Mobility Management for Hybrid LiFi and WiFi Networks in the Presence of Light-path Blockage

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***Abstract*—Hybrid light fidelity (LiFi) and wireless fidelity (WiFi) networks (HLWNets) have been recently proposed as a promising technique for indoor wireless communications. Such a network combines the high-speed transmission of LiFi and the ubiquitous coverage of WiFi. Meanwhile, in addition to user mobility, intermittent light-path blockages make the handover issue intricate in HLWNets. Also, load balancing (LB) is necessary because the coverage areas of LiFi and WiFi networks are completely overlapped. This further increases the difficulty in handover as the decision for a vertical or a horizontal handover in a mobile environment with ultra-small cells is non-trival. Aimed at providing an optimal solution to the access point selection (APS) with given channel state information (CSI), the conventional LB method might cause frequent and unnecessary handovers. In this paper, a joint optimisation problem is formulated to simultaneously consider LB and handover in HLWNets. Results show that compared with the conventional LB method, the proposed method can improve the system throughput by up to 60%.**

***Index Terms*—Light fidelity (LiFi), hybrid network, handover, user mobility, light-path blockage**

I. Introduction

Global mobile data traffic is expected to grow over 4 times in 4 years, reaching 48.3 exabytes per month at the end of 2021 [1]. The exponentially increasing demand for mobile data is about to outstrip the spectrum capacity of radio-frequency (RF) in the near future, leading to the looming crisis of a spectrum crunch [2]. In order to exploit the spectrum of higher frequencies, visible light communication (VLC) and its use for wireless networking, which is termed light fidelity (LiFi) [3], have drawn significant research attention in recent years. LiFi modulates the light intensity of light-emitting diodes (LEDs) to carry information bits and employs photodiodes (PDs) to detect the transmitted signals. LiFi can offer many advantages over wireless fidelity (WiFi), including access to a much wider and unregulated spectrum, more secure communications and the ability to be used in RF-restricted areas. Moreover, LiFi is capable of providing high-speed data transmissions in the range of Gbps [3].

A LiFi access point (AP) usually covers a relatively small area, of approximately 2-3m in diameter. In order to combine the high-speed transmission of LiFi and the ubiquitous coverage of WiFi, hybrid LiFi and WiFi networks (HLWNets) are developed. Such a network is able to achieve a greater throughput than a stand-alone LiFi or WiFi network [4]. Meanwhile, the issue of access point selection (APS) becomes challenging mainly due to two reasons: i) WiFi APs have relatively large coverage areas but limited system capacities in comparison to LiFi APs; and ii) the coverage areas of different networks overlap each other. Using the signal strength strategy (SSS) method, which assigns a user to the AP offering the highest received signal power, would render the WiFi system susceptible to traffic overloads. Thus load balancing (LB) is essential for HLWNets. Studies are carried out in this field in [5]–[7], but they are all focused on optimising the instant system throughput and might result in frequent handovers.

In a hybrid network there are two types of handovers: horizontal handover (HHO) and vertical handover (VHO). HHOs occur within the domain of a single wireless access technology, whereas VHOs happen between different wireless access technologies. Due to different medium access control protocols, a VHO normally causes a much longer delay than a HHO [8]. Therefore frequent VHOs would significantly reduce the system capacity of a HLWNet. Only a few studies consider the handover cost caused by user mobility in a LiFi-involved hybrid network, e.g. [9]. Light-path blockages are another significant factor that causes handovers in HLWNets [10]. However, this research field is underdeveloped in the current literature. When light-path blockages happen to a LiFi user, it can be transferred to WiFi until the LiFi connectivity is restored. But if light-path blockages occur frequently, conducting the above action could potentially result in an overall throughput even lower. Thus it is vital to selectively switch LiFi users to WiFi when they experience light-path blockages. Taking both user mobility and light-path blockages into account, the LB issue becomes more complicated. To the best of the authors' acknowledge, this issue has not been addressed so far.

In this paper, a novel APS method is proposed for HLWNets by jointly performing LB and handover. Specifically, the handover cost caused by both user mobility and light-path blockages is involved in the optimisation problem of LB. Instead of choosing a specific AP at a given time instant, the proposed method determines the type of network access for each user over a period of time. Within this period, the users can only be transferred among homogeneous APs as long as the light path is not blocked. In the event of a light-path blockage, selective LiFi users are allowed to temporarily

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access the WiFi network.

The remainder of this paper is organised as follows. In Section II, the system model of an indoor HLWNet is described, including the network deployment and channel model. A conventional LB method is introduced in Section III, and a novel method is proposed in Section IV. Simulation results are presented in Section V. Finally, conclusions are drawn in Section VI.

II. System Model

An indoor HLWNet consisting of one WiFi AP and a number of LiFi APs is considered. The WiFi AP is deployed on the ground and in the centre of the room, whereas each LiFi AP is integrated into the ceiling LED lamps, which face downward vertically. Note that the WiFi AP provides coverage for the entire room, while each LiFi AP covers a confined area. The LiFi APs operate with different spectra and thus do not interfere with each other. The mobile users are assumed to follow the random waypoint (RWP) model [11]. The user's speed is a random variable uniformly distributed between 0 and a maximum speed. During the period of interest the user's speed is assumed to be constant. Each user is equipped with a upward-oriented PD and can only be connected to one AP. Time-division multiple accessing (TDMA) is employed to enable the APs to serve multiple users.

A. LiFi Channel Model

Fig. 1 shows the geometry of a LiFi channel, which is comprised of two components: i) line-of-sight (LoS) and ii) non line-of-sight (NLoS). With respect to AP i and user u, the LoS path is the straight line between them, and its Euclidean distance is denoted by $d_{i,u}$. Let $\phi_{i,u}$ and $\psi_{i,u}$ denote the angles of irradiance and incidence, respectively. The channel gain of the LoS path is expressed as [12, eq. (10)]:

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

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

$$g_c(\psi_{i,u}) = \begin{cases} \dfrac{n^2}{\sin^2(\Psi_{\max})}, & 0 \le \psi_{i,u} \le \Psi_{\max} \\ 0, & \psi_{i,u} > \Psi_{\max} \end{cases}, \tag{2}$$

where n stands for the refractive index, and $\Psi_{\max}$ denotes the semi-angle of the field of view (FoV) of the PD.

Regarding the NLoS paths, only first-order reflections are taken into account as the second-order reflections typically contribute little [12]. A first-order reflection has two segments: a) from AP i to a point w on the wall, and b) from the point w to user u. The corresponding Euclidean distances are denoted by $d_{i,w}$ and $d_{w,u}$, 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 channel gain provided by the NLoS paths is written as (3),

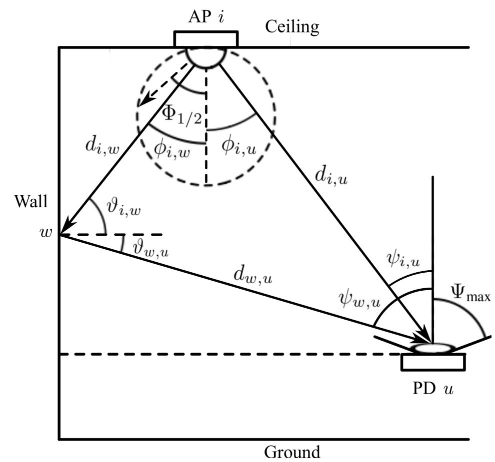

Fig. 1. The LoS and first-order NLoS paths of a LiFi channel.

where A_w denotes a small area on the wall and ρ_w is the wall reflectivity. Adding (1) to (3), the total gain of a LiFi channel is given by:

$$H_{\text{LiFi}}^{i,u} = H_{\text{LoS}}^{i,u} + H_{\text{NLoS}}^{i,u}. \tag{4}$$

At the receiver of user u, the PD gathers photons and converts them into an electric current:

$$I_{\text{elec}} = R_{\text{pd}} H_{\text{LiFi}}^{i,u} P_{\text{opt}}/\zeta, \tag{5}$$

where R_{pd} is the detector responsivity; P_{opt} is the transmitted optical power; and ζ is the ratio of the transmitted optical power to the optical signal power.

B. Light-path Blockage

Regarding the light-path blockage, there are three key elements: occurrence rate, occupation rate and blockage degree. Occurrence rate, denoted by λ_u, is defined as the number of light-path blockages that happen in a time unit. Occupation rate, denoted by η_u, means the proportion of time during which a user experiences light-path blockages. A parameter ξ_u is used to indicate the existence of the light-path blockage [13]: $\xi_u = 1$ signifies there is a light-path blockage, while $\xi_u = 0$ means otherwise. Then (5) is modified to:

$$I_{\text{elec}} = (1-\xi_u) R_{\text{pd}} H_{\text{LiFi}}^{i,u} P_{\text{opt}}/\zeta. \tag{6}$$

The signal-to-noise ratio (SNR) of a LiFi user can be computed as:

$$\gamma_{\text{LiFi}}^{i,u} = \frac{\left[(1-\xi_u) R_{\text{pd}} H_{\text{LiFi}}^{i,u} P_{\text{opt}}/\zeta\right]^2}{N_{\text{LiFi}} B_{\text{LiFi}}}, \tag{7}$$

where B_{LiFi} is the system bandwidth of the LiFi AP and N_{LiFi} is the power spectral density (PSD) of noise at the PD, including shot noise and thermal noise.

$$H_{\text{NLoS}}^{i,u} = \int_{A_w} \frac{(m+1)A_{\text{pd}}}{2(\pi d_{i,w} d_{w,u})^2} \rho_w \cos^m(\phi_{i,w}) g_f g_c(\psi_{w,u}) \cos(\psi_{w,u}) \cos(\vartheta_{i,w}) \cos(\vartheta_{w,u}) dA_w. \tag{3}$$

C. WiFi Channel Model

Although only a single WiFi AP is used, the index of the AP is retained for the purpose of generality. The gain of a WiFi channel is given by [14]:

$$G_{\text{WiFi}}^{i,u} = \left| H_{\text{WiFi}}^{i,u} \right|^2 10^{\frac{-L(d_{i,u})+X_\sigma}{10}}, \tag{8}$$

where $H_{\text{WiFi}}^{i,u}$ describes the channel transfer function, which follows a standard Rayleigh distribution; the shadow fading X_σ is a zero-mean Gaussian random variable with a standard deviation of 10 dB; and $L(\cdot)$ represents the free-space path loss:

$$L(d) = \begin{cases} 20\log_{10}(f_c d) - 147.5, & d < d_{\text{ref}} \\ 20\log_{10}\left(f_c \dfrac{d^{2.75}}{d_{\text{ref}}^{1.75}}\right) - 147.5, & d \geq d_{\text{ref}} \end{cases}, \tag{9}$$

where f_c is the central carrier frequency and $d_{\text{ref}} = 10$ m is the reference distance. The SNR of a WiFi user is written as:

$$\gamma_{\text{WiFi}}^{i,u} = \frac{G_{\text{WiFi}}^{i,u} P_{\text{WiFi}}}{N_{\text{WiFi}} B_{\text{WiFi}}}, \tag{10}$$

where N_{WiFi} is the PSD of noise at the receiver; B_{WiFi} and P_{WiFi} denote the system bandwidth and transmit power of the WiFi AP, respectively.

III. Conventional Load Balancing

Proportional resource allocation can be achieved by [15]:

$$\text{maximise} \sum_u \log(R_u), \tag{11}$$

where R_u is the actual throughput obtained by user u. For a given instant t, $R_u^{(t)}$ is calculated by [5, eq. (15)]:

$$R_u^{(t)} = \sum_i \chi_{i,u}^{(t)} \rho_{i,u}^{(t)} r_{i,u}^{(t)}, \tag{12}$$

where $\chi_{i,u}^{(t)} = 1$ means that a connection exists between AP i and user u, while $\chi_{i,u}^{(t)} = 0$ means otherwise; $\rho_{i,u}^{(t)}$ is a fraction variable between 0 and 1, which denotes the proportion of time that AP i allocates to user u; $r_{i,u}^{(t)}$ represents the Shannon capacity that AP i can provide to user u:

$$r_{i,u}^{(t)} = B_i \log_2\left(1 + \gamma_{i,u}^{(t)}\right). \tag{13}$$

Since this method offers a LB solution for a given instant, it is referred to as instant load balancing (ILB). Each user can only be assigned to one AP. Thus the term $\sum_i \chi_{i,u}^{(t)}$ can be moved out of the logarithmic function when substituting (12) into (11). The objective function of ILB becomes:

$$F_{\text{ILB}}\left(\boldsymbol{\chi}^{(t)}, \boldsymbol{\rho}^{(t)}\right) = \sum_u \sum_i \chi_{i,u}^{(t)} \log\left(\rho_{i,u}^{(t)} r_{i,u}^{(t)}\right), \tag{14}$$

where $\boldsymbol{\chi}^{(t)}$ and $\boldsymbol{\rho}^{(t)}$ are the sets of all possible $\chi_{i,u}^{(t)}$ and $\rho_{i,u}^{(t)}$, respectively. The optimisation problem of ILB is formulated as:

$$\begin{aligned} \text{maximise} \quad & F_{\text{ILB}}\left(\boldsymbol{\chi}^{(t)}, \boldsymbol{\rho}^{(t)}\right) \\ \text{subject to} \quad & \chi_{i,u}^{(t)} \in \{0,1\}, \quad \forall i,u; \\ & \sum_i \chi_{i,u}^{(t)} = 1, \quad \forall u; \\ & 0 \leq \rho_{i,u}^{(t)} \leq 1, \quad \forall i,u; \\ & \sum_u \chi_{i,u}^{(t)} \rho_{i,u}^{(t)} \leq 1, \quad \forall i. \end{aligned} \tag{15}$$

IV. Proposed Method

In order to take into account the handover cost caused by user mobility and light-path blockages, the average throughput over the period of interest needs to be measured. Let α denote the type of network which is either LiFi or WiFi. Let κ denote the type of network access which falls into three categories: 'LiFi only', 'WiFi only' and 'LiFi/WiFi'. Note that the AP assigned to a user is dynamic and agnostic over a period of time. Therefore we focus on deciding the type of network access. The first two categories restrict the user to a certain type of network. Accordingly, the user can only be transferred among homogeneous APs, where the SSS method is applicable. The third category allows LiFi users to be served by WiFi in the event of a light-path blockage.

First, we consider the situation that does not involve user mobility. The average throughput achieved by user u can be computed as follows:

$$\bar{R}_u = \sum_\kappa \chi_{\kappa,u} \sum_\alpha \rho_u^\alpha \tau_{\kappa,u}^\alpha r_u^\alpha, \tag{16}$$

where $\chi_{\kappa,u} = 1$ means that user u chooses κ-type of network access, while $\chi_{\kappa,u} = 0$ means otherwise; ρ_u^α denotes the proportion of time that α-type network allocates to user u; and r_u^α is the average Shannon capacity that the α-type network can provide to user u:

$$r_u^\alpha = \sum_{i \in \alpha} \chi_{i,u} \int_t B_i \log_2(1 + \gamma_{i,u}^{(t)}) dt. \tag{17}$$

The coefficient $\tau_{\kappa,u}^\alpha$ in (16) denotes the proportion of time during which user u is served by the α-type network. Let T_{VHO} denote the VHO overhead. For different choices of κ, $\tau_{\kappa,u}^{\text{LiFi}}$ and $\tau_{\kappa,u}^{\text{WiFi}}$ are given by:

$$\tau_{\kappa,u}^{\text{LiFi}} = \begin{cases} 1 - \eta_u & \text{if } \kappa \text{ is 'LiFi only'} \\ 0 & \text{if } \kappa \text{ is 'WiFi only'} \\ \max\{1 - \eta_u - \lambda_u T_{\text{VHO}}, 0\} & \text{if } \kappa \text{ is 'LiFi/WiFi'} \end{cases}. \tag{18}$$

and:

$$\tau_{\kappa,u}^{\text{WiFi}} = \begin{cases} 0 & \text{if } \kappa \text{ is 'LiFi only'} \\ 1 & \text{if } \kappa \text{ is 'WiFi only'} \\ \max\{\eta_u - \lambda_u T_{\text{VHO}}, 0\} & \text{if } \kappa \text{ is 'LiFi/WiFi'} \end{cases}. \tag{19}$$

Now we take into account user mobility. For a user that is connected to the α-type network, the proportion of time taken up by HHOs is denoted by ϱ_u^α. Denoting the HHO overhead with respect to the α-type network by T_{HHO}^α, ϱ_u^α can be calculated by:

$$\varrho_u^\alpha = \begin{cases} \dfrac{T_{\text{HHO}}^\alpha}{T_u^\alpha} & \text{if } T_{\text{HHO}}^\alpha \leq T_u^\alpha \\ 1 & \text{if } T_{\text{HHO}}^\alpha > T_u^\alpha \end{cases}, \tag{20}$$

where T_u^α is the average cell dwell time (CDT) of user u, which can be collected by statistics [16]. The average throughput in (16) is then modified to:

$$\bar{R}_u = \sum_\kappa \chi_{\kappa,u} \sum_\alpha \tau_{\kappa,u}^\alpha r_u^\alpha \min\{\rho_u^\alpha, 1 - \varrho_u^\alpha\}. \tag{21}$$

The term $\min\{\rho_u^\alpha, 1 - \varrho_u^\alpha\}$ signifies the proportion of time that is available for data transmissions. Since a single WiFi AP is deployed, the WiFi users do not experience HHOs and thus $\varrho_u^{\text{WiFi}} = 0$. Consequently, $\min\{\rho_u^\alpha, 1 - \varrho_u^\alpha\}$ reduces to ρ_u^α. The same is valid for those LiFi users that always stay within the coverage area of a certain AP. On the contrary, $1 - \varrho_u^\alpha$ becomes very small for the fast-moving LiFi users with a short CDT, limiting the time that is available for data transmissions.

Substituting (21) into (11), the objective function of the proposed method is written as follows:

$$\Gamma(\boldsymbol{\chi}, \boldsymbol{\rho}) = \sum_u \sum_\kappa \chi_{\kappa,u} \log\left(\sum_\alpha \tau_{\kappa,u}^\alpha r_u^\alpha \min\{\rho_u^\alpha, 1 - \varrho_u^\alpha\}\right). \tag{22}$$

The optimisation problem of the proposed method is expressed as:

$$\begin{aligned} \text{maximise} \quad & \Gamma(\boldsymbol{\chi}, \boldsymbol{\rho}) \\ \text{subject to} \quad & \chi_{\kappa,u} \in \{0,1\}, \quad \forall \kappa, u; \\ & \sum_\kappa \chi_{\kappa,u} = 1, \quad \forall u; \\ & 0 \leq \rho_u^\alpha \leq 1, \quad \forall \alpha, u; \\ & \sum_u \chi_{\kappa,u} \rho_u^\alpha \tau_{\kappa,u}^\alpha \leq N_{\text{AP}}^\alpha, \quad \forall \alpha. \end{aligned}, \tag{23}$$

where N_{AP}^α is the number of α-type APs.

V. Simulation Results

In this section, Monte Carlo simulations are carried out to evaluate the performance of the proposed method. Four LiFi APs are considered and they are placed at the four corners of a square. The length of each side of the square is set to be 2.5 m. The poisson point process is commonly used in queueing theory [17] to model random events such as the arrival of packages at a router. Here the events of light-path blockages are assumed to follow a Poisson point process, with the expected occurrence rate being Gamma distributed (the shape factor is 1 and the mean is λ). The occupation rate is uniformly distributed between 0 and 1. Other parameters are summarised in Table I.

TABLE I
Simulation Parameters

Parameter	Value
Room size (length by width by height)	$5 \times 5 \times 3$ m
The physical area of the PD, A_{pd}	1 cm^2
The 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 PD, Ψ_{max}	90°
The ratio of P_{opt} to the optical signal power, ζ	3
Detector responsivity, R_{pd}	0.53 A/W
Wall reflectivity, ρ_w	0.8
Transmitted optical power per LiFi AP, P_{opt}	3 Watt
Transmitted power per WiFi AP, P_{WiFi}	20 dBm
Bandwidth per LiFi AP, B_{LiFi}	20 MHz
Bandwidth per WiFi AP, B_{WiFi}	20 MHz
PSD of noise in LiFi, N_{LiFi}	10^{-21} A^2/Hz
PSD of noise in WiFi, N_{WiFi}	-174 dBm/Hz
The HHO overhead, T_{HHO}	200 ms [18]
The VHO overhead, T_{VHO}	500 ms [8]

In Fig. 2, the system throughput is shown as a function of the number of users. It is observed that the proposed method can greatly outperform ILB, while ILB is marginally better than SSS. This is because the proposed method can effectively reduce VHOs. When 14 users are involved, for example, the proposed method achieves a system throughput of 747 Mbps, which is 48% more than ILB and 68% more than SSS. Fig. 3 presents the system throughput in relation to the user's average speed. As shown, the proposed method is outperformed by ILB with a fairly modest gap only when users move very slowly. The reason for this is that ILB provides an optimal solution for stationary users. When the average speed increases beyond 0.16 m/s, the proposed method always surpasses ILB. With every 1 m/s increase in speed, the throughput gap between the proposed method and ILB increases by about 20%.

Finally, the effect of the occurrence rate of light-path blockages is analysed. As shown in Fig. 4, the system throughput achieved by the proposed method decreases slowly when λ increases. As for ILB, the system throughput drops quite dramatically. At $\lambda = 0$, i.e., there is no light-path blockage, the throughput gap between ILB and SSS is 50 Mbps. When λ reaches 20 times per minute, ILB achieves almost the same system throughput as SSS. In the meantime, the proposed method can improve the system throughput over ILB by about 60%.

VI. Conclusion

In this paper, the handover issue caused by both user mobility and light-path blockages was studied for HLWNets. A novel APS method was proposed by performing a joint optimisation of LB and handover. Unlike the ILB method

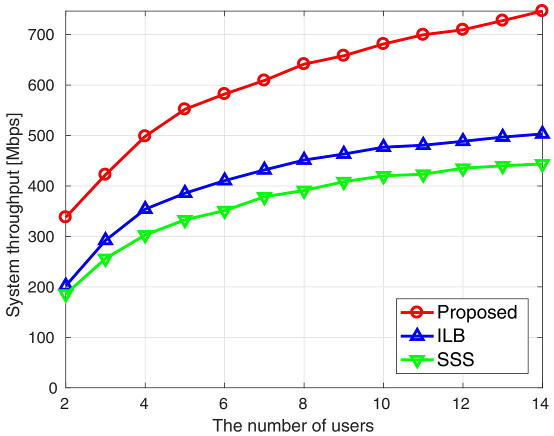

Fig. 2. System throughput versus the number of users (the user's average speed is 2.5 m/s and λ = 10/min).

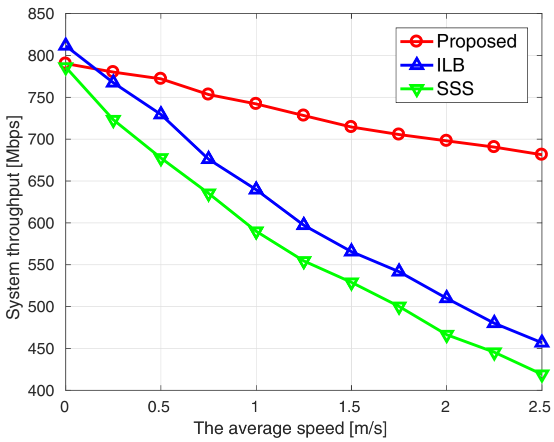

Fig. 3. System throughput versus the user's average speed (the number of users is 10 and λ = 10/min).

selecting a specific AP at a given instant, the proposed approach decides the type of network access for a period of time. Results show that the proposed method can improve the system throughput by up to 60% over ILB. Future research will study practical user behaviours and the resulting change in performance.

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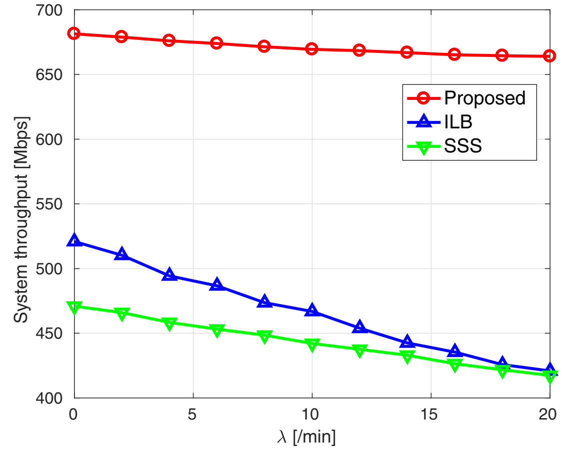

Fig. 4. System throughput versus λ (the user's average speed is 2.5 m/s and the number of users is 10).

References

[1] "Cisco Visual Networking Index: Forecast and Methodology, 2016-2021," Cisco, San Jose, CA, USA, Tech. Rep., Jun. 2017.

[2] D. C. Sicker and L. Blumensaadt, "The wireless spectrum crunch," in *Fundamentals of 5G Mobile Networks*, 1st ed., J. Rodriguez, Ed. West Sussex, U.K.: Wiley, 2015.

[3] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?" *J. Lightw. Technol.*, vol. 34, no. 6, pp. 1533–1544, Mar. 2016.

[4] D. Basnayaka and H. Haas, "Hybrid RF and VLC systems: Improving user data rate performance of VLC systems," in *IEEE 81st Vehicular Technology Conf. (VTC Spring)*, Glasgow, May 2015, pp. 1–5.

[5] 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.

[6] Y. Wang, X. Wu, and H. Haas, "Distributed load balancing for internet of things by using Li-Fi and RF hybrid network," in *IEEE 26th Annu. Int. Symp. on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Hong Kong, Aug. 2015, pp. 1289–1294.

[7] X. Wu, M. Safari, and H. Haas, "Access point selection for hybrid Li-Fi and Wi-Fi networks," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5375–5385, Dec. 2017.

[8] H. Kwon, K.-Y. Cheon, and A. Park, "Analysis of WLAN to UMTS handover," in *IEEE 66th Vehicular Technology Conf. (VTC Fall)*, Baltimore, MD, Sep. 2007, pp. 184–188.

[9] L. Li, Y. Zhang, B. Fan, and H. Tian, "Mobility-aware load balancing scheme in hybrid VLC-LTE networks," *IEEE Commun. Lett.*, vol. 20, no. 11, pp. 2276–2279, Nov. 2016.

[10] X. Wu and H. Haas, "Access point assignment in hybrid LiFi and WiFi networks in consideration of LiFi channel blockage," in *IEEE 18th Int. Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Sapporo, Jul. 2017, pp. 1–5.

[11] D. Johnson and D. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*, T. Imelinsky and H. Korth, Eds. Dordrecht, the Netherlands: Kluwer Academic Publishers, 1996, pp. 153–181.

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

[13] S. Jivkova and M. Kavehrad, "Shadowing and blockage in indoor optical wireless communications," in *2003 IEEE Global Telecommunications Conf. (GLOBECOM)*, vol. 6, Dec. 2003, pp. 3269–3273 vol.6.

[14] E. Perahia and R. Stacey, *Next Generation Wireless LAN: 802.11n and 802.11ac*. Cambridge, U.K.: Cambridge Univ. Press, 2013.

[15] F. Kelly, "Charging and rate control for elastic traffic," *Eur. Trans. Telecommun.*, vol. 8, no. 1, pp. 33–37, Jan./Feb. 1997.

[16] M. Ruggieri, F. Graziosi, and F. Santucci, "Modeling of the handover dwell time in cellular mobile communications systems," *IEEE Trans. Veh. Technol.*, vol. 47, no. 2, pp. 489–498, May 1998.

[17] L. Kleinrock, *Queueing Systems: Theory*. West Sussex, U.K.: Wiley, 1976.

[18] J. Xiao and F. Liu, "A pre-scanning fast handoff scheme for VoIP in WLANs," *International Journal of Future Computer and Communication*, vol. 8, no. 2, pp. 343–354, 2015.