Cellular Coverage Optimization for Indoor Visible Light Communication and Illumination Networks

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***Abstract*—**In visible light communication (VLC) systems, cellular networks are required for large indoor environment and built as a kind of new networks when combining the LED illumination, named communication and illumination networks (CIN). The co-channel interference (CCI) between adjacent cells leads to large areas of communication dead zones. Users covered by access points (APs) within illumination region are not necessarily covered within communication region and vice versa. In order to achieve seamless coverage, it is necessary to mitigate CCI and maximize the effective coverage of communication and illumination synchronously. In this paper, a coverage optimization model is built when APs share the same frequency resources. Genetic algorithm is used for optimizing LED arrangements, semi-angles at half-power and heights, and improving SINR and illuminance in CIN. The results show that the communication and illumination can be approximate seamless coverage after optimization and about 75% communication coverage improvement is achieved when illumination requirement is fulfilled. The solution has a better downlink throughput and complexity than state-of-the-art solutions when cellular coverage is approximate.

***Index Terms*—**Visible light communication, communication and illumination network, co-channel interference, coverage optimization

I. Introduction

Recently, visible light communication (VLC) attracts increasing attention with the development of the light emitting diode (LED) illumination. Emerging as a solution to overcome the crowded radio spectrum for radio frequency (RF) communications, VLC provides data services with higher speed and lager capacity, and becomes an advantageous complement of other indoor networks. Especially in some large indoor environment, like an office, a train/airport waiting room or a shopping mall, which has large areas, high person flows and terminal mobility, VLC has a natural advantage of communication and illumination. Meanwhile, cellular network technique is significant in that environment because of the small coverage of LED.

In order to achieve communication and illumination to multiple roaming mobile terminals (MTs) for a large indoor environment, a communication and illumination network (CIN) composed of small optical cells is proposed. The seamless cellular coverage of the communication, as well as the illumination, is focused on in CIN. An optical atto-cell [1] can be realized by installing multiple LEDs which act as an access point (AP) in the ceiling of a room. Handover techniques can help MT to select the most suitable AP to guarantee seamless wireless service when a MS is on the edge of the coverage region of an AP.

In CIN, users covered by APs within illumination region are not necessarily covered within communication region and vice versa. The existence of co-channel interference (CCI) in adjacent cells degrades the signal to interference plus noise ratio (SINR) available to a cell-edge user. This significantly affects seamless wireless service and leads to high outage probability. Furthermore, it is important that the desired illumination should be provided when fulfilling communication requirements. Therefore, maximizing the effective cellular coverage of communication and illumination is required in CIN.

Optimal designs of lightings layout are researched for requirements of both illumination and communication. Reference [2] proposes a base station layout support system and provides an appropriate base station layout satisfying all conditions given by a user. The relation between the lightings layout and received power is studied in [3] and a best scheme is proposed to solve the design of lightings layout. Using a multi-objective optimization method for a VLC system [4], the parameters are determined to get an optimal performance in respect of maximum link quality and minimum power consumption while illumination and other constraints are all satisfied. The lightings layout proposed by [2]-[4] is applied to the condition that all the lights in the system work as one AP and the total received power is the sum of the received power from each light. In cellular networks, the simplest approaches to mitigate CCI are frequency partitioning. In [1], the concept of multi-point joint transmission (JT) is adapted to a VLC cellular network to improve cell-edge user SINR. It proposes two frequency-reuse plans to achieve seamless coverage, high data rate and multiple access. Reference [5] uses cell

Manuscript received August 15, 2014; revised November 26, 2014.
This work was supported by the China National "863" Program under Grant 2013AA013603.
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doi:10.12720/jcm.9.11.891-898

zooming method to improved traffic distribution in multi-user environments. The coverage variability is shown when system is static resource partitioning system with a reuse factor of four and capable of dynamically changing their signal power. A busy-burst-based self-organized interference coordination technique is proposed in [6]. It uses the uplink signal to acquire channel information and applies a dynamic interference-aware resource allocation scheme.

However, frequency partitioning decreases available bandwidth in each cell, which limits the user data rate, and increases the complexity of the VLC system. In CIN, the AP coverage area of communication and illumination region depends on the parameters of LEDs, like LED semi-angle at half-power, LED height, distances between APs, etc. Through adjusting those parameters, it is possible to minimize the CCI in adjacent cells to satisfy communication requirements as well as illumination requirements without frequency partitioning. The contribution of this work is first to optimize the cellular coverage using the same frequency resources in CIN.

The remainder of the paper is organized as follows. Section II describes the system models. Section III describes optimization problem in CIN. Section IV analyses and presents the simulation discussions and optimization results. Section V compared the performance with the state-of-the-art solutions. Finally, the paper is concluded in section VI.

II. System Model

The system of interest is deployed in a large indoor environment. The entire coverage area is divided into N cells with circular shape. Since a single LED cannot provide sufficient optical power for communication or illumination, an array of LEDs are equipped to an AP below the ceiling of room and work as a large LED. The system performance is evaluated at desktop above the floor in a horizontal plane containing the users' optical receiver photo diode (PD).

A. Illumination

The illuminance expresses the brightness of an illuminated surface. An illuminance E at point *(x,y)* at the receiver plane from a LED to a PD detector is given by [7]

$$E = \frac{I(0)}{D^2}\cos^m(\phi)\cos(\psi) \tag{1}$$

where $I(0)$ is the center luminous intensity of an LED, ϕ is the angle of irradiance, ψ is the angle of incidence, and D represents the distance between the LED and the PD detector, m is the Lambertian emission order, which is related to the LED semi-angle at half-power $\Phi_{1/2}$ by $m = \ln 2/\ln(\cos\Phi_{1/2})$. The total illuminance at point *(x,y)* in room with N APs is expressed as

$$E_T = \sum_{i=1}^{N} E_i \tag{2}$$

Generally, the desired illuminance in indoor environment is 100 lx to 500 lx standardized by GB 50034-2004 in China.

B. Optical Channel

Considering only the line-of-sight (LOS) signal path from each LED, the optical channel DC gain from a LED to a PD detector is given by [8]

$$H(0) = \frac{(m+1)A}{2\pi D^2}\cos^m(\phi)T_S(\psi)\,\mathrm{g}(\psi)\cos(\psi) \tag{3}$$

where A is the physical area of the PD detector, $T_S(\psi)$ is the gain of an optical filter which is assumed to be 1 in this paper, $\mathrm{g}(\psi)$ is the gain of an optical concentrator, and other variables in this equation have the same meaning with the ones in Eq. (1). The optical concentrator can be given as

$$\mathrm{g}(\psi) = \begin{cases} \dfrac{n^2}{\sin^2\Psi_c}, & 0 \le \psi \le \Psi_c \\ 0, & 0 \ge \Psi_c \end{cases} \tag{4}$$

where n represents the refractive index and Ψ_c denotes the receiver field of view (FOV).

The received optical power P_r is derived by the transmitted optical power P_t as follow

$$P_r = P_t \cdot H(0) \tag{5}$$

C. SINR

SINR is the relative metric of interest when considering CCI in adjacent cells, which use the same frequency resources, and is defined as

$$SINR = \frac{(rP_{t,x}H_x(0))^2}{(\sum_{i\neq x} rP_{t,i}H_i(0))^2 + n_0 W} \tag{6}$$

where r is the reflectance factor of PD, x represents the associated AP and $P_{t,x}H_x(0)$ is the received power from the associated AP, $P_{t,i}H_i(0)$ is the received power from the ith interfering AP, W denotes the LED nodulation bandwidth and n_0 is the noise power spectral density of shot noise. The shot noise stemming from ambient light is assumed to be the dominant noise contribution.

Considering a channel with NRZ On-Off Key (OOK) modulation, bit-error rate (BER) of the channel is defined as $BER = Q(\sqrt{SINR})$, where $Q(\mathrm{x}) = 1/\sqrt{2\pi}\int_x^{\infty} e^{-y^2/2}dy$.

The required BER for communication is at least 10^{-3}. To achieve $BER = 10^{-3}$ it requires $SNIR = 9.8\mathrm{dB}$ in the OOK modulation. As a result, a received optical power of $SNIR = 9.8\mathrm{dB}$ is required for a basic communication link.

In this paper, the downlink capacity is computed using the Shannon-Hartley theorem:

$$C = \sum B \log_2(1 + SINR_k) \tag{7}$$

III. Coverage Problem Formulation

In CIN, the point at which its illuminance meets the illumination requirement is not always the one at where its SINR meets the communication requirement and vice versa. A room, whose size is $5m \times 5m \times 3m$, is installed 4 APs using the same frequency resources at the height of 2.5m from the floor, and the space between APs is 2.5m. Different cases are obtained when simulating with different LED parameters.

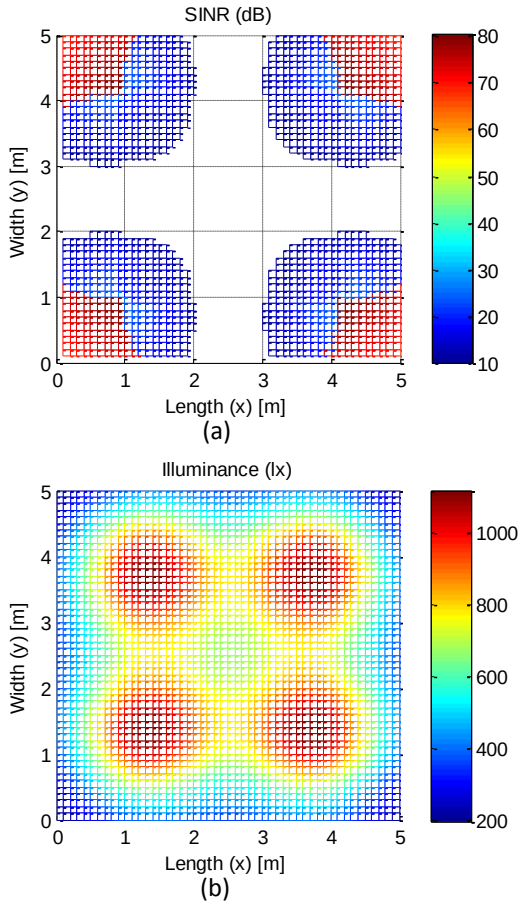

Fig. 1. Comparison of SINR (a) and illuminance (b) distribution for the case of fulfilling illumination but being failed to communication when the LED semi-angle at half-power is 50°

Fig. 1 shows the case of fulfilling illumination but being failed to communication. The minimum illuminance of the entire room is higher than 200 lx, but it is not able to communication with low SINR in the middle of the room because of the CCI between the APs. However, the contrary case is presented in Fig. 2. At the corner of the room, SINR is about 60 dB but the illuminance is lower than 100 lx.

The set of points whose SINR is lower than 9.8 dB is named as communication dead zone (CDZ) and the set of points whose illuminance is lower than 100 lx is called illumination dead zone (IDZ). In order to achieve seamless coverage of the communication and illumination, the area of IDZ and CDZ should be minimized. The area of the IDZ and CDZ is related to the overlap area between adjacent cells. And the parameters we can set to influence each cell coverage size include transmitted optical power P_t, the LED semi-angle at half-power $\Phi_{1/2}$, the LED height h, FOV Ψ_c, distances between APs d according to (2), (6). The combination of those parameters makes an influence to values of P_r and E, the receiving range of a PD detector and the overlap areas of APs. Since varying all those parameters has the similar effect to the result and brings more complicated, $\Phi_{1/2}$ and h is optimized and other parameters are fixed in this paper.

Consequently, the cellular optimization goal is defined as two objective formulations which is given by

$$\begin{cases} \min(1 - \iint f(x,y)dxdy \Big/ \iint dxdy) \\ \min(1 - \iint g(x,y)dxdy \Big/ \iint dxdy) \end{cases} \tag{8}$$

where

$$f(x,y) = \begin{cases} 1, & SINR(x,y) \geq 9.8 \\ 0, & SINR(x,y) < 9.8 \end{cases} \tag{9}$$

$$g(x,y) = \begin{cases} 1, & E_T(x,y) \geq 100 \\ 0, & E_T(x,y) < 100 \end{cases} \tag{10}$$

where The SINR and illuminance at point (x,y) is represented by $SINR(x,y)$ and $E_T(x,y)$ according to (6) and (2), respectively.

The constraint formulations, which are related to the range of the variables in the objective formulations, are given in section IV.

IV. Optimization and Simulation

Some system specific properties support the implementation of the coverage optimization: 1) all LEDs share the same frequency resources; 2) there is no fading effect in IM/DD systems and an OOK modulation is used; 3) Only the LOS path is significant and considered.

The investigated network scenario is deployed in a $12m \times 12m \times 3m$ office room with 9 APs. For simplicity, the APs are symmetrically distributed as well as the corresponding parameters of the LEDs. Each AP is filled with 3600 LEDs. It is assumed that MTs with a PD detector are located 0.85 m above the floor, and all PDs are facing upward towards the ceiling. All LEDs have the same average optical transmit power. Table I outlines the key simulation parameters. In order to optimize the distribution of SINR and illuminance, $\Phi_{1/2}$ and h are the parameters we can control to enhance the system performance.

The working mechanism of the system involves the following basic steps: 1) the position of the desired MTs

is picked inside the room area with a traversal behavior; 2) the distances and received powers from each AP to the desired MT are calculated; 3) the desired MT selects the AP providing the strongest signal as serving AP and selects other APs as interfering APs; 4) the SINR and the illuminance of the desired MT are estimated according to (6) and (2) respectively.

TABLE I. SIMULATION PARAMETERS

LEDs optical power	P_t	20 mW
LED modulation bandwidth	W	20 MHz
PD physical area	A	1.0 cm^2
FOV	Ψ_c	60°
refractive index of a lens at a PD	n	1.5
gain of an optical filter	$T_S(\psi)$	1.0
PD responsivity	r	0.54 A/W
Noise power spectral density,	n_0	10^{-21} A^2/Hz
LED center luminous intensity	$I(0)$	0.73 cd

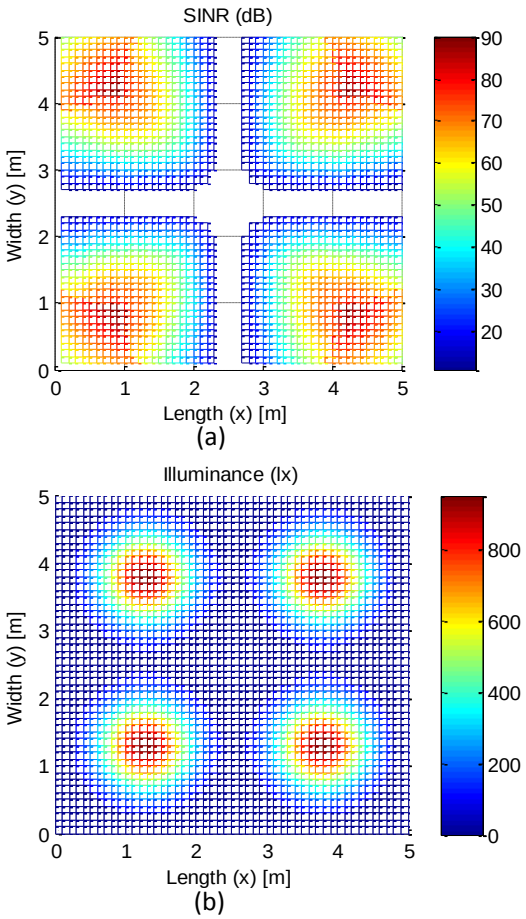

Fig. 2. Comparison of SINR (a) and illuminance (b) distribution for the case of keeping communication but being failed to illumination when the LED semi-angle at half-power is 20°

A. AP Arrangements

There are two basic AP arrangements, lattice and hexagon structures, as shown in Fig. 3. The projection of an AP on the ground can be regarded as a circle. AP is installed in the center of the circles, and the radius of the circles depends on the receiving range of PD detector, whose value is 2.8 m when $h = 2.5m$ and $\Psi_c = 60^\circ$. For the maximum receiving range and the symmetrical AP arrangements, the distance between APs is 3 m. The lattice structure is simple, but the hexagon structure is used to approximate a circle in communication systems.

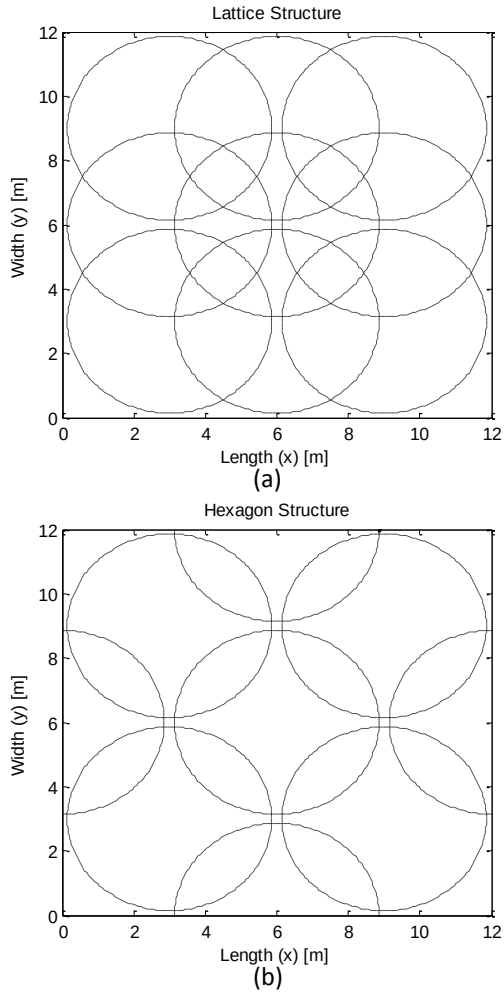

Fig. 3. Two basic AP arrangements: (a) lattice structure; (b) hexagon structure

Fig. 4 shows the comparison of the SINR distribution between lattice and hexagon structures in the room, when the $\Phi_{1/2} = 70^\circ$ and $h = 2.5m$. All LEDs have the same semi-angle at half-power. The white areas in the figure represent the CDZ area. Fig. 5 presents the cumulative distribution function (CDF) of the SINRs in two structures. The communication conditions are fulfilled for about 52% of the room area for lattice structure. However, a 21% improvement is shown by hexagon structure compared to lattice structure. Meanwhile, the illumination conditions are fulfilled for about 95% and 96% of the room area for lattice and hexagon structures, respectively.

The effective areas of communication and illumination are compared between lattice and hexagon structures

when $\Phi_{1/2}$s have different values in Table II. The effective communication areas of hexagon structure are larger than the ones of lattice structure no matter what value the $\Phi_{1/2}$ is. The effective illumination areas of hexagon are larger only when $\Phi_{1/2}$ is big, but when the value of $\Phi_{1/2}$ is lower than 50, the area for effective illumination is too small to illuminate. Obviously, the hexagon structure has a better performance in communication when fulfilling the illumination conditions and is more suitable for CIN, when using the same number of APs.

TABLE II. COMPARISON OF EFFECTIVE AREAS

$\Phi_{1/2}$	Effective Communication		Effective Illumination	
	Lattice	Hexagon	Lattice	Hexagon
70°	52%	64%	95%	96%
50°	59%	68%	76%	86%
30°	70%	76%	49%	33%
15°	59%	60%	11%	8%

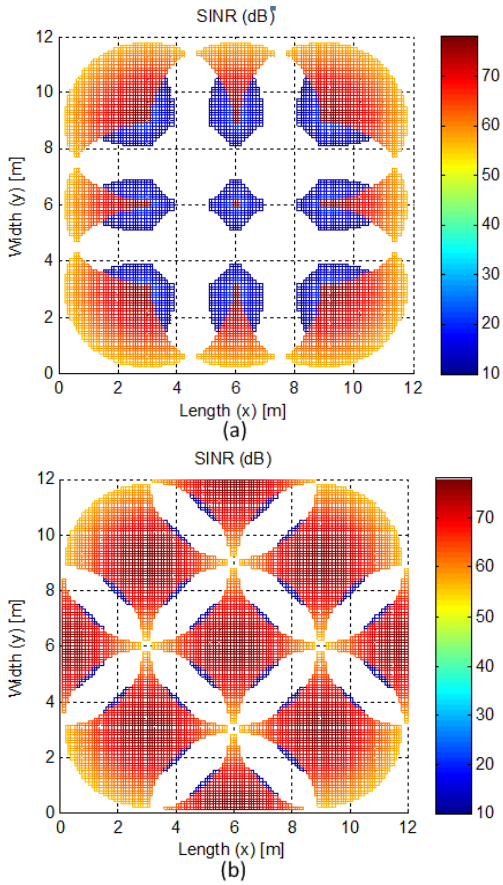

Fig. 4. The comparison of the SINR distribution between (a) lattice and (b) hexagon structures

B. LED Parameters Optimizaition

The hexagon structure is used for the AP arrangements according to above discussion. The system can be optimized using (8) (9) (10). The optimization problem is multi-objectives and multi-variable and variables have a large number of possible combinations. The Multi-objective Optimization using Genetic Algorithm Toolbox in MATLAB 7.11.0 is selected for solving this optimization problem. A genetic algorithm (GA) is a search heuristic and is routinely used to generate useful solutions to optimization and search problems. The optimized parameters include semi-angles at half-power and heights of the 9 APs.

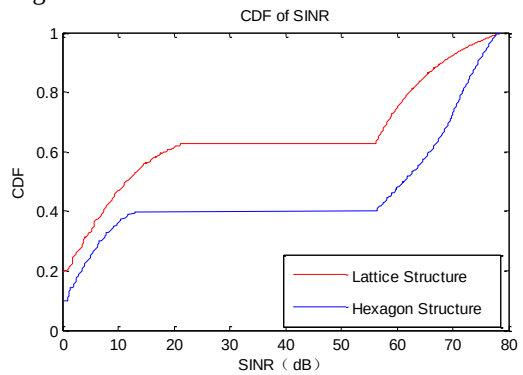

Fig. 5. Cumulative distribution function of SINRs

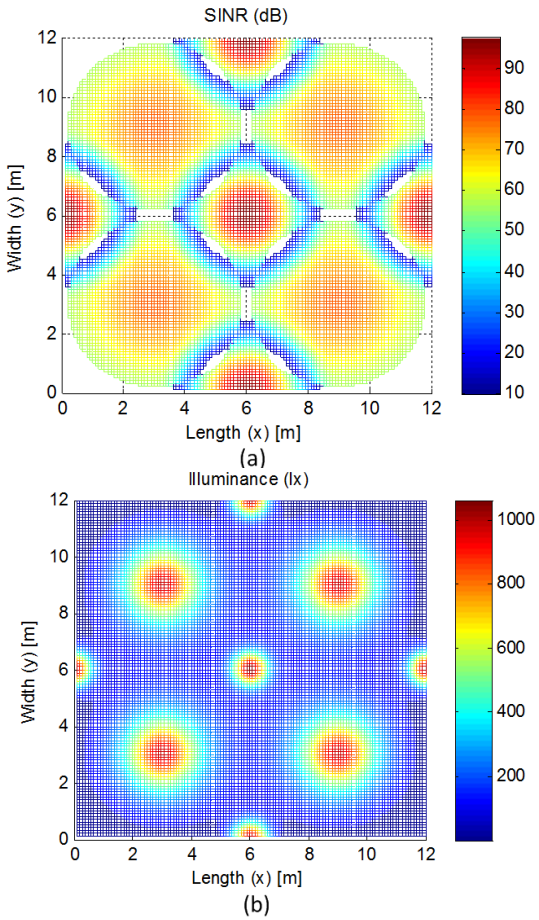

Fig. 6. SINR (a) and illuminance (b) distribution after semi-angles at half-power optimization

For simplify the algorithm, semi-angles at half-power are optimized first when all LED heights are 2.5 m. There are 9 inputs for GA, and the range of $\Phi_{1/2}$ is from 15 to 70. Seven linear equalities constraints are built for symmetrical AP arrangements, which mean the four corner APs have the same parameters and so do the other five APs. The results of the first optimization is

$$\Phi_{1/2} = [70,\ 17.4678,\ 70,\ 17.4678,\ 17.4678,\ 17.4678,\ 70,\ 17.4678,\ 70] \quad (11)$$

The effective areas of communication and illumination are more than 90% and 86% of the room, respectively. Fig. 6 shows the distribution of SINR and illuminance under the optimization results. Majority communication and illumination dead zones distribute in the corner of the room, and the areas of the maximum consecutive communication dead zone in the room are less than 0.5 m^2.

Then, the LED heights are optimized when using above optimization results (10) to set $\Phi_{1/2}$ values. There are 9 inputs for GA, and the range of h is from 2.5 to 3 m. The same seven linear equalities constraints are built. The results of LED height optimization is

$$h = [2.5635, 2.5014, 2.5635, 2.5014, 2.5014, 2.5014, 2.5635, 2.5014, 2.5635] \quad (12)$$

The effective area of communication improves about 1% than before while the effective area of illumination has the same value. And the area of the dead zones in the four corners is about 5% of the room, where user's movement may be inactive. Fig. 7 shows the SINR CDF comparisons of different cases. After heights optimization, about 75% communication coverage improvement is achieved when SINR is equal to 9.8 dB, compared to the case of $\Phi_{1/2} = 70^{\circ}$ and $h = 2.5m$.

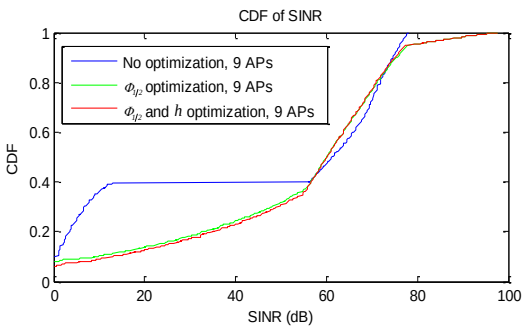

Fig. 7. SINR CDF comparisons

If four more APs are installed in the corner, the SINR and illuminance distributions are shown in Fig. 8. The effective areas of communication and illumination are more than 96% and 90% of the room, respectively. Since the width of the consecutive communication dead zones is less than 0.5 m, users can communicate continuously in the dead zone through moving his hand with a small distance. Further, the illumination dead zones distribute at the room edges. As a result, the communication and illumination can be approximate seamless coverage in CIN.

V. Comparisons and Discussion

The optimized system in this paper is compared against frequency partitioning systems with multi-point joint transmission [1]. In order to guarantee fair comparisons, the simulation parameters for them are the same as listing before, and the number of APs installed in systems is 13.

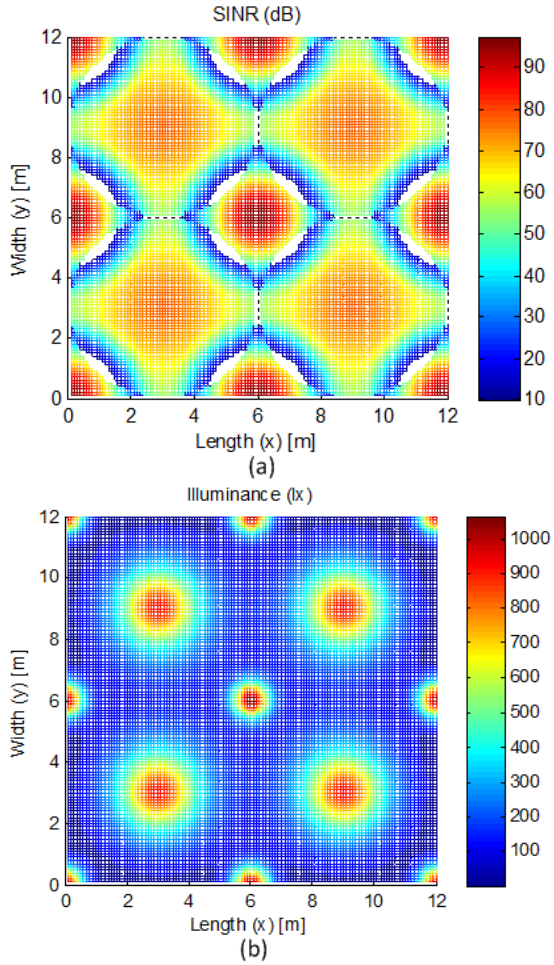

Fig. 8. SINR (a) illuminance (b) distribution after semi-angles at half-power and height optimization

A. Received SINR

The CDF of the SINRs in different systems are presented in Fig. 9. The more than 90% areas of the room benefit from illumination for each system. However, Due to the lack of interference mitigation between adjacent JT regions, the benchmark JT1 system achieves the worst SINRs. Approximate 20% areas in the room are communication dead zone for the JT1 system. In the JT2 system, the same frequency band is not reused in adjacent JT regions. Therefore, this system has little position whose SINR values below 9.8 dB. In contrast, the full frequency system optimized in this paper has similar effective area of communication (more than 96%) in the room. The proposed system exhibits about 30 dB and 15 dB improvement, in terms of median SINR relative to JT1 and JT2 system, respectively, because transmission on one subcarrier uses only less than half number of LEDs on an AP in JT systems.

B. Downlink Throughput

Fig. 10 shows the CDF of the downlink system throughput in different systems. The system throughput is defined as the aggregate data rate in the given cell. The JT1 and JT2 achieve similar median system throughput of

200Mbps. Because of a stronger robustness to CCI, the lowest throughput for the JT2 system is higher than the JT1 system. However, the proposed system shows a higher median system capacity of about 400Mbps using the same frequency resource in CIN. This number is 100% higher than the system throughput achieved by the benchmark system, and the effective areas of communication and illumination have approximate performance to JT systems at the same time.

C. Complexity Analysis

In order to achieve seamless coverage of communication and illumination without frequency partitioning in CIN, the solution proposed by this paper is to optimization the layout of LEDs. As a result, the complexity of the solution focuses to the layout optimization.

The GA is adopted for the optimization. In GA, the amount of calculation is used for the calculation of fitness scaling, which is solving the function of SINR in this paper. If the amount of calculation is measured by the amount of multiplication operation, it is expressed as

$$W = Popsize \times Maxepoch \times (M^2 \times N \times \log_2 N) \quad (13)$$

where *Popsize* is population size, *Maxepoch* notes the total number of generations, $(M^2 \times N \times \log_2 N)$ is the amount of multiplication operation need by one SINR distribution function with N semi-angles at half power and M^2 position points.

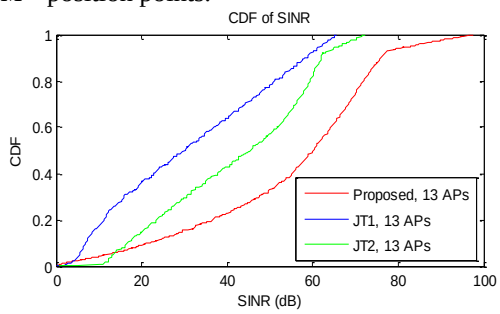

Fig. 9. CDF comparisons of SINR

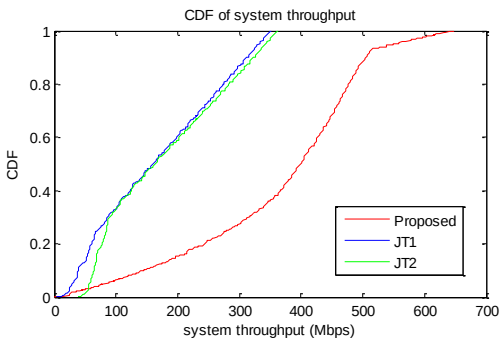

Fig. 10. CDF comparison of system throughput

After optimization, the LEDs can be selected and installed as the optimization results. All the LEDs communicate with the same frequency resource. Simple modulation mode, like OOK, and common handover algorithms can be used in this cellular network directly. By contrast, the solution used by JT systems focus to frequency allocation at different position. The LEDs of the JT systems are necessary to be installed with a special structure. An OFDM-based modulation is used which is more complex than OOK modulation in front end circuit of LED. The system execution refers to the corporations of uplink channel, and the handover, which may happen in one cell, can be more frequent than other systems. Consequently, the system complexity of the proposed system is lower than the benchmark system.

VI. Conclusions

This paper investigates the communication and illumination coverage in VLC and addressed multi-variable optimization in CIN when the same frequency resources are shared by APs. The result shows that the coverage of the communication and illumination can be approximate seamless coverage through optimizing LED arrangements, semi-angles at half-power and heights in CIN. About 75% communication coverage improvement is achieved under assumed room condition when illumination requirement is fulfilled. Compared with frequency partitioning systems, the proposed solution achieves approximate performance on communication and illumination coverage, while higher downlink system throughput and lower system complexity.

Tasking also into consideration the fact that LED position, modulation methods and handover algorithms continue to improve for VLC cellular network.

Acknowledgment

The authors wish to thank Dr. J.P. Du and Dr. Y.Y. Zhang for valuable comments and a fruitful discussion. This work was supported in part by a grant 2013AA013603 of the China National “863” Program.

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