduction of the $G(CIR_{i,k})$ term, which favors users with better channel fidelity and improves the throughput. Since three-term model scheduling favors a user with better channel conditions, users with "good" channels have a higher chance of transferring data than in two-term scheduling, and consequently other users with "bad" channel conditions experience a delay. For a small number of users, the differences in channel conditions in the network experienced by users can be large due to their movement and locations, and therefore fairness among users is decreased by a small amount. So for small number of users, the function $G(CIR_{i,k})$ in the three-term model improves throughput but potentially undermines the fairness among users. Note that when the number of users grows larger (K≥29), the two curves crossover and the three-term scheduling shows an improvement in SFI in comparison to two-term scheduling. This may arise from the fact that, as the number of users increases, the wireless network becomes more crowded. Users therefore tend to experience similar channel conditions irrespective of their location. This reduces the undermining effect of $G(CIR_{i,k})$ on fairness. The exponential term we introduced into the fairness function $F(r_{i,k})$ gives more weight to fairness scheduling than the two-term model. For a large number of users, it results in our three-term scheduling achieving superior fairness performance.

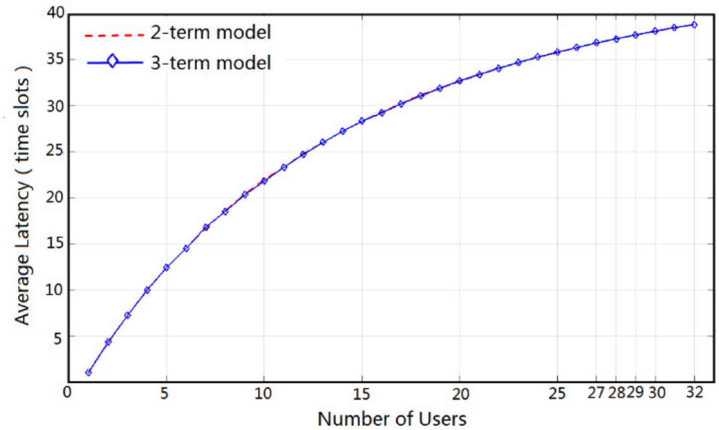

Fig. 4. Average latency performance as function of number of users.

From Fig. 4, we can see that two-term and three-term scheduling achieve an almost identical time latency performance for different numbers of users. Note in the three-term model we introduced an exponential term into the fairness function $F(r_{i,k})$. This non-linearity is stronger than that in the two-term model, so fairness is given more weight in the three-term model scheduling, which is supposed to degrade the latency performance. Nevertheless, we also introduced another strong non-linearity into the delay-aware function $Q(D_{i,k})$, i.e. a power law of time difference, which enhances the weight of given to latency performance in the three-term model. From Fig. 4, we can see that the nonlinearity order of the latency-difference term has correctly balanced the time delay performance against the effect of fairness function $F(r_{i,k})$, so the two scheduling schemes achieve similar latency performance. Simulations for different nonlinearities in the delay-aware term show that the latency performance can be improved only at the cost of impacting negatively either the throughput or the fairness. The nonlinearity order we used in Eq. (12) strikes a good balance between its sensitivity to time-difference fluctuations and its impact on the other two system parameters.

Table 1. Performance comparison summary

	Throughput	SFI	Latency
Two-term priority model		Better with small number of users	same
Proposed three-term priority model	Better with all users		same

Table 1 summarizes the behavior of the scheduling schemes. Scheduling with the proposed three-term priority model always achieves better throughput and the same latency performance, while having a small degradation on fairness for the situation of a small number of users. Generally we can say that the proposed priority model improves the scheduling performance and achieves a balance among all the system indicators.

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5. Summary

We have studied multi-user scheduling and resource allocations in VLC downlink networks. By application of the interference graph, the ICI-avoiding scheduling and allocation is performed by finding the MWIS of the graph. A new priority factor model has been established to fully cover the three main objectives of scheduling and allocation in a QoS-oriented network.

The essence of our proposed scheduling scheme is based on graph theory under the PFS principle and can be summarized as

i) under the principle of PFS, users in conflict are scheduled with time-division multiplexing (TDM) to ensure fairness and conflict avoidance;

ii) by activating users in the MWIS, the cells cause ICI are scheduled by space division multiplexing (SDM) which removes the ICI and therefore increases the achievable throughput;

iii) by inserting the channel condition information function $G(CIR_{i,k})$ into the priority factor model, by exploiting time-varying nature of wireless channel the throughput is improved. This model schedule users in an opportunistic way to achieve high network performance while assuring the level of QoS among different users.

iv) by appropriately adjusting the weight of proportional fairness function $F(r_{i,k})$ and delay-aware function $Q(D_{i,k})$ in the three-term model, the fairness and latency performance is maintained while the throughput performance is improved.

Under the principle of PFS and with the aid of graph theory, the proposed scheduling achieves a higher throughput without compromising fairness and latency performance. We recommend the improvement should be implemented in a practical network in the near future, including the real-time estimation of the channel gain matrix **H** and the CIR information of all users.

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