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Visible Light Wireless Data Center Links with Distinct Beam Configurations

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Abstract. Visible light communication (VLC) is being explored as one promising approach to enable wireless data centers (WDC). Up to now, the visible light wireless data center links are still limited to the conventional Lambertian beam paradigm. The potential coverage gain relevant to the optical beam space is waiting for sufficient investigation. For addressing this issue, in this paper, the dynamic optical beam based WDC coverage enhancement scheme is introduced, and for each transmitter, the best candidate asymmetrical optical beam is selected to load the data signal. Numerical evaluation shows that, compared with the conventional static beam configuration, up to 6.76 dB peak signal to noise ratio (SNR) gain and 4.46 dB average SNR gain could be provided by the proposed dynamic beam scheme. Moreover, this SNR dynamic range is reduced to 36.65 dB while the counterpart of the static non-Lambertian beam configuration is up to 44.78 dB.

Keywords. Wireless data center, visible light communications, beam effect, non-Lambertian optical beams, wireless link characteristics

1. Introduction

Computation-intensive applications are pushing existing access networks and data center networks (DCN) to their performance limits. Conventional DCN with wired links and finite network interfaces, limit the possible topologies and could result into development and design issues relevant to heat dissipation, power consumption and maintenance [1-4]. Simultaneously, the increasingly emerging disadvantages of wired DCN include overwhelming cabling cost and cost, flexibility lack to tackle the traffic outbursts [5-8]. Thanks to the scalability, flexibility and energy efficiency of emerging visible light communication (VLC) techniques, it has recently attracted attention and could be employed in future-oriented wireless data centers (WDC) to address the cabling complexity, capital expenditures and other inherent restrictions of wired DCN [5-8].

To date, impressive potential performance has been identified for VLC-based WDC via angle diversity receiver, imaging receiver in typical data center scenario [2].

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Moreover, one wavelength division multiple access scheme is also proposed to enhance the transmission capacity of the visible light WDC links [1]. Nevertheless, all above visible light link configurations remain constrained in the sufficiently discussed Lambertian optical source beam pattern [4-10]. Actually, the potential design and optimization exploration via distinct non-Lambertian beams is still absent in the investigation of visible light WDC links.

Based on the above review, the typical non-Lambertian beams are adopted to construct the WDC VLC transmitter. The basic methodology of this design is to dynamically select non-Lambertian beam in order to provide more focused transmission performance. This scheme smartly utilize the radiation pattern of the commercially available LED optical sources without inducing the increase of the whole emitted optical power and the available optical transmitter location resource.

In this paper, the visible light WDC links with static and dynamic beam configuration are presented in Section II. And link performance metric are discussed in Section III. Numerical evaluation is presented in Section IV. Finally, the Section V concludes this paper.

2. Visible Light Wireless Data Center Link Design

To a large extent, the VLC link gain and coverage characteristic are influenced by the optical beam pattern of light emitting diodes (LED) in the involved transmitters. As a matter of fact, the distinct beam patterns objectively provide one novel design space for visible light WDC link performance.

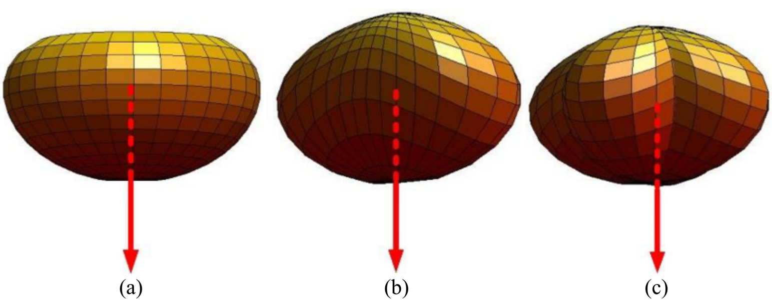


Figure 1.3D radiation pattern of (a) conventional Lambertian optical beam, (b) typical non-Lambertian optical beam and (c) dynamic beam configuration with two candidate non-Lambertian optical beams.

2.1. Link with Non-Lambertian Beam Configuration

Unlike the generalized Lambertian beam, the spatial radiation characteristic of the non-Lambertian beam could be dependent on the azimuth and elevation angle of the emission direction simultaneously [10].

Typically, this paperdiscusses the non-Lambertian beam pattern of commercially available NSPW345CS Nichia LEDs. The respective radiation intensity could be given by [10]:

$$I_{\mathrm{NSPW}}(\phi,\alpha+\Delta\alpha)=\sum_{i=1}^{2} g1_i \exp\left[-(\mathrm{In}2)(|\phi|-g2_i)^2\left(\frac{\cos^2(\alpha+\Delta\alpha)}{(g3_i)^2}+\frac{\sin^2(\alpha+\Delta\alpha)}{(g4_i)^2}\right)\right] \quad (1)$$

where a is the azimuth angle within the source plane. Specifically, the values of coefficients in this expression are: $g1_1$ = 0.13, $g2_1$ = 45°, $g3_1$ = $g4_1$ =18°, $g1_2$ =1, $g2_2$ =0, $g3_2$ =38° and $g4_2$ =22°. From the sideview angles, $\mathrm{D}a$ denotes the original azimuth offset and equal 90° in this static configuration. Fig. 1 show the 3D beam pattern of this non-Lambertian optical beam and red arrow presents the normal direction of the optical source. Accordingly, the channel gain expression must be renewed and given as:

$$H(S^{\mathrm{NSPW}},R)=\begin{cases}\dfrac{A_R I_{\mathrm{NSPW}}(\phi,\alpha+\Delta\alpha)}{P_{\mathrm{norm}} d_0^{\,2}}\cos\theta_0 G_{\mathrm{of}} G_{\mathrm{oc}}, & 0\le\theta_0\le\theta_{FOV}\\ 0, & \theta_0>\theta_{FOV}\end{cases} \quad (2)$$

where P_{norm} denotes the power normalization factor of this non-Lambertian beam, to ensure that the emission power accumulation in all spatial directions equals 1W.

2.2. Link with Dynamic Beam Configuration

In the proposed dynamic WDC beam configuration scheme, the transmitter include two mentioned NSPW345CS Nichia candidate beams with different original azimuth offset. For the ith candidate beam, the respective radiation intensity could be given by

$$\begin{aligned}&I_{\mathrm{NSPW}}(\phi,\alpha+\Delta\alpha_k)\\&=\sum_{i=1}^{2} g1_i \exp\left[-(\mathrm{In}2)(|\phi|-g2_i)^2\left(\frac{\cos^2(\alpha_0+\Delta\alpha_i)}{(g3_i)^2}+\frac{\sin^2(\alpha_0+\Delta\alpha_i)}{(g4_i)^2}\right)\right]\end{aligned} \quad (3)$$

where $\mathrm{D}a_k$ is the azimuth offset of the *k*th candidate beam. In this work, for clearity, the specific offset value is set as 45° and 135° to both beams, respectively.

It should be noted that, the signal is merely loaded to one selected beam, and for the left candidate beam in each transmitter, only direct current is set to drive the sources lighting, such that the fundamental luminaire function of the optical sources is not affected by the proposed dynamic configuration.

Similar to equation (2), for one receiver on the data center racks top, the visible light line of sight channel gain between the selected beam and the receiver could be given as:

$$H(S_{\mathrm{Beam}}^{\mathrm{NSPW}},R,\Delta\alpha_k)=\begin{cases}\dfrac{A_R I_{\mathrm{NSPW}}(\phi_0,\alpha_0+\Delta\alpha_k)}{d_0^{\,2}}\cos\theta_0 G_{\mathrm{of}} G_{\mathrm{oc}}, & 0\le\theta_0\le\theta_{FOV}\\ 0, & \theta_0\ge\theta_{FOV}\end{cases} \quad (4)$$

For clarity, Fig. 1 describe the potential 3D radiation pattern including two candidate beams.

3. Link Performance Metric

In this paper, at the receiver end, signal to noise ratio (SNR) is utilized as the link performance key metric to numerically compare the conventional and proposed dynamic configuration scheme. As for the discussed static non-Lambertian beam configuration, the SNR could be given by:

$$\mathrm{SNR}_{\mathrm{NSPW}} = \frac{\left(P_{\mathrm{T}}\sum_{j=1}^{\mathrm{N}} H(S_j^{\mathrm{NSPW}}, R)r\right)^2 F_{\mathrm{OE}}}{\delta^2} \tag{5}$$

where r is the PD responsivity, P_{T} is the emitted optical power, $H(S_j^{\mathrm{NSPW}}, R)$ is the optical channel gain between the $j$thNSPW345CS Nichia non-Lambertian source S_j^{NSPW} and the receiver R, N is the amount of the visible light transmitter, F_{OE} is optical - electrical conversion faxtor, and δ^2denotes the additive noise variance at the receiver. Accordingly, this noise variance at the receiver could be given by [9, 14]:

$$\delta^2 = 2qI_{\mathrm{bg}}B + \frac{4K_{\mathrm{b}}TB}{R_{\mathrm{f}}} \tag{6}$$

where q is the electronic charge, I_{bg} is the background light current, K_{b} is Boltzmann constant, T isthe absolute temperature, B is modulation bandwidth and R_{f} is the feedback resistance of transimpedance amplifier (TIA) of the visible light receiver.

As for the proposed dynamic beam configuration scheme, in each visible light transmitter, assuming the channel state information (CSI) of the receiver is perfectly known to the transmitters. The candidate optical beam that could provide the best coverage SNR, is dynamically selected to transmit the information signal. For the jth visible light transmitter, the estimation of the selected candidate beam index k could be identified as:

$$\hat{k} = \arg\max_{k\in\mathrm{K}} \left[H(S_{jk}^{\mathrm{NSPW}}, R, \Delta\alpha_{jk})\right]^+ \tag{7}$$

where $\mathrm{D}\alpha_{jk}$ is the azimuth offset of the kth candidate beam in the jth transmitter, K is the amount of candidate optical beams. Such that, the SNR expression for this dynamic beam scheme can be given by:

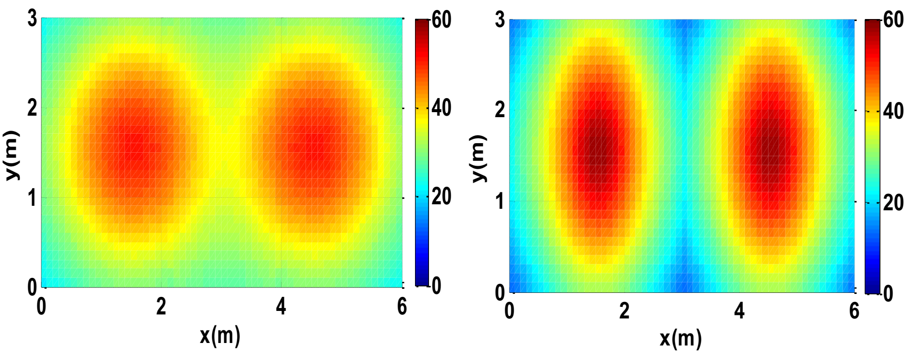
$$\mathrm{SNR}_{\mathrm{dyna}} = \frac{\left(P_{\mathrm{T}}\sum_{j=1}^{\mathrm{N}} H(S_{j\hat{k}}^{\mathrm{NSPW}}, R, \Delta\alpha_{j\hat{k}})r\right)^2 F_{\mathrm{OE}}}{\delta^2} \tag{8}$$

4. Numerical Evaluation

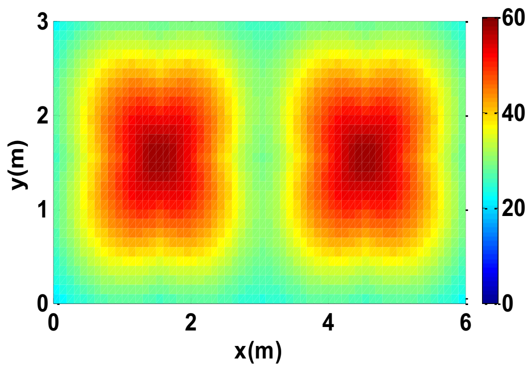
In this section, the numerical evaluation is made between the conventional static optical beam configuration and dynamic optical beam configuration in visible light WDC link performance. Specifically, one typical data center scenario is considered. In envisioned WDC scenario with two transmitters, the receivers are located on the top of the WDC racks, such that the height of receiver working plane equals to 2 m. In addition, the main parameters are presented in Table 1.

Table 1. The main parameters configuration

Parameters	Values	Parameters	Values
Room size (W×L×H)	3 ×6 ×3 m^3	LED Lambertian index	10.2
Emitted power of each transmitter	14.7 W	Receiver field of view	70°
Amount of VLC transmitters	2	Height of receiving plane	2 m
Boltzmann constant	1.38×10^{-23}	Physical area of PD	1.5 cm2
Electronic charge	1.6022×10^{-19}	Responsivity of PD	0.28 A/W



(a)(b)



(c)

Figure 2.SNR spatial distribution in envisioned wireless data center scenario of (a) Lambertian beam configuration; (b) typical non-Lambertian beam configuration; (c) dynamic non-Lambertian beam configurationand (d) respective cumulative distribution function.

In Fig. 2, the SNR spatial distribution in envisioned visible light WDC scenario is illustrated for conventional Lambertian beam configuration, typical non-Lambertian beam configuration and dynamic non-Lambertian beam configuration, respectively. In the first case, the SNR range between 21.56 and 51.18 dB while the average SNR is about 41.72 dB. As for the non-Lambertian beam configuration, the average SNR is increased to 45.21 dB while the dynamic range is varied to between 13.16 and 57.94 dB. Moreover, when the dynamic non-Lambertian beam configuration is adopted, the average SNR is further recovered to 46.18 dB. And the respective dynamic range lies between 21.29 and 57.94 dB. Accordingly, the cumulative distribution function of SNR spatial distribution is shown in Fig. 3.

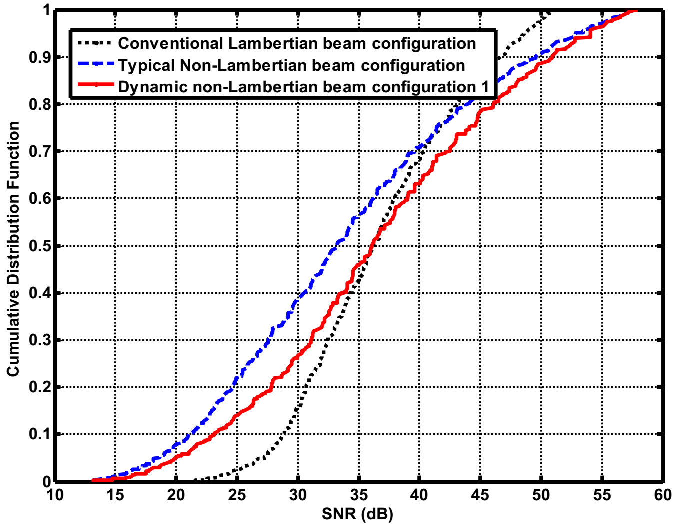


Figure3. Cumulative distribution function of SNR spatial distribution.

For the dynamic configuration, the percentage of SNR less than 30 dB is kept to about 23.74%, while the counterpart of the static Lambertian link configuration and the static non-Lambertian link configuration is 15.76% and 38.97%, respectively. Moreover, this peak SNR will be further up to 57.94 dB from the original 51.18 dB of the Lambertian link configuration, up to 6.76 dB peak SNR gain could be provided by the proposed dynamic beam scheme.

5. Conclusion

One wireless data center link design that utilize distinct optical beam configurations for downlink communications is proposed in this paper. This dynamic beam scheme is motivated by potential optical beam space, to provide coverage flexibility. The proposed dynamic scheme could take the peak SNR, fluctuation range into consideration simultaneously. For the dynamic configuration, the percentage of SNR less than 30 dB is reduced to about 23.74%, while the counterpart of the static non-Lambertian link configuration is more than 38.97%. Moreover, this peak SNR will be further up to 57.94 dB from the original 51.18 dB of the Lambertian link configuration.

Acknowledgments

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References

[1] O. Z. Alsulami, S. O. M. Saeed, S. H. Mohamed, T. E. H. El-Gorashi, M. T. Alresheedi and J. M. H. Elmirghani, "Data Centre Optical Wireless Downlink with WDM and Multi-Access Point Support," 2020 22nd International Conference on Transparent Optical Networks (ICTON), 2020, pp. 1-5.

[2] O. Z. Alsulami, M. O. I. Musa, M. T. Alresheedi and J. M. H. Elmirghani, "Visible Light Optical Data Centre Links," 2019 21st International Conference on Transparent Optical Networks (ICTON), 2019, pp. 1-5.

[3] M. Kavehrad, "Reconfigurable optical wireless applications in data centers," 2016 IEEE Photonics Society Summer Topical Meeting Series (SUM), 2016, pp. 6-7.

[4] Kupferman, J,S. Arnon. "Energy saving for data centers using spatial multichannel optical wireless communication." Journal of Communications & Information Networks, vol. 2, no. 2, pp. 88-99, 2017.

[5] Abdulkadir C, Basem S, and Mohamed-Slim Alouini "Optical wireless data center networks: potentials, limitations, and prospects", Proc. SPIE 10945, Broadband Access Communication Technologies XIII,2019, pp.109450I.

[6] Shlomi A "Review of optical wireless communications for data centers ", Proc. SPIE 10437, Advanced Free-Space Optical Communication Techniques and Applications III, 2017, pp.1043703.

[7] E. CalvaneseStrinati et al., “6G: the next frontier: from holographic messaging to artificial intelligence using subterahertz and visible light communication,” IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 42-50, Sept. 2019.

[8] T. Komine, M. Nakagawa, “Fundamental analysis for visible-light communication system using LED lights,” IEEE Transactions on Consumer Electronics, vol. 50, no. 1, pp. 100-107, 2004.

[9] J. Ding, Z. Xu and L. Hanzo, "Accuracy of the Point-Source Model of a Multi-LED Array in High-Speed Visible Light Communication Channel Characterization," in IEEE Photonics Journal, vol. 7, no. 4, pp. 1-14, Aug. 2015.

[10] I. Moreno, C. Sun, “Modeling the radiation pattern of LEDs,” Optics Express, vol. 16, no. 3, pp. 1808-1819, 2008.