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Authors(s)	Wu, Xiping, Nag, Avishek, Jin, Xianqing
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On Adaptive Network Deployment for Visible Light Communications

Xiping Wu[1,2], Avishek Nag[1,2] and Xianqing Jin[3]

[1] *School of Electrical and Electronic Engineering, University College Dublin, Dublin, Ireland*
[2] *Beijing-Dublin International College, University College Dublin, Dublin, Ireland*
[3] *School of Computer Science and Electronic Engineering, Bangor University, Bangor, United Kingdom*
{xiping.wu@ucd.ie, avishek.nag@ucd.ie, x.jin@bangor.ac.uk}

***Abstract*—This work studies adaptive network deployment for visible light communications (VLC), which exploit light wave as signal bearers. In most of the current literature, the VLC user is served by a single access point (AP), called serial transmission. To enhance network flexibility, parallel transmission (PT) was developed for VLC, enabling the user to be served by multiple APs simultaneously. Specifically, each AP consists of different coloured light-emitting diodes (LEDs) and modulates only one of them to mitigate inter-cell interference. The receiver, equipped with wavelength division concentrators, can distinguish signals carried by different wavelengths. To further improve network flexibility, adaptive network deployment is proposed in this paper, by allowing the APs to modulate a dynamic number of LEDs. The adaptive scheme is comprised of three modes of network deployment, and the mode selection is formulated as an optimisation problem to maximise network capacity with proportional fairness. Results show that compared with the original PT method, the new scheme can significantly improve network throughput, especially with an increase of up to 40% for room corner users.**

***Index Terms*—Visible light communications (VLC), parallel transmission, adaptive network deployment**

I. INTRODUCTION

EXPLOITING the visible light spectrum to carry information bits, visible light communication (VLC) has been identified as a key wireless technology for the 6th generation (6G) of mobile communications [1]. While the radio frequency (RF) spectrum is scarce and regulated, the visible light spectrum is huge (about 300 THz) and unregulated. Apart from that, VLC offers a number of advantages over the conventional RF technologies, including: i) provision of illumination, ii) availability in RF-restricted areas, and iii) secure communication. Moreover, VLC can provide high-speed data transmission to help accommodate the constant increase in mobile data traffic. Recent research demonstrates that with off-the-shelf light-emitting diodes (LEDs), VLC is capable of achieving link data rates above 15 Gb/s [2].

With respect to the network level, carrier-sense multiple access with collision avoidance (CSMA/CA) is adopted for VLC in the IEEE 802.11bb and IEEE 802.15.7 standards, to mitigate inter-cell interference (ICI). Alternatively, frequency reuse schemes have also been investigated for VLC. In [3], orthogonal frequencies are employed by neighbouring cells with a frequency reuse factor of 2. The authors in [4] analysed fractional frequency reuse (FFR) for VLC, including strict FFR and soft frequency reuse (SFR). The former approach partitions the cell area into three equal sectors, whereas the SFR method provides a two-tier cellular structure to achieve a higher reuse ratio. In some other papers, e.g. [5], the same frequency is used for all VLC cells, while ICI is suppressed through intelligent access point selection methods.

However, the user is served by a single access point (AP) in most of the current literature on VLC, including the above studies. This is referred to as serial transmission (ST), which is restricted by the conventional transmission control protocol (TCP). As a result, the user can only access the resources of one AP, limiting the capability of load balancing. Since 2013, the Internet Engineering Task Force (IETF) has been working on multipath TCP (MPTCP) [6], which enables the user to be served by multiple APs at the same time. The data traffic for one user is split among its host APs, leading to a more flexible way of load balancing. Based on MPTCP, a parallel transmission (PT) scheme was proposed for VLC for the first time in [7]. With this scheme, each AP contains 4 different coloured LEDs and modulates only one of them to offer a frequency reuse factor of 4. The user can receive and distinguish the signals sent by different APs, with the help of wavelength division concentrators. Results show that the PT scheme is able to improve network throughput by up to 150% over the conventional ST-VLC systems [7].

The pattern of modulated LEDs is fixed in the original PT scheme, making the system less efficient for crowded users, especially those in the room corners. In this paper, we propose a novel adaptive network deployment (AND) approach for VLC. Unlike the current research in this area focusing on layout optimisation and power control [8], our work introduces a dynamic arrangement of the modulated LEDs in each AP. Specifically, three modes of network deployment are constructed in consideration of ICI mitigation. An optimisation problem is formulated to switch among the modes adaptively. Results show that compared with the original PT scheme, the proposed AND method can greatly improve network throughput, especially by up to 40% for corner users.

The remainder of this paper is organised as follows. The network structure and channel model of VLC are introduced in Section II. The novel AND scheme is proposed in Section III, including its concept, optimisation problem formulation and complexity analysis. Simulation results are presented in Section IV. Finally, conclusions are drawn in Section V.

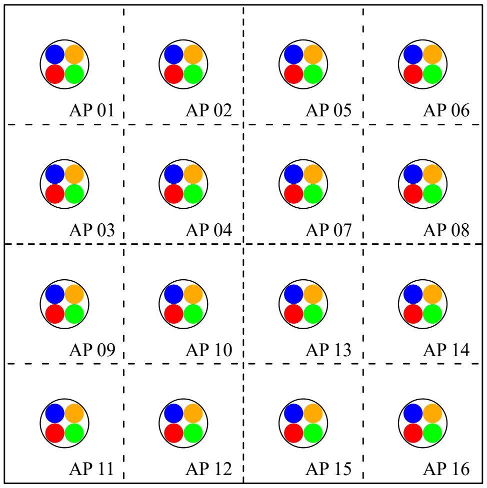


Fig. 1. VLC network structure and AP composition.

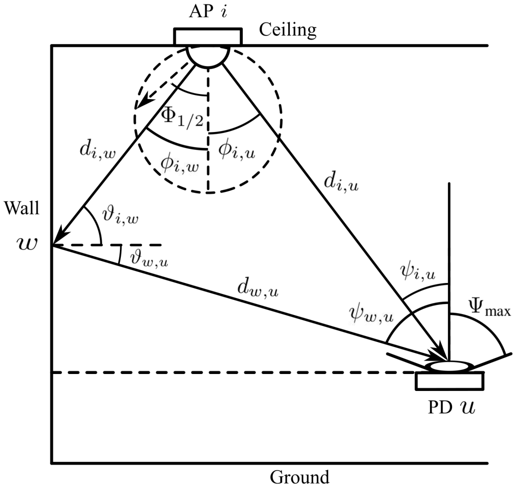


Fig. 2. The LoS and first-order NLoS channels of VLC.

TABLE I
PARAMETERS OF DIFFERENT COLOURED LEDS [7]

Wavelength (nm)	**450**	**500**	**600**	**650**
Luminous efficacy L_{eff} (lm/W)	27	205	340	68
PD responsivity R_{pd} (A/W)	0.15	0.23	0.37	0.44
Intensity percentage ξ	10%	55%	20%	15%
Optical output power P_{out} (W)	9.3	6.7	1.5	5.5
Modulated optical power P_{mod} (W)	3.6	2.3	1.5	1.2

II. SYSTEM MODEL

An indoor VLC network that consists of N_{AP} APs is considered, as demonstrated in Fig. 1. Each AP, which is embedded into a ceiling lamp, is comprised of 4 different coloured LEDs to compose a white light. The LED settings are referred to Table I, including their wavelengths, luminous efficacy, photodiode (PD) responsivity, intensity percentage, optical output power and modulated optical power. It is worth noting that the illuminance is set by the direct current (DC) fed to each LED. As a result, whether the LEDs are used to modulate signals does not affect the illuminance. This enables a flexible selection of the LEDs for data transmission. A number of users are randomly located. Each user can be simultaneously served by multiple APs, and the link between one AP and the user is called a subflow. Each AP can also serve multiple users through time-division multiple access.

The VLC channel is comprised of two components: line-of-sight (LoS) and non line-of-sight (NLoS) paths, as shown in Fig. 2. The Euclidean distance of the LoS path between AP i and user u is denoted by $d_{i,u}$. The channel gain of LoS is given by [9, eq. (10)]:

$$H_{i,u}^{\text{LoS}} = \frac{(m+1)A_{\text{pd}}}{2\pi d_{i,u}^{2}} \cos^{m}(\phi_{i,u}) g_f g_c \cos(\psi_{i,u}), \tag{1}$$

where $m = -\ln 2/\ln(\cos\Phi_{1/2})$ denotes the Lambertian emission order, and $\Phi_{1/2}$ is the angle of half intensity; A_{pd} is the physical area of the PD; $\phi_{i,u}$ denotes the angles of irradiance; and g_f is the optical filter gain.

As for the NLoS paths, only first-order reflections are considered since higher-order reflections typically contribute little [9]. A first-order reflection consists of two segments: a) from the AP to a small area w on the wall, and b) from w to the user. Let $d_{i,w}$ and $d_{w,u}$ denote the Euclidean distances of these segments, respectively. The angles of radiance and incidence with respect to the first segment are $\phi_{i,w}$ and $\vartheta_{i,w}$, and for the second segment they are $\vartheta_{w,u}$ and $\psi_{w,u}$. The area of w is A_w, and the wall reflectivity is ρ_w. The channel gain of NLoS is given by (2) [7, eq. (3)].

The total channel gain is $H_{i,u} = H_{i,u}^{\text{LoS}} + H_{i,u}^{\text{NLoS}}$. At the receiver, the photons of different wavelengths are filtered and guided into separate PDs. Each PD converts the received photons into an electric current:

$$I_{i,u}^{l} = R_{\text{pd}}^{l} H_{i,u}^{l} P_{\text{mod}}^{l}, \tag{3}$$

where l denotes the index of LEDs, with each LED having its own R_{pd}^{l} and P_{mod}^{l} shown in Table I. With respect to the link between the l-th LED of AP i and user u, the signal-to-interference-plus-noise ratio (SINR) can be expressed as follows:

$$\gamma_{i,u}^{l} = \frac{\eta_{i,u}(R_{\text{pd}}^{l} H_{i,u}^{l} P_{\text{mod}}^{l})^2}{N_{\text{VLC}} B_{\text{VLC}} + \sum\limits_{j\in\mathcal{I}_i, j\neq i} \eta_{j,u}(R_{\text{pd}}^{l} H_{j,u}^{l} P_{\text{mod}}^{l})^2}, \tag{4}$$

where N_{VLC} denotes the power spectral density (PSD) of noise, which is assumed to be signal independent; B_{VLC} is the bandwidth per LED; $\mathcal{I}_i$ is the set of APs that employ the same optical spectrum as AP i; $\eta_{i,u}$ denotes the blockage coefficient: $\eta_{i,u} = 1$ means a clear transmission path, and $\eta_{i,u} = 0$ indicates a complete blockage.

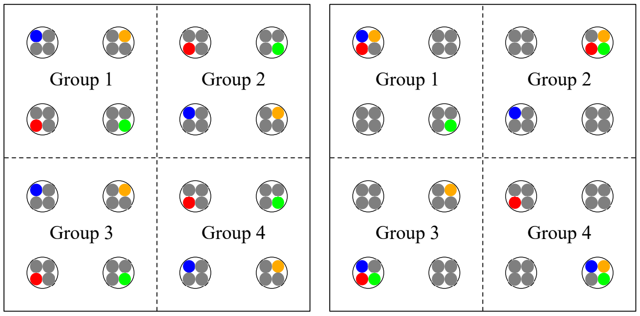
III. ADAPTIVE NETWORK DEPLOYMENT

In this section, the novel adaptive network deployment (AND) scheme is proposed for VLC networks. The target is to maximise the network capacity with proportional fairness.

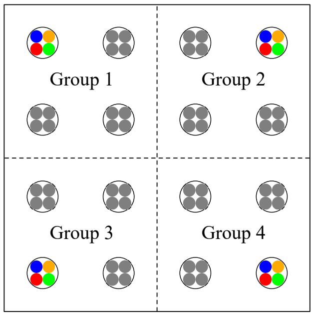
A. Concept

To suppress inter-cell interference (ICI), the network deployment in [7] activates a single coloured LED for each AP, as shown in Fig. 3(a). This arrangement can prevent any

$$H_{i,u}^{\mathrm{NLoS}} = \int_{A_w} \frac{(m+1)A_{\mathrm{pd}}}{2(\pi d_{i,w} d_{w,u})^2} \rho_w \cos^m(\phi_{i,w}) g_f g_c \cos(\psi_{w,u}) \cos(\vartheta_{i,w}) \cos(\vartheta_{w,u}) dA_w. \tag{2}$$



(a) Mode 1 (b) Mode 2



(c) Mode 3

Fig. 3. Different modes of VLC network deployment (Coloured dots: modulated LEDs; grey dots: non-modulated LEDs).

two neighbouring APs from modulating LEDs of the same colour. There are two types of transmission schemes: serial transmission (ST) and parallel transmission (PT). With ST, each user is assigned to a single AP, while PT enables each user to be served by multiple APs simultaneously. Using PT, the traffic between each host AP and the user is called a subflow. However, mode 1 in Fig. 3(a) is not always the best way of network deployment. For instance, when the users are gathered around a certain AP, the usage of other APs is less efficient. In this circumstance, it would be better to modulate more than 1 LED in that AP. With ICI mitigation considered, we propose two new modes depicted in Fig. 3(b) and Fig. 3(c), respectively. In mode 2, each corner AP consists of 3 modulated LEDs, while each centre AP modulates 1 LED in the same way as mode 1 does. The remaining APs in mode 2 only provide illuminations, without modulating any LEDs. In mode 3, only the corner APs contain modulated LEDs. It is evident that mode 1 suits uniformly distributed or centre gathered users, whereas mode 3 can better serve corner gathered users. As for mode 2, it covers the situation in-between. Switching among the above 3 modes, the basic concept is to make the network deployment adapt to different user/traffic situations.

B. Optimisation Problem

A commonly used proportional fairness scheduler to maximise the network capacity is given by [10, eq. (9)]:

$$\max \quad \sum_{u \in \mathbf{U}} \log(R_u), \tag{5}$$

where R_u is the overall data rate that user u achieves, and $\mathbf{U}$ is the set of all users. Let N_f denote the number of subflows, meaning that the user is served by N_f LEDs (of different colours) which provide the highest values of SNR. The set of APs that serve the user is denoted by $\mathbf{I}_u$, and the set of LEDs used in a specific AP is denoted by $\mathbf{L}_{i,u}$. Thus, R_u can be computed as follows:

$$R_u = \sum_{i \in \mathbf{I}_u} \sum_{l \in \mathbf{L}_{i,u}} \rho_{i,u}^l r_{i,u}^l, \tag{6}$$

where $\rho_{i,u}^l \in (0, 1]$ denotes the proportion of time resource; and $r_{i,u}^l$ is the link capacity. Since $\gamma_{i,u}^l$ is an electrical SINR for non-negative signals, a tighter capacity bound of link capacity is given as follows [7, eq. (7)]:

$$r_{i,u}^l = \frac{B_{\mathrm{VLC}}}{2} \log_2\left(1 + \frac{e}{2\pi}\gamma_{i,u}^l\right). \tag{7}$$

For each mode, the network capacity can be maximised through solving the following optimisation problem:

$$\begin{aligned} \max_{\rho_{i,u}^l} \quad & \sum_{u \in \mathbf{U}} \log\left(\sum_{i \in \mathbf{I}_u} \sum_{l \in \mathbf{L}_{i,u}} \rho_{i,u}^l r_{i,u}^l\right) \\ \text{s.t.} \quad & 0 < \rho_{i,u}^l \leq 1 \qquad \forall i, u, l; \\ & \sum_{u \in \mathbf{U}_i^l} \rho_{i,u}^l \leq 1 \qquad \forall i, l. \end{aligned} \tag{8}$$

where $\mathbf{U}_i^l$ denote the set of users served by the same LED in the same AP. Let $C(m)$ denote the maximum network capacity provided by mode m. Then the optimisation problem of adaptive network deployment can be formulated as:

$$\begin{aligned} \max_{m} \quad & C(m) \\ \text{s.t.} \quad & m \in [1, 2, 3]. \end{aligned} \tag{9}$$

C. Complexity

The above problem can be solved through the MATLAB function fmincon, with minimising $-C(m)$ instead of maximising $C(m)$. It is difficult to theoretically analyse the computational complexity of a gradient-based optimisation method. Alternatively, the runtime for computing the optimal solution is presented. As shown in Fig. 4, the amount of runtime is almost the same for different numbers of subflows. As the number of users increases, the amount of runtime exhibits approximately a linear growth.

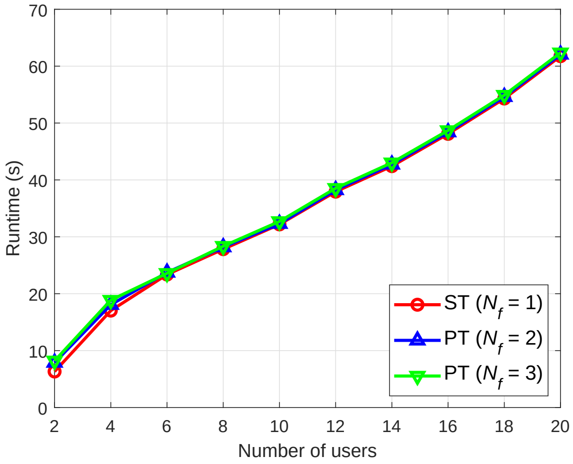


Fig. 4. Runtime of the proposed AND scheme.

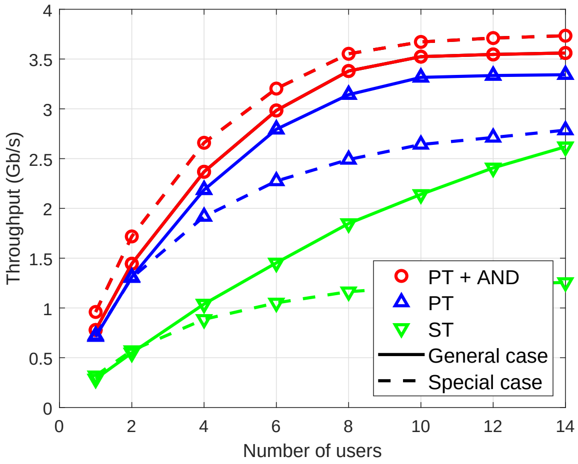


Fig. 5. Throughput versus the number of users.

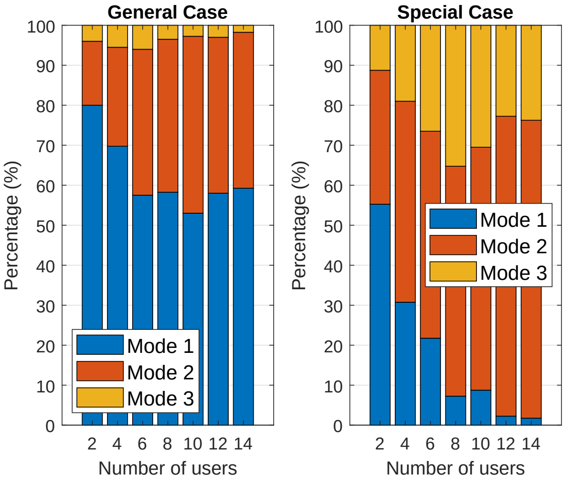


Fig. 6. Distribution of Modes.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Physical area of the PD, A_{pd}	1 cm^2
Gain of the optical filter, g_f	1
Refractive index, n	1.5
Half-intensity radiation angle, $\Phi_{1/2}$	60°
FoV semi-angle of the receiver, Ψ_{max}	90°
Wall reflectivity, ρ_w	0.8
Bandwidth per LED, B_{VLC}	20 MHz
PSD of noise, N_{VLC}	10^{-21} A^2/Hz

IV. SIMULATION RESULTS

In this section, Monte Carol simulations are carried out to evaluate the performance of the proposed AND scheme. The number of APs is set to be 16, with a 4m separation between the two nearest APs. It is assumed that all users have the same vertical distance from the APs, which is set to be 2m. As for user locations, two cases are considered. In the general case, users are uniformly distributed over the entire room, and in the special case they gather around the corner APs. The study in [7] proves that PT with $N_f = 3$ provides a prominent improvement over ST. For this reason, we choose $N_f = 3$ and focus on comparing the performance of PT with and without the proposed AND scheme. The impact of light-path blockage is studied in Section IV-D, whereas other situations do not involve blockage. Other parameters used for the simulations are summarised in Table II.

A. Throughput

In Fig. 5, the network throughput is presented as a function of the number of users, which is denoted by N_u. As shown, the AND scheme can noticeably improve network throughput, especially in the special case. When there are 14 users in the special case, for instance, AND achieves a throughput of 3.73 Gb/s, 34.1% higher than the 2.79 Gb/s provided by PT. In the general case this improvement is 6.5%. This reflects that the proposed method can well adapt to the situation of corner gathered users. Also, AND outperforms PT more significantly for a smaller number of users. As N_u decreases from 14 to 6, the throughput gap between AND and PT further increases to 40.8%. When compared to ST, AND can triple the network throughput at most.

B. Distribution of Modes

Fig. 6 shows the distribution of modes for different values of N_u. Three outcomes are observed. First, in general, the percentage of mode 1 decreases as the number of users increases in both cases. Specifically, mode 1 accounts for less than 3% in the special case when N_u increases to 14. The highest percentage of mode 1 appears when $N_u = 2$ in the general case. Despite this, modes 2 and 3 contribute 20% in this situation. This validates the adaptivity of the proposed AND scheme. Second, the special case has a much lower percentage of mode 1 than the general case. As explained, the proposed method is designed to improve the performance of corner users. Third, mode 3 has a significant portion in the special case but very little in the general case. As shown, the percentage of mode 3 is less than 6% in the general case, while in the special case it is up to 35%. This is because in

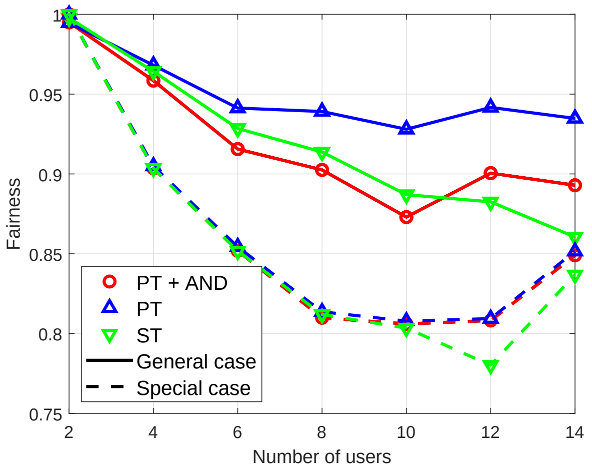


Fig. 7. User fairness versus the number of users.

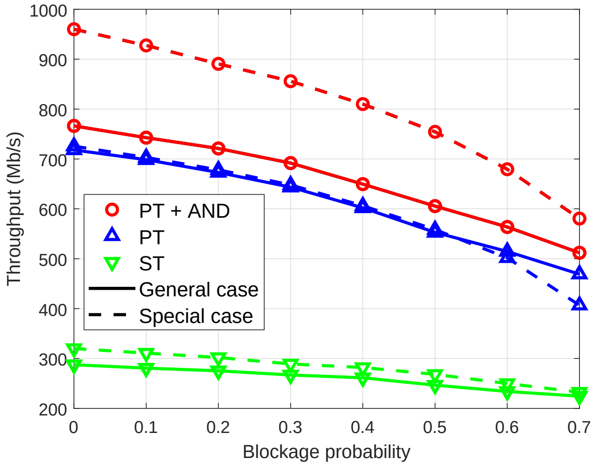


Fig. 8. Throughput versus blockage probability ($N_u = 1$).

the special case, corner gathered users can well exploit the benefit of mode 3.

C. User Fairness

Apart from the overall throughput, fairness measures are used to determine whether the users receive a fair share of system resources. The Jain's fairness index [7, eq. (15)] is studied in Fig. 7. As can be seen, AND and PT exhibit a similar user fairness in the special case. However, in the general case, AND has a noticeably lower fairness than PT, and this gap increases as the number of users. The reason for this trend is that while the two new modes in AND can improve throughput for corner users, the performance of other users is compromised. As a result, the user fairness reduces to some extent when the AND method is adopted in the general case. Despite this, the user fairness of AND is still above 87%, which is only 5% less than PT.

D. Impact of Light-path Blockage

Fig. 8 presents the throughput as a function of blockage probability, which indicates how likely a VLC link would encounter a complete blockage. As the blockage probability increases, the achievable throughput decreases for all the considered methods. Meanwhile, the improvement provided by AND over PT becomes slightly larger. For example, when the blockage probability increases from 0 to 0.7, the gap between AND and PT increases from 6.7% to 9.5% in the general case. As for the special case, this gap increases from 32.3% to 42.7%. This signifies that compared to PT, the proposed adaptive method is robust against light-path blockage.

V. CONCLUSION

In this paper a novel adaptive network deployment was proposed for VLC networks. With this AND scheme, each AP contains multiple LEDs and can modulate some of them for data transmission. Taking ICI mitigation into account, three modes are constructed to arrange the modulated LEDs among the APs. The proposed AND scheme can adaptively switch among these three modes to maximise the network capacity. Compared to the original PT method, the AND scheme can particularly improve the network capacity for corner users. Results show that the AND scheme can improve the network throughput over PT by up to 40%. Future work will explore artificial intelligence algorithms to reduce the computational complexity. Facilitated by parallel transmission and adaptive network deployment, the VLC technology will become more promising for the 6G era.

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REFERENCES

[1] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," *IEEE Network*, vol. 34, no. 3, pp. 134–142, 2020.

[2] R. Bian, I. Tavakkolnia, and H. Haas, "15.73 Gb/s visible light communication with off-the-shelf LEDs," *J. Lightw. Technol.*, pp. 1–1, May 2019.

[3] X. Li, R. Zhang, and L. Hanzo, "Cooperative load balancing in hybrid visible light communications and WiFi," *IEEE Trans. Commun.*, vol. 63, no. 4, pp. 1319–1329, Apr. 2015.

[4] C. Chen, S. Videv, D. Tsonev, and H. Haas, "Fractional frequency reuse in DCO-OFDM-based optical attocell networks," *J. Lightw. Technol.*, vol. 33, no. 19, pp. 3986–4000, Oct. 2015.

[5] Y. Wang, X. Wu, and H. Haas, "Load balancing game with shadowing effect for indoor hybrid LiFi/RF networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2366–2378, Apr. 2017.

[6] A. Ford, C. Raiciu, M. Handley, and O. Bonaventure, "TCP extensions for multipath operation with multiple addresses," RFC 6824, Fremont, CA, USA, Tech. Rep., Jan. 2013.

[7] X. Wu and D. C. O'Brien, "Parallel transmission LiFi," *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6268–6276, Oct. 2020.

[8] X. Wu, M. D. Soltani, L. Zhou, M. Safari, and H. Haas, "Hybrid LiFi and WiFi networks: A survey," *IEEE Commun. Surveys. Tuts.*, vol. 23, no. 2, pp. 1398–1420, 2nd Quart. 2021.

[9] J. Kahn and J. Barry, "Wireless infrared communications," *Proc. IEEE*, vol. 85, no. 2, pp. 265–298, Feb. 1997.

[10] X. Wu, M. Safari, and H. Haas, "Joint optimisation of load balancing and handover for hybrid LiFi and WiFi networks," in *2017 IEEE Wireless Communications and Networking Conf. (WCNC)*, San Francisco, CA, 2017, pp. 1–5.