IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 6, 2021, accepted September 28, 2021, date of publication October 4, 2021, date of current version October 12, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3117341

Feedback Interval Optimization for MISO LiFi Systems

FAN ZHANG[1], JIAXUAN CHEN[1], TIANQI MAO[1], AND ZHAOCHENG WANG[1,2], (Fellow, IEEE)

[1]Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
[2]Department of Broadband Communication, Peng Cheng Laboratory, Shenzhen 518055, China

Corresponding author: Zhaocheng Wang (zcwang@tsinghua.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61871253, in part by the Major Key Project of Peng Cheng Laboratory (PCL) under Grant PCL2021A15, in part by Guangdong Optical Wireless Communication Engineering and Technology Center, and in part by Shenzhen Visible Light Communication (VLC) System Key Laboratory under Grant ZDSYS20140512114229398.

ABSTRACT Utilizing the densely deployed light-emitting diodes (LEDs) as transmitters, multiple-input-single-output (MISO) becomes an attractive technique to improve the transmission throughput of light-fidelity (LiFi) systems. To fully exploit the benefits of joint transmission of multiple LEDs, beamforming techniques are usually employed to improve the downlink throughput, which requires the knowledge of channel state information (CSI) at transmitter. Since frequent CSI feedback leads to heavy overhead, the optimization of feedback interval, defined as the time period between two adjacent feedbacks, is investigated in this paper, which aims at maximizing the weighted bidirectional transmission throughput. Additionally, a quasi-optimal solution is calculated as a well approximation of the exact optimal solution in order to reduce the computational complexity. Simulation results show that, the proposed feedback interval optimization is capable of improving the weighted bidirectional throughput considerably thanks to the reduced CSI feedback overhead, compared with its conventional counterparts using classical feedback mechanisms. Besides, by employing the obtained quasi-optimal feedback interval, the weighted bidirectional throughput approaches that of the optimal interval with much lower computational complexity.

INDEX TERMS Light-fidelity, channel state information, feedback interval, multiple-input single-output, optical wireless communication.

I. INTRODUCTION

To cope with the ever increasing data traffic, optical wireless communication (OWC) has received much attention from both academia and industrial field as a promising complement to radio frequency (RF) communications, due to its advantages of abundant unregulated spectrum, high spatial reuse, data security, etc [1]–[3]. Light-fidelity (LiFi) is one of the representatives of OWC technologies, which enables networked and bidirectional wireless links and is usually used to connect fixed and mobile devices at high data rates [4]. Typically, light-emitting diodes (LEDs) are densely deployed indoor in order to provide adequate illumination, which can be naturally exploited to realize LiFi systems [5].

In LiFi systems, visible light communication (VLC) is employed for downlink communication, whilst the infrared (IR) spectrum is utilized in the uplink to avoid the cross-interference with the downlink [6]. In downlink transmission, multiple-input single-output (MISO) technique is widely employed to improve the transmission throughput [5], [7]. To attain the performance gain of joint transmission of multiple LEDs, beamforming techniques are usually employed, which requires the accuracy and timeliness of channel state information (CSI) at transmitter [8], [9]. Since different frequency bands are occupied in the downlink and uplink, respectively, the channel reciprocity is not satisfied. Therefore, feedback is required after downlink channel estimation to ensure the knowledge of CSI at transmitter, which however causes inevitable degradation of the uplink throughput. The resultant overhead for unlink transmission increases with the required accuracy and timeliness of CSI, as well as the number of used LEDs in the MISO systems [10]. Therefore, a number of studies have been carried out to save resources allocated to CSI feedback while maintaining the system performance.

The associate editor coordinating the review of this manuscript and approving it for publication was Stanley Cheung.

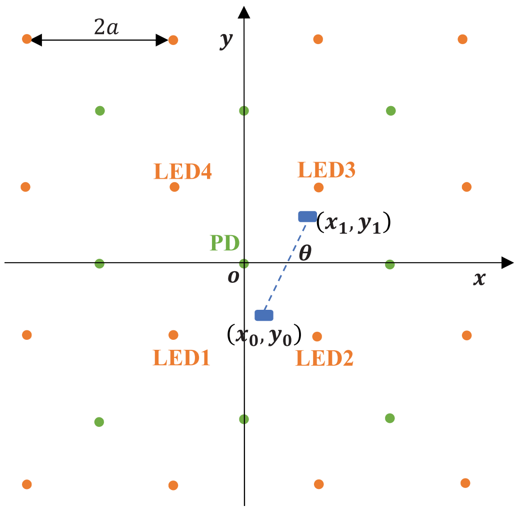

FIGURE 1. A typical layout of LEDs and PDs. The orange points are LEDs, the green points are PDs, and the blue rectangle is the moving UE.

A one-bit feedback scheme was proposed in [11], where the access point (AP) gets only one-bit feedback indicating whether the distance between the user equipment (UE) and itself exceeds a predefined threshold. In [12], a two-bit feedback scheme, where two thresholds are set for both the distance and the vertical angle, was proposed to improve the effectiveness of CSI feedback. However, the aforementioned limited-content feedback schemes always require complex algorithms to find the optimal threshold [13], [14].

On the other hand, it is evident that the OWC channels mainly depend on the relative location between the transmitters and receivers [15]. As a result, OWC channels change slowly when UEs are moving at low speed, and thus the overhead of CSI feedback can be further reduced by adjusting the frequency of feedback in aligned with the UE velocity. To the best of our knowledge, so far only limited literature focuses on reducing the CSI feedback frequency whilst maintaining the downlink throughput at an acceptable level. In [16], an optimal CSI feedback interval, defined as the time period between two adjacent feedbacks, was derived for single-input single-output (SISO) LiFi systems, where the multi-LED case was not considered.

To this end, this paper investigates the optimization of the CSI feedback interval for MISO LiFi systems, which is firstly formulated as a maximization problem of the weighted bidirectional throughput. Then, a closed-form quasi-optimal solution of the feedback interval is derived, which is demonstrated via simulations to approach the optimal solution. Simulation results also show that, by employing the proposed quasi-optimal feedback interval, the weighted bidirectional throughout can be improved significantly due to the reduced CSI feedback overhead, compared with the conventional feedback schemes.

II. SYSTEM DESCRIPTION

An indoor LiFi system is considered, where visible light and infrared band are utilized for downlink and uplink transmissions, respectively. As shown in Fig. 1, LEDs are densely deployed in a grid on the ceiling, as the optical transmitters for downlink data transfer. On the other hand, several PDs are also deployed on the ceiling to receive the uplink information. These LEDs and PDs are assumed to be oriented vertically downwards, both of which are connected with the central controller through powerline communications (PLC) for instance [17].

Moreover, for the UEs on the floor, their movement is assumed to follow the random waypoint (RWP) model [18], where the velocity and moving direction are assumed to be constant in a short period of time. Different UEs might avoid interference by a Time-Division-Multiple-Access (TDMA) scheme proposed in [19]. Besides, each UE is restricted to be served by the nearest k ceiling LEDs in downlink transmission, and would merely connect to the nearest ceiling PD for uplink transmission.

A two-dimensional coordinate system is introduced to describe the relative position between the ceiling transceiving components and the UE. The UE location at time t_0 is assumed to be (x_0, y_0). After passing a sufficiently short time period Δt, by denoting the UE velocity and moving direction as v and θ, respectively, the distance between the UE and the ith ($i = 1, 2, \ldots, k$) ceiling LED serving the UE at time $t = t_0 + \Delta t$, can be derived as

$$\begin{aligned} d_i(t) &= (r_i^2(t) + z^2)^{\frac{1}{2}} \\ &= (r_i^2(t_0) + v^2\Delta t^2 - 2r_i(t_0)v\Delta t \cos\theta_i + z^2)^{\frac{1}{2}}, \end{aligned} \tag{1}$$

where z is the height of the ceiling, and $r_i(t)$ is the horizontal distance between the UE and the ith ceiling LED at time t. Besides, $\theta_i = \theta - \tan^{-1}\frac{y_0 - y_i}{x_0 - x_i}$, and (x_i, y_i) is the coordinate of the ith LED.

Similarly, the distance between the UE and the ceiling PD at time t can be derived as

$$\begin{aligned} d_u(t) &= (r_u^2(t) + z^2)^{\frac{1}{2}} \\ &= (r_u^2(t_0) + v^2\Delta t^2 - 2r_u(t_0)v\Delta t \cos\theta_u + z^2)^{\frac{1}{2}}, \end{aligned} \tag{2}$$

where $r_u(t)$ is the horizontal distance between the UE and the ceiling PD at time t. Besides, $\theta_\mathrm{u} = \theta - \tan^{-1}\frac{y_0 - y_\mathrm{u}}{x_0 - x_\mathrm{u}}$, and (x_u, y_u) is the coordinate of the PD.

A. SYSTEM MODEL FOR LiFi MISO SYSTEMS

In downlink transmission, the input binary bits are firstly mapped to the data symbol $x(t)$ by the modulator. Then, based on the real-valued beamforming vector $\mathbf{w}(t) = [w_1(t), w_2(t), \ldots, w_k(t)]$, the central controller determines the power allocation strategy of the nearest k LED transmitters, which are chosen to serve the UE. Finally $x(t)$ is transmitted by these k LEDs to the UE, with the electrical power of the ith LED as $w_i^2(t)$, converting the electrical signal into intensity modulated optical signal. By such arrangement, the received signal $y(t)$ can be formulated as

$$y(t) = \mathbf{h}_\mathrm{d}{}^T(t)\mathbf{w}(t)x(t) + n(t), \tag{3}$$

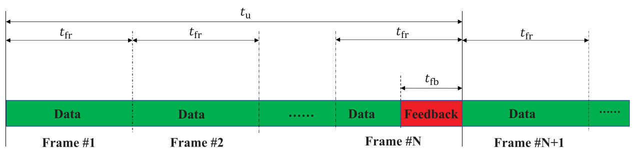

FIGURE 2. The diagram of uplink transmission with CSI feedback mechanism in the MISO LiFi systems.

where $\mathbf{h}_d(t) = [h_{d,1}(t), h_{d,2}(t), \ldots, h_{d,k}(t)]$ is the $1 \times k$ channel fading vector corresponding to the k LEDs, and $n(t)$ denotes the noise component. For brevity, time variable "(t)" is omitted in the notations of this section.

The beamforming vector $\mathbf{w}$ can be flexibly designed following different criterions according to the feedback of the downlink CSI. For instance, given the sum of the k LEDs' electrical power $P_d = |\mathbf{w}|^2$, the received signal power reaches its maximum when $\mathbf{w}$ is assigned as

$$\mathbf{w} = \sqrt{P_d}\frac{\hat{\mathbf{h}}_d}{|\hat{\mathbf{h}}_d|}, \tag{4}$$

where $\hat{\mathbf{h}}_d$ denotes the estimated CSI and $|\hat{\mathbf{h}}_d|$ is its Euclidean norm. If the feedback of estimated CSI is accurate, i.e., $\hat{\mathbf{h}}_d = \mathbf{h}_d$, the maximal downlink throughput can be obtained by (4) under the electrical power constraint.

Since the knowledge of downlink CSI is required at the central controller for beamforming operations, the downlink channel should be estimated at the UE, and sent back to the ceiling during uplink transmission periodically, as shown in Fig. 2. The CSI feedback of length t_{fb} is performed every feedback interval t_u, which equivalently contains N consecutive data frames of length t_{fr}, yielding $t_u = Nt_{fr}$. Here we suppose that the beginning of one feedback interval is $t = t_0$, then the next feedback interval begins at $t = t_0 + t_u$. Based on the updated CSI, the beamforming vector $\mathbf{w}$, i.e., the power allocation of ceiling LEDs, is re-calculated at the central controller, which is applied for downlink transmission in the next feedback interval.

B. CHANNEL MODEL

The channel gain between the ith ceiling LED and the UE consists of line of sight (LOS) and non-line of sight (NLOS) components. Since the LOS channel gain is usually much larger than the NLOS channel gain [20], only the LOS channel gain is considered in the optimization of the feedback interval. Specifically, the LOS channel gain between the ith LED and the UE can be calculated as [21]

$$h_{LoS,i} = g_f\frac{(m+1)A}{2\pi d_i^2}\cos^m(\phi_i)g(\psi_i)\cos(\psi_i), \tag{5}$$

where A, d_i, ϕ_i and ψ_i are the physical area of the detector, the distance between the ith ceiling LED and the UE, the radiance angle and the incidence angle, respectively. $g(\psi_i)$ is the optical concentrator gain, which equals $\varsigma^2/\sin^2\Psi_c$ for $0 \le \psi_i \le \Psi_c$, and equals 0 for $\psi_i > \Psi_c$, where Ψ_c is the field of view (FOV) of the receiver and ς is the refractive index. In addition, m is the order of Lambertian emission and g_f is the optical filter gain. It should be noted that the aforementioned channel model is similar with that of IR spectrum for the uplink transmission, whose description is omitted here for brevity [22].

Supposing that all the receivers and transmitters are oriented vertically, then $\cos\psi_i = \cos\phi_i = z/d_i$ can be substituted in (5), where z is the height of the ceiling. Therefore, we have

$$h_{LoS,i} = G_0/d_i^{m+3}, \quad 0 \le \psi_i \le \Psi_c, \tag{6}$$

where $G_0 = g_f\frac{(m+1)A}{2\pi\sin^2\Psi_c}z^{m+1}\varsigma^2$.

In addition, the PD responsivity ρ_{PD} is considered at the receiver end, and the downlink channel fading vector $\mathbf{h}_d$ can be expressed as

$$\mathbf{h}_d = \rho_{PD}[h_{LoS,1}, h_{LoS,2}, \ldots, h_{LoS,k}]. \tag{7}$$

Similarly, the uplink channel fading coefficient h_u can be obtained by

$$h_u = \rho_{PD}h_{LoS,u}, \tag{8}$$

where $h_{LoS,u}$ is the uplink LOS channel gain.

III. FEEDBACK INTERVAL OPTIMIZATION

To reduce the overhead of CSI feedback, whilst maintaining the downlink performance at an acceptable level, the optimization of the feedback interval is demonstrated in this section, which is formulated as a maximization problem of the weighted bidirectional throughput. Moreover, a closed-form quasi-optimal solution is proposed in order to reduce the computational complexity.

A. PROBLEM FORMULATION

In the LiFi system mentioned in Section II, if the feedback interval is too long, the UE location may change considerably within the feedback interval. As a result, the CSI knowledge at the central controller will become outdated, leading to the loss of the beamforming gain. On the contrary, if the feedback interval is too short, the downlink performance will increase. However, the uplink transmission would be degraded due to the heavy overhead of CSI feedback. To reach a desirable trade-off between the performances of downlink and uplink transmissions, we use the weighted average bidirectional throughput, considering the throughput of both links, as the optimization objective function to find the appropriate value of t_u [23]. The corresponding maximization problem is formulated as

$$\begin{aligned} &\max_{t_u}\ \mathbb{E}_{x0,y0,\theta}[w_d\overline{R_d}(t_u) + w_u\overline{R_u}(t_u)] \\ &s.t.\ t_{fb} < t_u, \end{aligned} \tag{9}$$

where w_d and w_u are the weights of downlink and uplink channels throughput, respectively, and $\mathbb{E}_{x0,y0,\theta}[\cdot]$ denotes the expectation operation on the initial location of UE (x_0, y_0) and the moving direction θ. In addition, $\overline{R_d}(t_u)$ and $\overline{R_u}(t_u)$ are the average downlink and uplink throughput, respectively, which are expressed as

$$\overline{R_{\mathrm{d}}}(t_{\mathrm{u}}) = \frac{1}{t_{\mathrm{u}}}\int_{t_0}^{t_0+t_{\mathrm{u}}} R_{\mathrm{d}}(t)\mathrm{d}t, \tag{10}$$

$$\overline{R_{\mathrm{u}}}(t_{\mathrm{u}}) = \frac{1}{t_{\mathrm{u}}}\int_{t_0}^{t_0+t_{\mathrm{u}}} R_{\mathrm{u}}(t)\mathrm{d}t, \tag{11}$$

where $R_{\mathrm{d}}(t)$ and $R_{\mathrm{u}}(t)$ are the uplink and downlink throughput, respectively. It should be noted that, the feedback interval t_{u} should be larger than the feedback duration t_{fb}, which is considered as a restraint condition in the maximization problem.

In consideration of the feedback overhead, the uplink throughput at time t can be calculated as [24]

$$R_{\mathrm{u}}(t) = (1-\frac{t_{\mathrm{fb}}}{t_{\mathrm{u}}})B_{\mathrm{u}}\log_2(1+\gamma_{\mathrm{u}}(t)), \tag{12}$$

where B_{u} is the uplink bandwidth and $\gamma_{\mathrm{u}}(t)$ is the SINR at the ceiling PD at time t given by

$$\gamma_{\mathrm{u}}(t) = \frac{h_{\mathrm{u}}^2(t)P_{\mathrm{u}}}{N_0 B_{\mathrm{u}}}, \tag{13}$$

where P_{u} is the transmitted power for uplink, $h_{\mathrm{u}}(t)$ is the uplink channel fading coefficient at time t, and N_0 is the power spectral density of the noise. By substituting $h_{\mathrm{u}}(t)$ with (8), (13) can be expressed as

$$\gamma_{\mathrm{u}}(t) = \frac{(\rho_{\mathrm{PD}}G_0)^2 P_{\mathrm{u}}}{(r_{\mathrm{u}}^2(t)+z^2)^{m+3}N_0 B_{\mathrm{u}}}. \tag{14}$$

On the other hand, the downlink throughput can be formulated as

$$R_{\mathrm{d}}(t) = B_{\mathrm{d}}\log_2(1+\gamma_{\mathrm{d}}(t)), \tag{15}$$

where B_{d} is the downlink bandwidth and $\gamma_{\mathrm{d}}(t)$ is the SINR at the UE at time t given by

$$\gamma_{\mathrm{d}}(t) = \frac{(\sum_{i=1}^{k} w_i h_{\mathrm{d},i}(t))^2}{N_0 B_{\mathrm{d}}}, \tag{16}$$

where w_i is the ith element of the beamforming vector, $h_{\mathrm{d},i}(t)$ is the downlink channel fading coefficient between the ith ceiling LED and the UE at time t. After substituting $h_{\mathrm{d},i}(t)$ given in (7), the SINR γ_{d} at time t can be given by

$$\gamma_{\mathrm{d}}(t) = \frac{\rho_{\mathrm{PD}}^2 G_0^2(\sum_{i=1}^{k} w_i (r_i^2(t)+z^2)^{\frac{-(m+3)}{2}})^2}{N_0 B_{\mathrm{d}}}. \tag{17}$$

The beamforming vector $\mathbf{w}$ during a feedback interval can be determined given the CSI feedback $\hat{\mathbf{h}}_{\mathrm{d}}(t_0)$ from the UE, namely the channel fading coefficient at time t_0. Accordingly, the downlink throughput at time t during a feedback interval can be calculated using (15).

B. QUASI-OPTIMAL SOLUTION AND ANALYSIS

Obviously, the optimization problem of the CSI feedback interval can be addressed accurately by exhaustive search, which, however, involves high computational complexity. Therefore, a closed-form quasi-optimal solution is given, which makes the proposed feedback scheme practical for the central controller. Furthermore, performance analysis is carried out based on the obtained expression of the quasi-optimal feedback interval.

Because of the linearity of the expectation operation and the differentiability of the functions $\overline{R_{\mathrm{d}}}(t_{\mathrm{u}})$ and $\overline{R_{\mathrm{u}}}(t_{\mathrm{u}})$ in terms of t_{u}, the maximization problem (9) can be addressed by solving the following equation as

$$w_{\mathrm{d}}\mathbb{E}_{x0,y0,\theta}[\frac{\partial\overline{R_{\mathrm{d}}}(t_{\mathrm{u}})}{\partial t_{\mathrm{u}}}] + w_{\mathrm{u}}\mathbb{E}_{x0,y0,\theta}[\frac{\partial\overline{R_{\mathrm{u}}}(t_{\mathrm{u}})}{\partial t_{\mathrm{u}}}] = 0, \tag{18}$$

where the $\frac{\partial\overline{R_{\mathrm{d}}}(t_{\mathrm{u}})}{\partial t_{\mathrm{u}}}$ and $\frac{\partial\overline{R_{\mathrm{u}}}(t_{\mathrm{u}})}{\partial t_{\mathrm{u}}}$ are the partial derivatives of the average downlink throughput and uplink throughput, respectively.

To simplify the derivation of the quasi-optimal solution, we assume that the UE moves along a straight line from the initial location (x_0,y_0) with the moving direction θ chosen randomly within $(0, 2\pi)$. Under this assumption, based on the derivations in Appendix, (18) can be simplified as

$$\frac{2(m+3)v^2}{3\ln 2}(w_{\mathrm{u}}B_{\mathrm{u}}C_2 + w_{\mathrm{d}}B_{\mathrm{d}}C_1)t_{\mathrm{u}}^3 - w_{\mathrm{u}}B_{\mathrm{u}}C_3 t_{\mathrm{fb}} = 0, \tag{19}$$

where the parameters C_1, C_2 and C_3 are formulated as

$$C_1 = \sum_{i=1}^{k}\mathbb{E}_{x0,y0,\theta}[\frac{w_i^2}{|\mathbf{w}|^2}\frac{(z^2+(r_i(t_0)\sin\theta_i)^2)^2}{(z^2+r_i(t_0)^2)^3}], \tag{20}$$

$$C_2 = \mathbb{E}_{x0,y0,\theta}[\frac{(z^2+(r_{\mathrm{u}}(t_0)\sin\theta_{\mathrm{u}})^2)^2}{(z^2+r_{\mathrm{u}}(t_0)^2)^3}], \tag{21}$$

$$C_3 = \mathbb{E}_{x0,y0}[\log_2(\frac{G_{\mathrm{u}}}{(z^2+r_{\mathrm{u}}(t_0)^2)^{m+3}})]. \tag{22}$$

Hereby we have $G_{\mathrm{u}} = \frac{(\rho_{\mathrm{PD}}G_0)^2P_{\mathrm{u}}}{N_0B_{\mathrm{u}}}$.

By solving (19), the solution of (18) can be approximated as

$$\tilde{t}_{\mathrm{u}} \approx (\frac{\frac{3\ln 2}{2(m+3)}w_{\mathrm{u}}B_{\mathrm{u}}t_{\mathrm{fb}}C_3}{w_{\mathrm{d}}B_{\mathrm{d}}C_1v^2 + w_{\mathrm{u}}B_{\mathrm{u}}C_2v^2})^{\frac{1}{3}}, \tag{23}$$

which is referred to as the quasi-optimal solution of the feedback interval.

As it can be seen from (23), the optimal feedback interval is proportional to $v^{-\frac{2}{3}}$, which can be explained as follows. When the UE kept unchanged or moves slowly, i.e., the value of v approaches 0, the frequency of the CSI feedback is low since the downlink channel keeps invariant; on the contrary, the frequent CSI feedback is required in order to catch up with the faster temporal variations of the downlink channel.

Moreover, $\tilde{t}_{\mathrm{u}}$ is also proportional to $(t_{\mathrm{fb}})^{\frac{1}{3}}$, which provides guidelines to set appropriate feedback interval. As the feedback duration becomes longer, the frequency of CSI feedback needs to be decreased to reduce the overhead of the feedback.

TABLE 1. Simulation parameters.

VLC parameters	Value
The order of the Lambertian emission m	1
Field of view of the receiver Ψ_c	$\pi/2$
The optical filter gain g_f	1
The refractive index ς	1
The physical area of the detector A	1 cm^2
PD responsivity ρ_{PD}	1 A/W
The uplink transmitted power P_u	0.04 W
The sum of downlink transmitted power P_d	16 W
The downlink bandwidth B_d	1.5 MHz
The uplink bandwidth B_u	0.5 MHz
The power spectral density of the noise N_0	10^{-20} A^2/Hz
The number of the full CSI bits β	8
The feedback duration t_{fb}	0.8 ms
Room Parameters	**Value**
The room size	$10 \times 10 \times 3$ m^3
The number of LEDs serving the UE k	4
The distance of two adjacent LEDs $2a$	2 m

On the contrary, more frequent feedback can be applied for timely CSI updates when the feedback duration is short.

It is evident that the obtained optimal feedback interval is affected by the weighted parameters w_d and w_u, which depends on the specific requirements of the LiFi network. For instance, if the downlink throughput is more emphasized than its uplink counterpart, then w_d/w_u will be set larger ($w_d > w_u$), leading to increased frequency of CSI feedback according to (19), and vice versa.

IV. NUMERICAL RESULTS

In this section, simulations are provided to validate the proposed feedback interval optimization scheme and the quasi-optimal solution obtained by the proposed closed-form expression. Firstly, the proposed quasi-optimal solution of the feedback interval is compared with the corresponding optimal solution obtained by exhaustive search. Afterwards, the performance of the proposed feedback interval optimization scheme is evaluated in terms of the bidirectional throughput and the CSI feedback overhead in comparison with its conventional counterparts.

Three benchmarks are considered in simulations, that is, the scheme without CSI feedback, the scheme with fixed CSI feedback interval proposed in [25], and the scheme proposed in [11] with only one bit feedback which indicates whether the distance exceeds a threshold. For clarification, these schemes are denoted as no-feedback scheme, fixed-feedback scheme and one-bit scheme. For fixed-feedback scheme and one-bit scheme, the fixed feedback interval is 10ms and the threshold of one-bit scheme is the optimal threshold obtained by exhaustive search.

In simulations, the beamforming designed in (4) is employed. Specifically, the expression of $\mathbf{w}$ in (4) is substituted into (20), yielding

$$C_1 = \sum_{i=1}^{k} \mathbb{E}_{x0,y0,\theta}\left[\frac{S_i}{S}\frac{(z^2 + (r_i(t_0)\sin\theta_i)^2)^2}{(z^2 + r_i(t_0)^2)^3}\right], \quad (24)$$

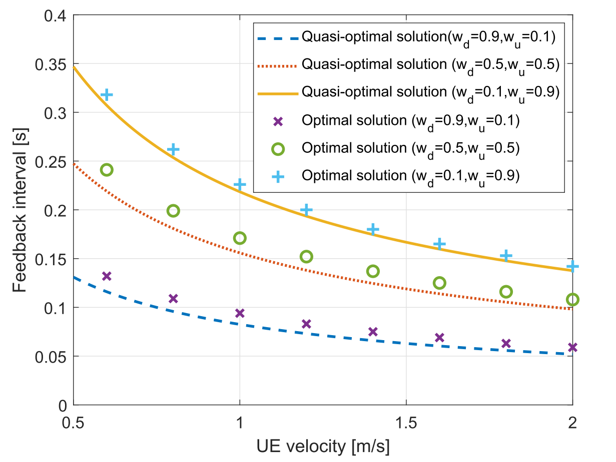

FIGURE 3. Comparison between the optimal solution and quasi-optimal solution.

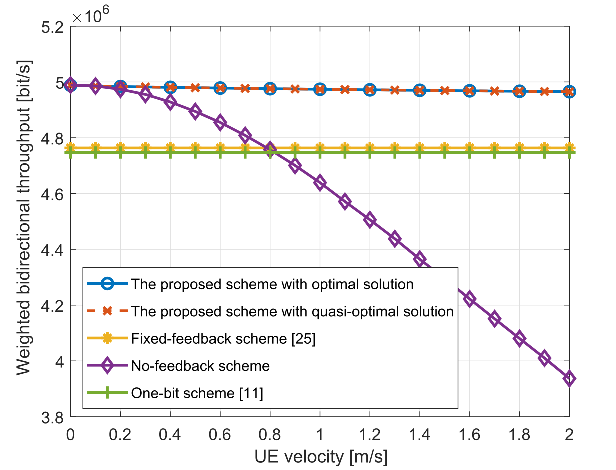

FIGURE 4. The weighted bidirectional throughput comparison when $w_d = 0.1$ and $w_u = 0.9$.

where $S_i = (r_i^2(t_0) + z^2)^{-(m+3)}$, $S = \sum_{i=1}^{k} S_i$. Other simulation parameters are listed in Table 1 [16]. The velocity of the UE is assumed to range from 0 to 2m/s according to the study of adults' walking speed [26]. Besides, the mobility of the UE is simulated using the RWP model in [18], and the bits for velocity feedback is relatively small in uplink transmission [24].

Figure 3 compares the proposed quasi-optimal solution of the feedback interval with the corresponding optimal solution obtained by exhaustive search. It is shown that the proposed quasi-optimal solution of the feedback interval fits well the actual optimal counterpart, which validates of our derivations. In addition, the optimal feedback interval decreases when the UE velocity and the value of $\frac{w_d}{w_u}$ increases, which is in aligned with the analysis in Section III-B. However, to find the optimal feedback interval for different UE velocities, the exhaustive search involves 10^4 times of simulations for each fixed t_u and each simulation involves the throughput integral with t going from t_0 to $t_0 + t_u$, which results in high computational complexity. On the contrary, the quasi-optimal

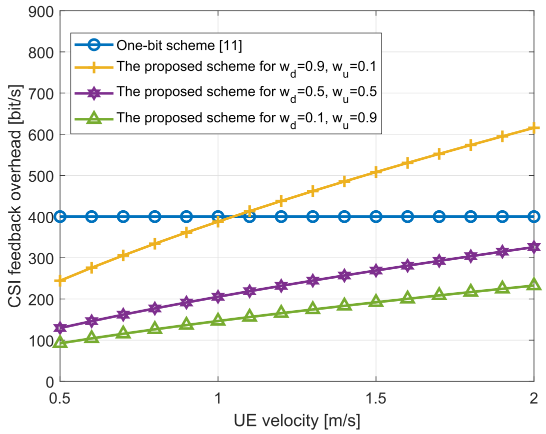

FIGURE 5. CSI feedback overhead comparison between the proposed scheme and one-bit scheme.

solution can be computed easily by the proposed closed-form expression in (23). Therefore, the central controller can react to the variation of UE velocity in time.

Figure 4 shows the weighted bidirectional throughput comparison between the proposed scheme of feedback interval optimization and three conventional benchmarks. In the fixed-feedback scheme, the feedback interval is always 10ms regardless of the UE velocity. As a result, constant feedback overhead is required even during low-speed movements of the UE, leading to unnecessary degradation of the uplink throughput. On the contrary, limited CSI feedback in one-bit scheme results in the degradation of the downlink throughput, and in the no-feedback scheme, the weighted bidirectional throughput decreases obviously as the velocity of UE increases due to the absence of CSI feedback. It can be seen that the proposed scheme with quasi-optimal solution outperforms all of the aforementioned schemes and is capable of approaching the optimal solution.

Figure 5 presents the feedback overhead comparison between the proposed scheme with quasi-optimal solution and one-bit scheme. The feedback overhead is defined as the uplink data rate occupied for CSI feedback. Whereas, in the proposed scheme, β bits are used to feedback CSI $h_{\mathrm{d},i}$ ($i = 1, 2, \ldots, k$). It is shown that the feedback overhead of the proposed scheme is lower than one-bit scheme when the UE moves slowly. Besides, when $\frac{w_\mathrm{d}}{w_\mathrm{u}} < 2.1$, the feedback overhead of the proposed scheme keeps lower than that of one-bit scheme in the range $0 < v < 2$. Therefore, merely by reducing the content of CSI feedback, the overhead cannot be reduced to the lowest while maintaining the downlink performance. In our future work, we would like to incorporate content-limited schemes with the proposed schemes.

V. CONCLUSION AND FUTURE PROSPECTS

In this paper, the optimization of CSI feedback interval is investigated for MISO LiFi systems, which is flexibly adjusted with respect to the UE velocity, in order to reduce the feedback overhead. More specifically, the optimal CSI feedback interval is firstly calculated as a function of the UE velocity, by maximizing the weighted bidirectional throughput. After that, a closed-form quasi-optimal solution of the feedback interval is derived in order to reduce the computational complexity, making the proposed scheme more suitable for practical implementations. This closed-form expression, which is validated by simulation results, also reveals how critical parameters affect the optimal value of the feedback interval. The weighted throughput of the proposed methodology outperforms three traditional benchmarks and consumes less CSI feedback overhead than one-bit scheme when the UE moves slowly or $\frac{w_\mathrm{d}}{w_\mathrm{u}}$ is relatively small.

APPENDIX
DERIVATION OF (19)

To simplify the left side of the equation (18), it is necessary to calculate the partial derivative of the average uplink throughput $\frac{\partial \overline{R_\mathrm{u}}(t_\mathrm{u})}{\partial t_\mathrm{u}}$ and downlink throughput $\frac{\partial \overline{R_\mathrm{d}}(t_\mathrm{u})}{\partial t_\mathrm{u}}$. Without loss of generality, $t_0 = 0$ is assumed in this section. In [16], two useful lemmas are proved, which are given here without proving for brevity.

Lemma 1: Consider the function

$$f(t_\mathrm{u}) = \frac{1}{t_\mathrm{u}} \int_0^{t_\mathrm{u}} B \log_2(\frac{G}{(r^2(t)+z^2)^{m+3}})dt, \tag{25}$$

where $r^2(t) = r^2(0) + v^2t^2 - 2r(0)vt\cos\theta$, $vt_\mathrm{u} \ll h$, and $B, G > 0$ are both constants. By using the derivation rules and Taylor expansion, the following approximation can be derived

$$\frac{\partial f(t_\mathrm{u})}{\partial t_\mathrm{u}} \approx \frac{-2(m+3)Bv^2(z^2+r^2(0)\sin^2\theta)^2 t_\mathrm{u}}{3\ln 2(z^2+r^2(0))^3}. \tag{26}$$

Lemma 2: Consider the function

$$g(t_\mathrm{u}) = \frac{1}{t_\mathrm{u}^2} \int_0^{t_\mathrm{u}} B \log_2(\frac{G}{(r^2(t)+z^2)^{m+3}})dt, \tag{27}$$

where $r^2(t) = r^2(0) + v^2t^2 - 2r(0)vt\cos\theta$, $vt_\mathrm{u} \ll h$, and $B, G > 0$ are both constants. By using the derivation rules and Taylor expansion, the following approximation can be derived

$$\frac{\partial g(t_\mathrm{u})}{\partial t_\mathrm{u}} \approx \frac{B}{t_\mathrm{u}^2} \log_2(\frac{G}{(r^2(0)+z^2)^{m+3}}). \tag{28}$$

The average uplink throughput $\overline{R_\mathrm{u}}(t_\mathrm{u})$, which is given by (10), can be approximated as

$$\begin{aligned}\overline{R_\mathrm{u}}(t_\mathrm{u}) \approx \frac{B_\mathrm{u}}{t_\mathrm{u}} &\int_0^{t_\mathrm{u}} \log_2(1+\frac{G_\mathrm{u}}{(r_\mathrm{u}^2(t)+z^2)^{m+3}})\mathrm{d}t \\ &- \frac{t_\mathrm{fb}B_\mathrm{u}}{t_\mathrm{u}^2} \int_0^{t_\mathrm{u}} \log_2(1+\frac{G_\mathrm{u}}{(r_\mathrm{u}^2(t)+z^2)^{m+3}})\mathrm{d}t,\end{aligned} \tag{29}$$

where $G_\mathrm{u} = \frac{(\rho_{PD}G_0)^2 P_\mathrm{u}}{N_0 B_\mathrm{u}}$. Based on the aforementioned lemmas, the partial derivative of the average uplink throughput can be obtained as

$$\begin{aligned}\frac{\partial \overline{R_\mathrm{u}}(t_\mathrm{u})}{\partial t_\mathrm{u}} \approx &\frac{-2(m+3)B_\mathrm{u}v^2(z^2+r_\mathrm{u}^2(0)\sin^2\theta_\mathrm{u})^2 t_\mathrm{u}}{3\ln 2(z^2+r_\mathrm{u}^2(0))^3} \\ &+ \frac{B_\mathrm{u}t_{fb}}{t_\mathrm{u}^2} \log_2(\frac{G_\mathrm{u}}{(r_\mathrm{u}^2(0)+z^2)^{m+3}}).\end{aligned} \tag{30}$$

The average downlink throughput $\overline{R}_{\mathrm{d}}(t_{\mathrm{u}})$, which is given by (11), can be approximated as

$$\begin{aligned}\overline{R}_d(t_{\mathrm{u}}) &= \frac{B_d}{t_{\mathrm{u}}}\int_0^{t_{\mathrm{u}}}\log_2(1+G_d(\sum_{w_i\neq 0}^{k} w_i d_i(t)^{-(m+3)})^2)\mathrm{d}t \\ &\approx \frac{B_d}{t_{\mathrm{u}}}\int_0^{t_{\mathrm{u}}}(\log_2 G_d + 2\log_2(\sum_{w_i\neq 0}^{k}\frac{w_i^2}{|\mathbf{w}|^2}\frac{G_i}{d_i(t)^{m+3}})\mathrm{d}t \\ &= C_{\mathrm{d}} + \frac{2B_d}{t_{\mathrm{u}}}\int_0^{t_{\mathrm{u}}}\log_2(\sum_{w_i\neq 0}^{k}\frac{w_i^2}{|\mathbf{w}|^2}\frac{G_i}{d_i(t)^{m+3}})\mathrm{d}t \end{aligned} \quad (31)$$

where $G_{\mathrm{d}} = \frac{\rho_{\mathrm{PD}}^2 G_0^2}{N_0 B_{\mathrm{d}}}$, $G_i = \frac{|\mathbf{w}|^2}{w_i}$ and $C_{\mathrm{d}} = B_{\mathrm{d}}\log_2 G_{\mathrm{d}}$.

According to Jensen's Inequality, the following inequality can be derived

$$\log_2(\sum_{i=1}^{k}\frac{w_i^2}{|\mathbf{w}|^2}\frac{G_i}{d_i(t)^{m+3}}) \geq \sum_{i=1}^{k}\frac{w_i^2}{|\mathbf{w}|^2}\log_2(\frac{G_i}{d_i(t)^{m+3}}). \quad (32)$$

Therefore, the average downlink throughput can be approximated by its lower bound as

$$\overline{R}_{\mathrm{d}}(t_{\mathrm{u}}) \approx \frac{B_{\mathrm{d}}}{t_{\mathrm{u}}}\sum_{i=1}^{k}\frac{w_i^2}{|\mathbf{w}|^2}\int_0^{t_{\mathrm{u}}}\log_2(\frac{G_i^2}{d_i(t)^{2m+6}})\mathrm{d}t + C_{\mathrm{d}}. \quad (33)$$

According to Lemma 1, the partial derivative of the average uplink throughput can be obtained as

$$\frac{\partial\overline{R_{\mathrm{d}}}(t_{\mathrm{u}})}{\partial t_{\mathrm{u}}} \approx \frac{-2(m+3)B_d v^2 t_{\mathrm{u}}}{3\ln 2}\sum_{i=1}^{k}\frac{w_i^2}{|\mathbf{w}|^2}\frac{(z^2+r_i^2(0)\sin^2\theta_i)^2}{(z^2+r_i^2(0))^3}. \quad (34)$$

Finally, by substituting $\frac{\partial\overline{R_{\mathrm{u}}}(t_{\mathrm{u}})}{\partial t_{\mathrm{u}}}$ and $\frac{\partial\overline{R_{\mathrm{d}}}(t_{\mathrm{u}})}{\partial t_{\mathrm{u}}}$ by (30) and (34), the following equation can be derived

$$\frac{2(m+3)v^2}{3\ln 2}(w_{\mathrm{u}}B_{\mathrm{u}}C_2 + w_{\mathrm{d}}B_{\mathrm{d}}C_1)t_{\mathrm{u}} - w_{\mathrm{u}}B_{\mathrm{u}}C_3\frac{t_{\mathrm{fb}}}{t_{\mathrm{u}}^2} = 0. \quad (35)$$

After organizing the left side of (35) into a cubic polynomial, the equation (19) can be obtained. The proof is completed.

REFERENCES

[1] S. Wu, H. Wang, and C.-H. Youn, "Visible light communications for 5G wireless networking systems: From fixed to mobile communications," *IEEE Netw.*, vol. 28, no. 6, pp. 41–45, Nov./Dec. 2014.

[2] Z. Wang, Q. Wang, W. Huang, and Z. Xu, *Visible Light Communications: Modulation and Signal Processing*. Hoboken, NJ, USA: Wiley, 2017.

[3] H. Schulze, "Frequency-domain simulation of the indoor wireless optical communication channel," *IEEE Trans. Commun.*, vol. 64, no. 6, pp. 2551–2562, Jun. 2016.

[4] H. Haas, L. Yin, C. Chen, S. Videv, D. Parol, E. Poves, H. Alshaer, and M. S. Islim, "Introduction to indoor networking concepts and challenges in LiFi," *J. Opt. Commun. Netw.*, vol. 12, no. 2, pp. A190–A203, Feb. 2020.

[5] J. Beysens, Q. Wang, and S. Pollin, "Increasing throughput of dense-transmitter VLC networks through adaptive distributed MISO," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kansas City, MO, USA, May 2018, pp. 1–6.

[6] Z. Zeng, M. Dehghani Soltani, Y. Wang, X. Wu, and H. Haas, "Realistic indoor hybrid WiFi and OFDMA-based LiFi networks," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 2978–2991, May 2020.

[7] Q. Wang, Y. Jiang, X. Zhu, and T. Wang, "Phase rotation based precoding for MISO DCO-OFDM LiFi with highly correlated channels," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Nanjing, China, Mar. 2021, pp. 1–5.

[8] J. Zhang and J. S. Lehnert, "Throughput-optimal precoding and rate allocation for MISO systems with noisy feedback channels," *IEEE Trans. Inf. Theory*, vol. 54, no. 5, pp. 2139–2155, May 2008.

[9] J. Lian, M. Noshad, and M. Brandt-Pearce, "Multiuser MISO indoor visible light communications," in *Proc. 48th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2014, pp. 1729–1733.

[10] G. Caire, S. A. Ramprashad, and H. C. Papadopoulos, "Rethinking network MIMO: Cost of CSIT, performance analysis, and architecture comparisons," in *Proc. Inf. Theory Appl. Workshop (ITA)*, La Jolla, CA, USA, Jan. 2010, pp. 1–10.

[11] Z. Ding, P. Fan, and H. V. Poor, "Random beamforming in millimeter-wave NOMA networks," *IEEE Access*, vol. 5, pp. 7667–7681, 2017.

[12] Y. Yapıcı and I. Güvenç, "NOMA for VLC downlink transmission with random receiver orientation," *IEEE Trans. Commun.*, vol. 67, no. 8, pp. 5558–5573, Aug. 2019.

[13] M. Hafez, A. El Shafie, M. Shaqfeh, T. Khattab, H. Alnuweiri, and H. Arslan, "Thresholds optimization for one-bit feedback multi-user scheduling," *IEEE Wireless Commun. Lett.*, vol. 7, no. 4, pp. 646–649, Aug. 2018.

[14] V. Hassel, D. Gesbert, M.-S. Alouini, and G. E. Oien, "A threshold-based channel state feedback algorithm for modern cellular systems," *IEEE Trans. Wireless Commun.*, vol. 6, no. 7, pp. 2422–2426, Jul. 2007.

[15] K. Lee, H. Park, and J. R. Barry, "Indoor channel characteristics for visible light communications," *IEEE Commun. Lett.*, vol. 15, no. 2, pp. 217–219, Feb. 2011.

[16] M. D. Soltani, X. Wu, M. Safari, and H. Haas, "Bidirectional user throughput maximization based on feedback reduction in LiFi networks," *IEEE Trans. Commun.*, vol. 66, no. 7, pp. 3172–3186, Jul. 2018.

[17] H. Ma, L. Lampe, and S. Hranilovic, "Hybrid visible light and power line communication for indoor multiuser downlink," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 9, no. 8, pp. 635–647, Aug. 2017.

[18] C. Bettstetter, H. Hartenstein, and X. Pérez-Costa, "Stochastic properties of the random waypoint mobility model," *Wireless Netw.*, vol. 10, no. 5, pp. 555–567, 2004.

[19] A. M. Abdelhady, O. Amin, A. Chaaban, and M.-S. Alouini, "Downlink resource allocation for multichannel TDMA visible light communications," in *Proc. IEEE Global Conf. Signal Inf. Process. (GlobalSIP)*, Washington, DC, USA, Dec. 2016, pp. 1–5.

[20] Y. Qiu, H. H. Chen, and W. X. Meng, "Channel modeling for visible light communications—A survey," *Wireless Commun. Mobile Comput.*, vol. 16, no. 14, pp. 2016–2034, Feb. 2016.

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

[22] Z.-Y. Wu, M. Ismail, J. Kong, E. Serpedin, and J. Wang, "Channel characterization and realization of mobile optical wireless communications," *IEEE Trans. Commun.*, vol. 68, no. 10, pp. 6426–6439, Oct. 2020.

[23] A. C. Cirik, R. Wang, Y. Hua, and M. Latva-Aho, "Weighted sum-rate maximization for full-duplex MIMO interference channels," *IEEE Trans. Commun.*, vol. 63, no. 3, pp. 801–815, Mar. 2015.

[24] M. D. Soltani, M. Safari, and H. Haas, "On throughput maximization based on optimal update interval in Li-Fi networks," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Montreal, QC, Canada, Oct. 2017, pp. 1–6.

[25] *Physical Layer Procedures*, document TS 36.213, 3GPP, 2016.

[26] R. W. Bohannon, "Comfortable and maximum walking speed of adults aged 20–79 years: Reference values and determinants," *Age Ageing*, vol. 26, no. 1, pp. 15–19, Jan. 1997.

FAN ZHANG is currently pursuing the B.S. degree with the Department of Electronic Engineering, Tsinghua University. Her current research interests include wireless communications, signal processing, and optical wireless communications. She was a recipient of Nanxiang Jiang Scholarship and December 9th Scholarship.

JIAXUAN CHEN received the B.S. degree from Tsinghua University, in 2016, where she is currently pursuing the Ph.D. degree with the Department of Electronic Engineering. Her current research interests include wireless communications, signal processing, optical wireless communications, and vehicular ad-hoc networks.

TIANQI MAO received the B.S. and M.S. degrees (Hons.) in electronic engineering from Tsinghua University, Beijing, China, in 2015 and 2018, respectively, where he is currently pursuing the Ph.D. degree with the Department of Electronic Engineering. His current research interests include modulation and signal processing for wireless communication, terahertz wireless communication, and visible light communication. He was a recipient of the Science and Technology Award (Second Prize) of China Institute of Communications, the Excellent Master Dissertation of Chinese Institute of Electronics, the Special Scholarship of Tsinghua University, the Outstanding Master Graduate of Tsinghua University, the Outstanding Master Graduate of Beijing City, the Excellent Master Dissertation of Tsinghua University, and National Scholarship.

ZHAOCHENG WANG (Fellow, IEEE) received the B.S., M.S., and Ph.D. degrees from Tsinghua University, in 1991, 1993, and 1996, respectively.

From 1996 to 1997, he was a Postdoctoral Fellow with Nanyang Technological University, Singapore. From 1997 to 1999, he was a Research Engineer/Senior Engineer with OKI Techno Centre (Singapore) Pte. Ltd., Singapore. From 1999 to 2009, he was a Senior Engineer/Principal Engineer with Sony Deutschland GmbH, Germany. Since 2009, he has been a Professor with the Department of Electronic Engineering, Tsinghua University, where he is currently the Director of the Broadband Communication Key Laboratory, Beijing National Research Center for Information Science and Technology (BNRist). He has authored or coauthored two books, which have been selected by IEEE Series on Digital and Mobile Communication and published by Wiley-IEEE Press. He has authored/coauthored more than 180 peer-reviewed journal articles. He holds 46 U.S./EU granted patents (23 of them as the first inventor). His research interests include wireless communications, millimeter wave communications, and optical wireless communications. He is a fellow of the Institution of Engineering and Technology. He was a recipient of the ICC2013 Best Paper Award, the OECC2015 Best Student Paper Award, the 2016 IEEE Scott Helt Memorial Award, the 2016 IET Premium Award, the 2016 National Award for Science and Technology Progress (First Prize), the ICC2017 Best Paper Award, the 2018 IEEE ComSoc Asia-Pacific Outstanding Paper Award, and the 2020 IEEE ComSoc Leonard G. Abraham Prize. He is also an Associate Editor of the IEEE Transactions on Communications, the IEEE Systems Journal, and the IEEE Open Journal of Vehicular Technology. He was an Associate Editor of the IEEE Transactions on Wireless Communications, from 2011 to 2015, and an Associate Editor of the IEEE Communications Letters, from 2013 to 2016.