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Load Balancing for Hybrid LiFi and WiFi Networks: To Tackle User Mobility and Light-path Blockage

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***Abstract*—Combining the high-speed data transmission of light fidelity (LiFi) and the ubiquitous coverage of wireless fidelity (WiFi), hybrid LiFi and WiFi networks (HLWNets) are recently proposed to improve the system capacity of indoor wireless communications. Meanwhile, load balancing becomes a challenging issue due to a complete overlap between the coverage areas of LiFi and WiFi. User mobility and light-path blockages further complicate the process of load balancing, since the decision for a horizontal or a vertical handover in a mobile environment with ultra-small cells is non-trivial. These issues are managed separately in most conventional methods, which might cause frequent handovers and compromise throughput. A few studies address these issues jointly for selecting access points at each time instant but require excessive computational complexity. In this paper, a joint optimisation problem is formulated to determine a network-level selection for each user over a period of time. A novel algorithm based on fuzzy logic is also proposed to reduce the computational complexity that is required to solve the optimisation problem. Results show that compared to the conventional method, the proposed approach can improve system throughput by up to 68%, while achieving very low computational complexity.**

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

I. Introduction

GLOBAL mobile data traffic will increase sevenfold between 2016 and 2021, reaching 48.3 exabytes per month by the end of 2021, and indoor wireless networks will account for over 80% of the total mobile data traffic [2]. This trend will cause an elevated burden on the existing wireless fidelity (WiFi) system due to its limited bandwidth and dense deployment. As a complementary solution to indoor wireless communications, light fidelity (LiFi) [3] exploits lightwaves from daily lighting infrastructure as signal bearers. LiFi offers many advantages over WiFi, such as: i) access to a huge and licence-free optical spectrum, ii) provision of secure communications, and iii) feasibility in radio-frequency (RF) restricted areas. More importantly, LiFi is capable of providing high-speed data transmissions in the range of Gbps [4]. In summary, LiFi is a promising technology to meet the future demand for high data rates in wireless communications.

Combining the high-speed data transmission of LiFi and the ubiquitous coverage of WiFi, hybrid LiFi and WiFi networks (HLWNets) have drawn significant research attentions in recent years [5]. This kind of network has been proven to be able to greatly improve the system capacity of indoor wireless communications [6]. In the meantime, the issue of access point selection (APS) becomes challenging. In a homogeneous network, the coverage overlap among access points (APs) is restricted to avoid inter-cell interference. Accordingly, the situation of unbalanced loads only occurs when the users' demands for data rates are non-uniform in geography. Otherwise load balancing is not required. Hence, in a homogeneous network signal strength strategy (SSS) is commonly used, which assigns each user to the AP that offers the strongest received signal strength. In a HLWNet, however, the coverage areas of LiFi and WiFi completely overlap each other. Also, a WiFi AP usually has a larger coverage area but a lower system capacity than a LiFi AP [7]. Consequently, a WiFi AP would serve more users than a LiFi AP if the SSS method is used. This renders the WiFi system susceptible to traffic overload. For this reason, load balancing becomes essential for HLWNets. A considerable quantity of research has been conducted to tackle this issue [8]–[10]. With proportional fairness resource allocation, the load balancing issue was formulated as an optimisation problem in [8]. In [9], an APS method based on fuzzy logic was reported, which is able to achieve near-optimal performance at significantly reduced computational complexity. The authors in [10] proposed an iterative algorithm to jointly solve load balancing and power allocation.

However, the above methods fail to consider the handover cost caused by user mobility. User movements impose a non-negligible influence on APS, especially for ultra-dense networks [11]. With respect to a hybrid network, handovers fall into two basic categories: horizontal handover (HHO) and vertical handover (VHO). HHOs occur within the domain of a single wireless access technology, whereas VHOs happen

[1]This paper was presented in part at IEEE VTC Fall 2018 [1].

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between different wireless access technologies. Due to different media access control (MAC) protocols, a VHO usually requires a much longer processing time than a HHO [12]. Using the load balancing methods in [8]–[10] might cause frequent and unnecessary VHOs, leading to a compromise in throughput. Also, LiFi APs have a relatively small coverage area, of approximately 2-3m in diameter [13]. This means that even with a moderate speed, mobile users could encounter frequent HHOs if they are served by LiFi. Therefore, it is imperative to consider mobility management in developing load balancing methods for HLWNets. A dynamic load balancing method was proposed in [14], which first measures the handover cost and then implements load balancing. However, this method is an iterative algorithm and requires quantities of iterations to reach a steady state. Based on the college admission model, a mobility-aware load balancing method was developed in [15]. This method needs knowledge about user's trajectories, and fails to consider the impact of user's speeds.

Apart from user mobility, light-path blockages are another important factor that affects the process of load balancing. To date, few studies have been carried out to investigate light-path blockages, and those few are focused on channel characterisation. In [16], the probability of light-path blockages was researched in a simplified indoor scenario. The authors in [17] considered a realistic environment and analysed the resulting changes in channel characteristics. But the influence of light-path blockages on load balancing is widely neglected in the current literature. When a LiFi user encounters light-path blockages, conventional methods always transfer it to WiFi in order to guarantee user fairness in terms of instantaneous throughputs. This user is then transferred back as soon as its LiFi connectivity is restored. However, this manner might cause frequent VHOs to users that experience frequent blockages. Therefore, not all LiFi users should be granted access to WiFi when light-path blockages occur. To the best of the authors' knowledge, no research has so far addressed this issue.

Taking user mobility and light-path blockages into account, the issue of load balancing is studied for HLWNets in this paper. By measuring the handover cost, this work is focused on achieving proportional fairness over a period of time. Specifically, a joint optimisation problem is formulated to determine the type of network access for each user. Three types of network access are designed: 'LiFi only', 'WiFi only' and 'LiFi/WiFi'. The first two types restrict users to a certain network, which is either LiFi or WiFi, while the third type allows selective LiFi users to access WiFi in the event of light-path blockages. To reduce computational complexity, an algorithm based on fuzzy logic is also proposed to narrow down the search range of the formulated optimisation problem. The optimality and computational complexity of the proposed algorithm are numerically analysed, in comparison with the optimal solution obtained by exhaustive search.

The main contribution of this paper is three-fold: i) a load balancing problem is formulated for HLWNets in consideration of both user mobility and light-path blockages; ii) a solution based on fuzzy logic is proposed to significantly reduce the computational complexity that is required to solve the problem; iii) the performance of the proposed method is comprehensively evaluated and compared with the existing related research. Although the load balancing methods in [8] and [14] are applicable to the studied problem, they work less effectively. In contrast with [8], the proposed method performs significantly better due to the joint optimisation of load balancing and handovers. Though [14] also takes handovers into account, the proposed method can still improve throughput by up to 11% as it investigates the impact of light-path blockages.

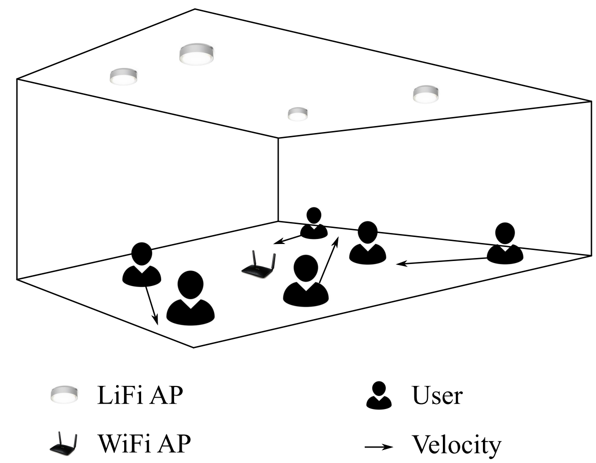

Fig. 1. System model of an indoor HLWNet with mobile users moving in random directions.

The remainder of this paper is organised as follows. The system model of HLWNets is described in Section II, including the network deployment, light-path blockage model and mobility model. The conventional load balancing method is introduced in Section III. In Section IV, the joint optimisation problem is formulated, and the novel fuzzy logic-facilitated algorithm is proposed. Simulation results are given in Section V. Finally, conclusions are drawn in Section VI.

II. System Model

Fig. 1 presents the system model of an indoor HLWNet, which consists of one WiFi AP and a number of LiFi APs. The WiFi AP is placed at the centre of the room and offers coverage for the entire room. Each LiFi AP is integrated into the ceiling light-emitting diode (LED) lamps and covers a confined area. The LiFi APs reuse the optical spectrum to keep inter-cell interference at a negligible level. Here the optical spectrum refers to light wavelengths. Specifically, a mixture of LEDs with different colours can be used to yield white light for illumination, while each coloured light can be modulated separately. These different coloured lights can be split at the receiver by optical apparatus such as in [18]. This setup can sufficiently support the simulations in this paper with up to 14 users. Time-division multiple accessing (TDMA) is used to enable one AP to serve multiple users, whereas each user can only be assigned to one AP. Interested readers are referred to [1] for channel modelling and parameter settings.

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A. Light-path Blockage Model

In [16], occurrence probability is used to characterise light-path blockages at a time point. When the situation is extended to a period of time, the duration of the light-path blockage also matters. In this paper two parameters, occurrence rate and occupation rate, are adopted to model light-path blockages. Occurrence rate, which is denoted by λ_u, is defined as the average number of blockages that occur in a time unit. In queueing theory [19], the Poisson point process is commonly used to model random events such as the arrival of packages at a switch. Accordingly, the events of light-path blockages are assumed to follow a Poisson point process, with the expected occurrence rate equal to λ_u. The parameter λ_u should be a non-negative number, and it is less likely for a user to experience very frequent blockages. Therefore, the gamma distribution with unit shape factor is chosen to model λ_u for different users, with the mean being denoted by λ. Occupation rate, which is denoted by η_u, is defined as the proportion of time that is occupied by light-path blockages. The parameter η_u is assumed to be uniformly distributed between 0 and 1.

Also, [16] assumes a complete blockage when a light-path blockage occurs. In practice, users barely receive any signal if the obstacle is near the transmitter or receiver. Otherwise, they can still acquire some non-line-of-sight (NLOS) signals. However, users would suffer a significant decrease in SNR when their line-of-sight (LOS) paths are blocked, since NLOS reflections typically contribute less than 20% of the total received signal power [20]. For this reason, the above assumption in [16] is adopted in this paper, i.e. the received signal power of a LiFi link is null during light-path blockages.

B. Mobility Model

The random waypoint (RWP) [21] is a commonly used synthetic model for mobility. Users are assumed to move in a straight line from one waypoint to the next, with the waypoints randomly selected over the room. The following modes are considered.

1) Constant Speed (CS): In this mode, the user's speed is constant during the period of interest. For each user, the speed is uniformly distributed between 0 and a maximum value, which is denoted by v_{max}. Since this paper is focused on an indoor scenario, it is reasonable to limit the maximum speed to 5 m/s. In addition, the user's position is measured every 10 ms, during which a user can move 5 cm at most. Taking the 2-3 m coverage range of LiFi into account, this setup can provide a high enough resolution to track the path of the user's movement.

2) Varying Speed (VS): The user's speed usually changes over time in practice. The original RWP model is designed for a large outdoor area, e.g. a 1000 m by 1000 m region in [22], and the users change their speeds when arriving at each waypoint. But the distance between two waypoints is relatively short in an indoor scenario. As a result, the user's speed is considered to remain the same for a short period of time. The user's movement during such a period is referred to as an excursion. Specifically, each user moves with a random speed for a random period that is uniformly distributed between 10 s and 20 s. When the next excursion begins, the user chooses a new speed and continues moving.

3) Varying Speed with Pausing (VSP): The above modes both assume that users are always on the move. In practice, users could be stationary for a while. This is called pausing time, and happens between two excursions. The probability density function of pausing time is usually a uniform distribution [22]. Here the range of pausing time is set to be between 0 s and 10 s.

III. Conventional Load Balancing Method

Denoting the achievable throughput of user u by R_u, proportional resource allocation can be realised by [23]:

$$\text{maximise} \sum_u \log(R_u). \tag{1}$$

For a given time instant t, the achievable throughput $R_u^{(t)}$ is computed by [8, eq. (15)]:

$$R_u^{(t)} = \sum_i \chi_{i,u}^{(t)} \rho_{i,u}^{(t)} r_{i,u}^{(t)}, \tag{2}$$

where $\chi_{i,u}^{(t)} = 1$ means that user u is assigned to AP i, while $\chi_{i,u}^{(t)} = 0$ means otherwise; $\rho_{i,u}^{(t)}$, a fraction variable between 0 and 1, denotes the proportion of time that AP i allocates to user u; $r_{i,u}^{(t)}$ is the capacity that AP i can provide to user u. In [8], Shannon capacity is directly used to represent $r_{i,u}^{(t)}$. However, this is inaccurate due to the non-negative signals in LiFi. A lower bound in [24, eq. (37)] is used, and $r_{i,u}^{(t)}$ can be written as follows:

$$r_{i,u}^{(t)} = \begin{cases} \dfrac{B_i}{2} \log_2\left(1 + \dfrac{e}{2\pi}\gamma_{i,u}^{(t)}\right), & \text{for LiFi} \\ B_i \log_2\left(1 + \gamma_{i,u}^{(t)}\right), & \text{for WiFi} \end{cases}, \tag{3}$$

where B_i is the system bandwidth of AP i, and $\gamma_{i,u}^{(t)}$ denotes the received signal-to-noise ratio (SNR) in regard to the link between AP i and user u at time point t. The expressions of $\gamma_{i,u}^{(t)}$ for LiFi and WiFi are given by [1, eq. (7)] and [1, eq. (10)], respectively.

The method in [8] can balance traffic loads among different APs for a given time instant, and thus is referred to as instantaneous load balancing (ILB). Substituting (2) into (1), the objective function of ILB is expressed as:

$$F_{\text{ILB}}\left(\boldsymbol{\chi}^{(t)}, \boldsymbol{\rho}^{(t)}\right) = \sum_u \log\left(\sum_i \chi_{i,u}^{(t)} \rho_{i,u}^{(t)} r_{i,u}^{(t)}\right), \tag{4}$$

where $\boldsymbol{\chi}^{(t)}$ and $\boldsymbol{\rho}^{(t)}$ denote the sets of $\chi_{i,u}^{(t)}$ and $\rho_{i,u}^{(t)}$, respectively. Since each user is only connected to one AP, (4) can be rewritten as:

$$F_{\text{ILB}}\left(\boldsymbol{\chi}^{(t)}, \boldsymbol{\rho}^{(t)}\right) = \sum_u \sum_i \chi_{i,u}^{(t)} \log\left(\rho_{i,u}^{(t)} r_{i,u}^{(t)}\right). \tag{5}$$

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The optimisation problem of ILB is formulated as:

$$\begin{aligned}
\text{maximise} \quad & F_{\text{ILB}}\left(\boldsymbol{\chi}^{(t)}, \boldsymbol{\rho}^{(t)}\right) \\
\text{subject to} \quad & \chi_{i,u}^{(t)} \in \{0,1\}, \quad \forall i,u; \\
& \sum_i \chi_{i,u}^{(t)} = 1, \quad \forall u; \\
& 0 \le \rho_{i,u}^{(t)} \le 1, \quad \forall i,u; \\
& \sum_u \chi_{i,u}^{(t)} \rho_{i,u}^{(t)} \le 1, \quad \forall i.
\end{aligned} \tag{6}$$

The first constraint indicates that a link connection is either on or off, while the second constraint restricts a single link to each user. As mentioned, $\rho_{i,u}^{(t)}$ ranges between 0 and 1, and this is reflected in the third constraint. The forth constraint limits the overall resources of an AP that are allocated to its users.

IV. Proposed Method

To take the handover cost into account, it is necessary to measure the average throughput over a period of time. During this period, the AP that serves a certain user is dynamic and agnostic. Hence, the proposed method determines the type of network access, which falls into three categories: 'LiFi only', 'WiFi only' and 'LiFi/WiFi'. Users in the first two categories are only granted access to a certain network. These users are handed over within the same network when needed. The third category allows LiFi users to be temporarily served by WiFi in the event of a light-path blockage. When the blockage ends, these users will restore their connections to LiFi. Based on the above categories, a centralised optimisation problem is formulated in this section. To reduce computational complexity, a novel algorithm based on fuzzy logic is also proposed.

A. Centralised Optimisation

First, the handover cost caused by light-path blockages is considered. Users in the category 'WiFi only' are not affected by light-path blockages, since they are always served by WiFi. As for the category 'LiFi only', data transmission is not available during blockages. Users in the category 'LiFi/WiFi' will experience one VHO when a light-path blockage occurs and another VHO when the blockage disappears. The VHO overhead is denoted by T_{VHO}. Let κ denote the type of network access. The proportion of time that is available for LiFi to serve user u is denoted by $\tau_{\kappa,u}^{\text{LiFi}}$, and regarding WiFi it is denoted by $\tau_{\kappa,u}^{\text{WiFi}}$. For different types of network access, $\tau_{\kappa,u}^{\text{LiFi}}$ and $\tau_{\kappa,u}^{\text{WiFi}}$ are expressed as:

$$\tau_{\kappa,u}^{\text{LiFi}} = \begin{cases} 1-\eta_u, & \text{if } \kappa \text{ is 'LiFi only'} \\ 0, & \text{if } \kappa \text{ is 'WiFi only'} \\ \max\{1-\eta_u-\lambda_u T_{\text{VHO}}, 0\}, & \text{if } \kappa \text{ is 'LiFi/WiFi'} \end{cases}. \tag{7}$$

and:

$$\tau_{\kappa,u}^{\text{WiFi}} = \begin{cases} 0, & \text{if } \kappa \text{ is 'LiFi only'} \\ 1, & \text{if } \kappa \text{ is 'WiFi only'} \\ \max\{\eta_u-\lambda_u T_{\text{VHO}}, 0\}, & \text{if } \kappa \text{ is 'LiFi/WiFi'} \end{cases}. \tag{8}$$

The average throughput achieved by user u is denoted by $\bar{R}_u$, and it can be calculated as follows:

$$\bar{R}_u = \sum_\kappa \chi_{\kappa,u} \left(\rho_u^{\text{LiFi}} \tau_{\kappa,u}^{\text{LiFi}} r_u^{\text{LiFi}} + \rho_u^{\text{WiFi}} \tau_{\kappa,u}^{\text{WiFi}} r_u^{\text{WiFi}}\right). \tag{9}$$

Denoting the type of network by α, which is either LiFi or WiFi, the above expression can be rewritten as:

$$\bar{R}_u = \sum_\kappa \chi_{\kappa,u} \sum_\alpha \rho_u^\alpha \tau_{\kappa,u}^\alpha r_u^\alpha, \tag{10}$$

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

$$r_u^\alpha = \begin{cases} \frac{1}{T}\sum\limits_{i\in\alpha} \chi_{i,u} \int_0^T \frac{B_i}{2}\log_2\left(1+\frac{e}{2\pi}\gamma_{i,u}^{(t)}\right)dt, & \text{for LiFi} \\ \frac{1}{T}\sum\limits_{i\in\alpha} \chi_{i,u} \int_0^T B_i\log_2\left(1+\gamma_{i,u}^{(t)}\right)dt, & \text{for WiFi} \end{cases}. \tag{11}$$

Now we consider the handover cost caused by user mobility. Let T_{HHO}^α denote the HHO overhead of the α-type network. The proportion of time spent on HHO is denoted by ϱ_u^α. This parameter can be measured through cell dwell time (CDT), which is defined as the average amount of time to stay in the same AP without handover. The CDT of a user might vary over time. As a result, this information can be statistically measured and updated on a regular basis. Accordingly, the proposed method is invoked repeatedly based on updated CDT. Denoting the CDT of user u within the α-type network by T_u^α, ϱ_u^α can be computed as follows:

$$\varrho_u^\alpha = \begin{cases} \frac{T_{\text{HHO}}^\alpha}{T_u^\alpha}, & \text{if } T_{\text{HHO}}^\alpha \le T_u^\alpha \\ 1, & \text{if } T_{\text{HHO}}^\alpha > T_u^\alpha \end{cases}. \tag{12}$$

Then the average throughput in (10) can be modified to:

$$\bar{R}_u = \sum_\kappa \chi_{\kappa,u} \sum_\alpha \tau_{\kappa,u}^\alpha r_u^\alpha \min\{\rho_u^\alpha, 1-\varrho_u^\alpha\}. \tag{13}$$

The coefficient $\min\{\rho_u^\alpha, 1-\varrho_u^\alpha\}$ signifies the proportion of time that is available for data transmission. As a single WiFi AP is involved in this paper, WiFi users do not experience HHO, i.e. $\varrho_u^{\text{WiFi}} = 0$. Hence, $\min\{\rho_u^{\text{WiFi}}, 1-\varrho_u^{\text{WiFi}}\}$ reduces to ρ_u^{WiFi}. In contrast, $1-\varrho_u^{\text{LiFi}}$ becomes very small for fast-moving LiFi users with a short CDT, restricting the time that is available for data transmission. Substituting (13) into (1), the objective function of the proposed method is expressed in (14). Let N_{AP}^α denote the number of the APs in the α-type network. The optimisation problem of the proposed method is formulated as follows:

$$\begin{aligned}
\text{maximise} \quad & F_{\text{prop.}}(\boldsymbol{\chi}, \boldsymbol{\rho}) \\
\text{subject to} \quad & \chi_{\kappa,u} \in \{0,1\}, \quad \forall \kappa,u; \\
& \sum_\kappa \chi_{\kappa,u} = 1, \quad \forall u; \\
& 0 \le \rho_u^\alpha \le 1, \quad \forall \alpha,u; \\
& \sum_u \chi_{\kappa,u} \rho_u^\alpha \tau_{\kappa,u}^\alpha \le N_{\text{AP}}^\alpha, \quad \forall \alpha.
\end{aligned} \tag{15}$$

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$$F_{\text{prop.}}(\boldsymbol{\chi},\boldsymbol{\rho}) = \sum_{u}\sum_{\kappa}\chi_{\kappa,u}\log\left(\sum_{\alpha}\tau_{\kappa,u}^{\alpha}r_{u}^{\alpha}\min\{\rho_{u}^{\alpha},1-\varrho_{u}^{\alpha}\}\right). \tag{14}$$

The above constraints are similar to the constraints in (6), but restrict $\chi_{\kappa,u}$ and ρ_u^α instead of $\chi_{i,u}^{(t)}$ and $\rho_{i,u}^{(t)}$. The difference between (6) and (15) is that (6) focuses on the instantaneous throughput, whereas (15) measures the throughput over a period of time and considers the handover cost.

B. Fuzzy Logic (FL)-Facilitated Algorithm

Similar to (6), (15) is a mixed integer nonlinear programming (MINLP) problem, which can be solved by the OPTI toolbox [25]. Note that for each user, there are only three options regarding network access in (15), whereas (6) has to search all possible APs. In other words, (15) requires much lower computational complexity than ILB. However, a prohibitive amount of processing power might still be needed to solve (15) via exhaustive search. To reduce computational complexity, FL can be used to facilitate solving (15) by narrowing down its search range. In the existing literature, FL has been applied for access point selection (APS) from the respective angles of load balancing, e.g. [9], and handover, e.g. [26]. However, so far no FL algorithm has been developed for mobility-aware load balancing. The main challenge is to tackle the complicated information of channel quality, resource availability, user movement and light-path blockages. Despite a careful design, the standard FL methods that output a direct solution might not deliver a satisfactory result. Therefore, we propose a two-stage algorithm. In the first stage, an FL system is developed to determine an initial assignment and score it for each user. In the second stage, the algorithm adopts the initial assignments for the users with a score above a pre-defined threshold, and searches among possible assignments for the remaining users.

1) Stage 1: An FL system is comprised of three steps: fuzzification, rule evaluation and defuzzification [27]. In the first step, single-valued parameters are converted into the values of a fuzzy set through membership functions. Here we employ a set of membership functions (MFs) commonly used in Matlab: Z-shaped, Π-shaped and S-shaped MFs [28], and each parameter is converted into the values of three categories: low, medium and high. Five parameters are considered: LiFi capacity, WiFi capacity, LiFi CDT, occurrence rate and occupation rate. For a parameter x, its minimum, median and maximum values are denoted by a, b, and c. The category low has a Z-shaped MF:

$$f_{\text{MF}}^{\text{low}}(x;a,b) = \begin{cases} 1, & x \le a \\ 1-2\left(\dfrac{x-a}{b-a}\right)^2, & a \le x \le \dfrac{a+b}{2} \\ 2\left(\dfrac{x-b}{b-a}\right)^2, & \dfrac{a+b}{2} \le x \le b \\ 0, & x \ge b \end{cases}. \tag{16}$$

The category medium has a Π-shaped MF:

$$f_{\text{MF}}^{\text{med}}(x;a,b,c) = \begin{cases} 0, & x \le a \\ 2\left(\dfrac{x-a}{b-a}\right)^2, & a \le x \le \dfrac{a+b}{2} \\ 1-2\left(\dfrac{x-b}{b-a}\right)^2, & \dfrac{a+b}{2} \le x \le b \\ 1-2\left(\dfrac{x-b}{c-b}\right)^2, & b \le x \le \dfrac{b+c}{2} \\ 2\left(\dfrac{x-c}{c-b}\right)^2, & \dfrac{b+c}{2} \le x \le c \\ 1, & x \ge c \end{cases}. \tag{17}$$

The category high has an S-shaped MF, which is the opposite of a Z-shaped MF:

$$f_{\text{MF}}^{\text{high}}(x;b,c) = 1 - f_{\text{MF}}^{\text{low}}(x;b,c). \tag{18}$$

In the second step, fuzzy rules are developed in Table I to measure the advantages and disadvantages of an assignment candidate, i.e. a type of network access. These rules are intuitively set and self-explanatory. For example, fast-moving users should be served by WiFi (rule 1), whereas slow-moving users with occasional light-path blockages prefer LiFi/WiFi (rule 3). The output value of each rule is the minimum value of all involved components, and the maximum value of the rules regarding the same candidate becomes its output value of the rule set. Then the value of two states, 'yes' and 'no', are obtained for each candidate. The 'yes' value is the output value of the rule set for the corresponding candidate, whereas the 'no' value is the larger 'yes' value of the other two candidates. For instance, the output values of the rule set are 0.6, 0.2 and 0.3 for 'LiFi only', 'WiFi only' and 'LiFi/WiFi', respectively. With respect to 'LiFi only', the 'yes' value is 0.6 and the 'no' value is 0.3.

In the defuzzification step, a single-valued score between 0 and 1 is calculated for each candidate. Similar to the fuzzification step, MFs are used to describe the relation between the states ('yes' and 'no') and the score:

$$f_{\text{MF}}^{\text{yes}}(y;a_1) = \begin{cases} 0, & 0 \le y \le a_1 \\ \dfrac{y-a_1}{1-a_1}, & a_1 \le y \le 1 \end{cases}, \tag{19}$$

and:

$$f_{\text{MF}}^{\text{no}}(y;a_2) = \begin{cases} \dfrac{a_2-y}{a_2}, & 0 \le y \le a_2 \\ 0, & a_2 \le y \le 1 \end{cases}, \tag{20}$$

where y is a variable with the same range as the score. The choices of a_1 and a_2 are not fixed, but normally need to provide an overlap between the MFs. Here we set $a_1 = 0.4$ and $a_2 = 0.6$. The defuzzification process is exemplified in Fig. 2, where for each state the area below both the MF and the state value is shaded. This area reflects how significantly

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TABLE I
FUZZY RULES.

Rule No.	LiFi capacity	WiFi capacity	LiFi CDT	Occurrence rate	Occupation rate	Assignment
1	-	*not* Low	Low	-	-	WiFi only
2	-	*not* Low	-	High	High	WiFi only
3	*not* Low	*not* Low	*not* Low	Low	*not* Low	LiFi/WiFi
4	*not* Low	*not* Low	High	*not* High	High	LiFi/WiFi
5	*not* Low	-	*not* Low	Med	*not* High	LiFi only
6	*not* Low	-	High	High	Low	LiFi only

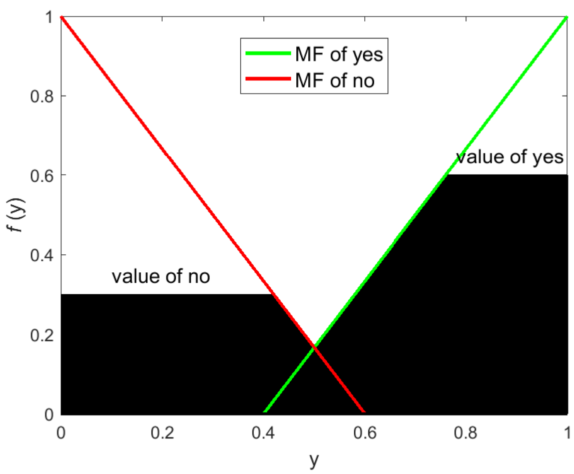

Fig. 2. An example of the defuzzification process.

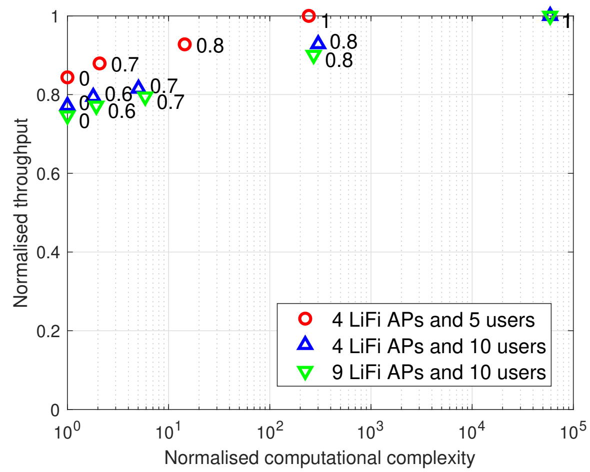

Fig. 3. Optimality versus complexity for different threshold values.

the state contributes to the score. The shaded areas of different states merge into a whole shaded area, of which the upper edge is denoted by $f(y)$. Using the centroid method [29], the score of the corresponding assignment candidate is computed by:

$$\zeta_{\kappa,u} = \frac{\int_0^1 f(y) y dy}{\int_0^1 f(y) dy}. \tag{21}$$

Each user then selects the candidate with the highest score as an initial assignment.

2) Stage 2: Now an initial assignment is obtained for each user, with a score indicating the possibility of the assignment. This assignment can be directly adopted if the corresponding score is larger than a pre-defined threshold. As a result, (15) only needs to provide solutions to the users with a score below the threshold.

C. Analysis of Optimality and Complexity

Due to the heuristic nature and non-linearity of FL, it is difficult to theoretically study the optimality of the proposed algorithm. Alternatively, a numerical comparison is implemented between the FL-based algorithm and exhaustive search, which can be deemed as a special case with a threshold value of 1. Fig. 3 presents system throughput and computational complexity for different threshold values. The throughput achieved by exhaustive search is normalised to 1, as well as the computational complexity required by the FL-based algorithm with a threshold value of 0. As shown, even with a zero threshold, the FL-based algorithm can achieve above 75% of the optimal throughput. In this case, the FL system provides a solution with negligible computational complexity. As the threshold increases, a higher throughput is obtained at the cost of increased complexity. Specifically, with a threshold of 0.8, the FL-based algorithm reaches about 93% of the optimal throughput for 4 LiFi APs and 90% for 9 LiFi APs. Meanwhile, the computational complexity required by the algorithm is related to the number of users. When there are 5 users, the required complexity is smaller than that of exhaustive search by one order of magnitude. This gap becomes two orders of magnitude as the number of users increases to 10.

V. SIMULATION RESULTS

In this section, Monte Carlo simulations are carried out to evaluate the performance of the proposed method, with the threshold value being set to be 0.8. Two network scales of LiFi are considered: 4 and 9 APs. The distance between the two closest LiFi APs is fixed to be 2.5 m. The size of the room depends on the network scale of LiFi. The side length of the room is 5 m for 4 LiFi APs, and for 16 LiFi APs it is 10 m. The height between the LiFi AP and the user is assumed to be 3 m. In wireless local area networks (WLANs), the average overhead of HHO is about 200 ms [30], whereas the average overhead of VHO is set to be 500 ms [31]. For each case

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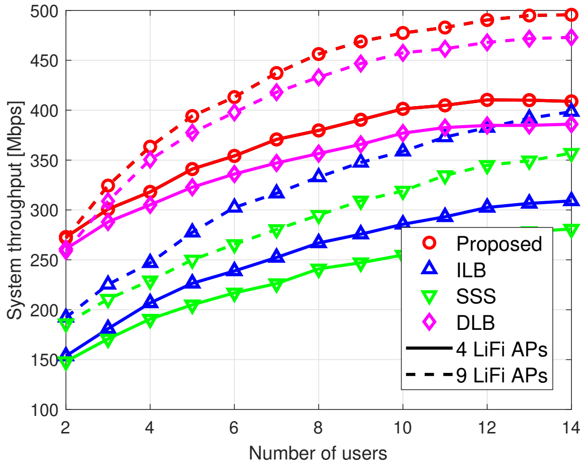

Fig. 4. System throughput versus the number of users ($v_{\max} = 5$ m/s and $\lambda = 10$/min).

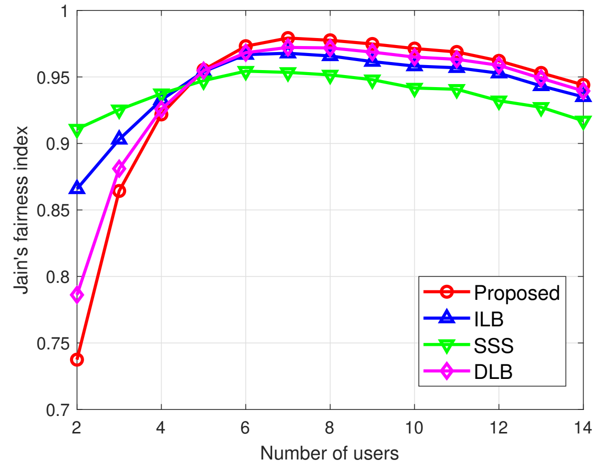

Fig. 5. Fairness versus the number of users ($v_{\max} = 5$ m/s and $\lambda = 10$/min).

of user movement, 1000 simulations are repeated and each simulation mimics an elapsed time of 200 s. Three methods are considered as baselines: ILB in [8], SSS and the dynamic load balancing (DLB) method in [14].

A. Throughput and Fairness

First, we study system throughput and user fairness when the CS mode is applied. The parameter $v_{\max}$ is set to be 5 m/s. Different values of $v_{\max}$ and other modes of the mobility model are analysed later. Fig. 4 presents system throughput as a function of the number of users. As shown, the proposed method noticeably outperforms DLB and ILB, while SSS performs the worst. In the case of 9 LiFi APs with 10 users, for example, the proposed method achieves a system throughput of 477 Mbps, which is about 33% more than the 359 Mbps obtained by ILB. Meanwhile, DLB achieves 20 Mbps less than the proposed method. Another finding is that the proposed method outperforms ILB more significantly when the number of LiFi APs decreases from 9 to 4. With 4 LiFi APs, the throughput gap between the proposed method and ILB increases to 40%. This is because within a smaller room, the WiFi AP has a stronger signal strength at the intersections among LiFi APs. Consequently, ILB is inclined to trigger VHOs when users move across the boundaries between LiFi APs. In this situation, the proposed method can greatly improve system throughput over ILB by reducing VHOs.

Jain's fairness index [32] is commonly used to measure the users' fairness, which can be computed as follows:

$$\xi = \frac{\left(\sum_{u=1}^{N_u} S_u\right)^2}{N_u \sum_{u=1}^{N_u} S_u^2}, \tag{22}$$

where N_u denotes the number of users, and S_u is the achieved throughput of user u.

In Fig. 5, Jain's fairness index is measured for 4 LiFi APs. Similar trends are found in the case of 9 LiFi APs. As can be seen, when the number of users increases from 2 to 14, user fairness first increases and then decreases. The reason for this trend is that when there are only a few users, user throughputs are mainly limited by their handover rates. As the number of users increases, handover rates are distributed more uniformly and thus user fairness increases. However, when more users participate, user throughputs are restricted by resource competitions among users and user fairness decreases. Comparing Fig. 4 and Fig. 5, it is found that when the number of users is less than 5, a trade-off exists between throughput and fairness. Specifically, the proposed method achieves the highest throughput among all methods but the lowest fairness. SSS performs in an opposite manner, i.e. with the lowest throughput but the highest fairness. This is because reducing handovers can increase throughput for individual users as well as enlarging the throughput difference across users. When there are more than 5 users, the proposed method achieves both the highest throughput and the highest fairness. As mentioned, users are competing for AP resources in this scenario. Therefore, an increase in the throughput of an individual user can also benefit other users by shifting more resources to them.

B. Effects of Light-path Blockage

Second, Fig. 6 shows system throughput in relation to the occurrence rate of light-path blockages λ. When $\lambda = 0$, i.e. there is no light-path blockage, handovers are only caused by user mobility. In this case, the proposed method achieves throughputs which are 30% and 26% higher than ILB for 4 and 9 LiFi APs, respectively. These improvements signify the outstanding performance of the proposed method in coping with user mobility. Meanwhile, the performance of DLB is close to that of the proposed method since DLB also considers user mobility. As λ increases, throughput decreases for all methods. However, it decreases much slower for the proposed method than for the other methods. In other words, the benefit of the proposed method becomes greater when light-path blockages occur more frequently. When λ increases from 0 to 20 times per minute in the case of 4 LiFi APs, the throughput

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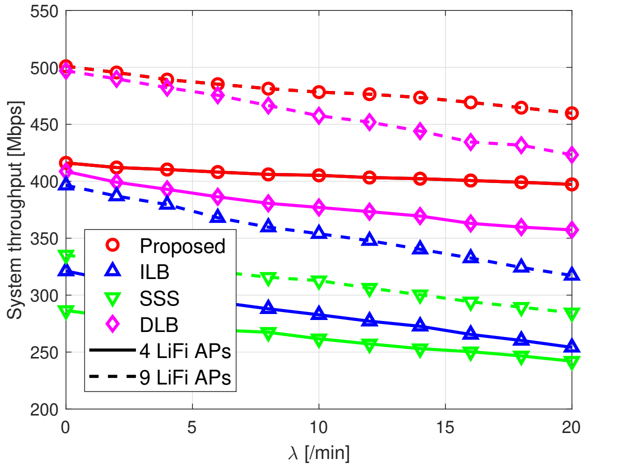

Fig. 6. System throughput versus the occurrence rate of light-path blockages ($N_u = 10$ and $v_{\max} = 5$ m/s).

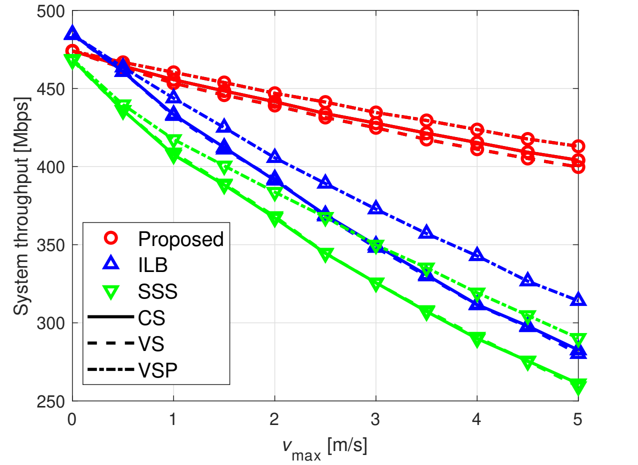

Fig. 7. System throughput versus the user's speed for different RWP modes (4 LiFi APs, $N_u = 10$ and $\lambda = 10$/min).

achieved by the proposed method drops from 447 Mbps to 427 Mbps (merely 4.7%). Meanwhile, ILB has a decrease of 26% in system throughput, and DLB has a decrease of 12%. This makes the proposed method obtain a system throughput 68% higher than ILB and 11% higher than DLB.

C. Different RWP Modes

Finally, the performance of the proposed method is studied for different RWP modes. Fig. 7 presents system throughput as a function of the user's speed. DLB is not included here since the underlying difference between it and the proposed method is about light-path blockages, rather than user mobility. Regarding ILB and SSS, the achieved throughput remains the same when the RWP mode changes from CS to VS. This is because ILB and SSS operate at a given time instant and are not affected by changes in speed. Meanwhile, the system throughput of the proposed method slightly decreases. The reason for this trend is that changes in speed force the proposed method to recompute solutions, causing an additional number of handovers. However, this causes a very slight decrease in throughput because the proposed method is invoked much less frequently than ILB. Also, it is found that ILB and SSS both achieve a noticeably higher throughput with the VSP mode than with the CS or VS mode. This is because the user's average speed is half of $v_{\max}$ in the CS and VS modes, whereas in the VSP mode it becomes lower due to the pausing time. Correspondingly, handover rates become lower in the VSP mode. In contrast, the proposed method only obtains a marginal increase in throughput, as a composite outcome of the change in speed and the decrease in the user's average speed.

Furthermore, we notice that the system throughput of the proposed method falls behind that of ILB when the user's average speed is below 0.15 m/s. This is because ILB provides an optimal solution in the scenario of stationary users. Despite this, the proposed method achieves a throughput very close to ILB, with a modest gap of less than 2%. Moreover, as the user's speed increases, the proposed method outperforms ILB more significantly. With every 1 m/s increase in speed, the throughput gap (in percentage) between the proposed method and ILB increases by about 10%. The reason for this trend is that the proposed method can effectively reduce the VHO rate against ILB, especially when users move relatively fast.

VI. Conclusions

In this paper, a novel load balancing scheme was proposed for HLWNets, to jointly tackle the issues of user mobility and light-path blockages. By exploiting information about CDT and blockage occurrence, the proposed method assigns a type of network access to each user over a period of time. There are three types of network access in a HLWNet: 'LiFi only', 'WiFi only' and 'LiFi/WiFi'. An FL-facilitated algorithm was also proposed to reduce computational complexity required by the formulated optimisation problem. The proposed method does not rely on instantaneous channel state information, and hence it requires much less frequent updates than ILB. Results show that the proposed method is able to obtain a higher throughput than ILB when the user's speed is greater than 0.15 m/s. When users move faster or light-path blockages occur more frequently, the throughput gap between the proposed method and ILB enlarges, reaching up to 68%. Future work will carry out experimental works to investigate the performance of the proposed method in a realistic environment, which involves user mobility and light-path blockages.

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