Cong-Nam Tran*, Trong-Minh Hoang and Nam-Hoang Nguyen*

Proactive link handover deploying coordinated transmission for indoor visible light communications (VLC) networks

https://doi.org/10.1515/joc-2019-0282
Received November 21, 2019; accepted May 4, 2020; Published online August 10, 2020

Abstract: Visible Light Communications (VLC) is considered as an emerging technology for indoor wireless communications to achieve high-speed and secure data transmission. Instead of using radio frequency (RF) spectrum, VLC uses the visible light spectrum to perform lighting and communications functions simultaneously. Multiple access points VLC (multi-AP VLC) networks use ceiling access point (ceiling-AP) and desk access point (desk-AP) to provide both uniform and spot lighting in order to achieve full coverage and high spectral efficiency. Because mobile user equipment (UE) require seamless connectivity when moving, fast link handover between VLC access points (VLC-AP) has to be supported in the VLC networks. In this paper, we present a coordinated multi-channel transmission method (CMcT) used to improve quality of service (QoS) of cell-edge UEs and propose a novel proactive link handover scheme deploying the CMcT method for multi-AP VLC networks. Performance results obtained by computer simulation show that the proactive link handover scheme deploying the CMcT method can significantly improve user throughput and packet delay comparing with those of other link handover schemes.

Keywords: coordinated transmission; fractional frequency reuse; link handover; visible light communications.

***Corresponding authors: Cong-Nam Tran**, Thang Long University, Hanoi, Viet Nam; and VNU University of Engineering and Technology, Vietnam National University, Hanoi, Viet Nam,
E-mail: namtc@thanglong.edu.vn; and **Nam-Hoang Nguyen**, VNU University of Engineering and Technology, Vietnam National University, Hanoi, Viet Nam, E-mail: hoangnn@vnu.edu.vn
Trong-Minh Hoang: Posts and Telecommunications Institute of Technology, Hanoi, Viet Nam, E-mail: hoangtrongminh@ptit.edu.vn

1 Introduction

The development of mobile networks has led to a huge data demand and requirements of safe and secure wireless communications. With the rapid development of recent material technologies, the light emitting diode (LED) technology brought great opportunities in applications and research of indoor visible light communications (VLC) [1]. VLC is an emerging optical wireless communication technology in which baseband signals are modulated on the light emitted by typically white LEDs [2]. VLC is considered as a promising indoor communications technology for next generation broadband communications due to its preeminent features such as wide unregulated bandwidth, high regional spectral performance, and high security. VLC does not cause electromagnetic interference to radio frequency sensitive electronic devices [3] whereas VLC is able to provide high data rate [4].

VLC is mostly based on intensity modulation (IM) and direct detection (IM-DD). At the transmitter side, VLC systems use the IM technique to encode data and then transmit signal by using LED sources. At the receiver side, the direct detection (DD) technique is used to convert the light intensity into an electrical signal by a photo detector (PD). Multiple carrier modulation such as orthogonal frequency division multiplexing (OFDM) has been considered for IM/DD VLC systems to achieve high spectral efficiency, immunity to channel frequency selectivity and mitigate the multipath-induced inter-symbol interference (ISI) [5, 6].

Because an AP attached to the ceiling of an indoor space ceiling access point (ceiling-AP) has small coverage area, a number of ceiling-AP is needed in order to satisfy communications and lighting requirements to multiple UEs in a large indoor environment forming the Multiple access points VLC (multi-AP VLC) network [6–9]. In multi-AP VLC networks, smaller APs with coverage areas of 1 or 2 m^2 can also be provided at specific positions such as tables, counters etc. (namely desk access point (desk-AP)). That means multi-AP VLC networks will provide both uniform and spot lighting by ceiling-AP and desk-AP, respectively [10, 11]. The uniform lighting is provided over the entire room by distributing LED on the ceiling. The spotlighting produces intense and focused light to achieve higher data rate comparing to uniform lighting.

When mobile UEs move between VLC access points (VLC-APs), link handover is implemented to maintain their network connectivity which switches UE's connection from one serving VLC-AP to a handover VLC-AP [12]. In [13], a link handover scheme using pre-scanning and received signal strength (RSS) prediction technique was proposed to reduce link handover delay and prevent unnecessary link handover. In [14], a handover skipping scheme based on the reference signal received power (RSRP) was proposed. The scheme combines the value of RSRP and its rate of change to determine the appropriate target AP. Link handover schemes using the location of UEs was proposed in [15, 16]. In [15], the UE's current serving AP uses location history of the user equipment (UE) to find out which neighbor AP the UE is approaching. The UE only scans these neighbor transmitters, since then the link handover delay is reduced. In [16], an optical positioning assisting handover procedure was proposed based on a pre-handover scheme to initiate broadcasting the UE data on the target cell. The procedure relies on position estimation obtained by optical positioning and a Kalman filter is utilized for improving the tracking performance of an UE. In [17], handover hysteresis regions are investigated for VLC networks under the illumination and signal to noise ratio (SNR) constraints for successful handover. A handover approach was proposed when taking into account the effects of both mobility and rotation for a connected UE indoor Li-Fi cellular network [18]. By using the geometric model for the receiver orientation, the probability of handover and the handover rate were calculated in this study. In [19] frequency and power based soft handover schemes were proposed to reduce data rate fluctuations as the UE moves from one AP to another. In the algorithm, while the user is in the intersection area of two APs, the second AP starts serving the user using either the same or different frequency range that the first AP uses. The statistical distribution of the received data rate is also studied using computer simulations. In [20], a handover scheme based on the coordinated multipoint joint transmission (ComP-JT) transmission scheme was proposed to improve the data rate of the cell edge UE based on improving signal-to-interference-noise-ratio (SINR).

In order to enhance the data rate of multi-AP VLC networks, the ComP-JT technique of wireless communications is adapted to a multi-AP VLC to increase SINR for UEs at cell edge area [7, 20–22]. When using ComP-JT in VLC systems, downlink signal sent to a single UE is simultaneously transmitted from multiple APs using the same optical bandwidth to improve the data transfer rate and also reduce the impact of blockages on UEs. However, the requirement of a special multi-light beam structure at the transmitter makes ComP-JT difficult to apply with conventional diffuse light sources [7]. Using coordinated transmission at the physical layer requires high transmission time synchronization between APs resulting in the complex design of VLC systems.

Regarding to the IEEE 802.15.7 standard of VLC communications, which provides MAC protocol specifications including cell design and mobility supports, a single coordinator is exploited to support mobility of the device through multiple cells [2]. However, the standard does not cover advanced VLC technologies which have been proposed recently such as OFDM. The link handover, known as link switching, provided in IEEE 802.15.7 is a hard handover which might cause long delay, throughput degradation and connection interruption. In our research, we will apply the cell design architecture of the IEEE 802.15.7 standard where a coordinator is responsible for handling mobility supports. The design assumptions of the physical layer are based on OFDM technology as proposed in [5, 6].

In summary, the recent related research only focused on investigating the link handover in the VLC networks which deploy ceiling APs. The proposed handover schemes did not solve the technical challenge of link handover when either UEs change their location suddenly or there is channel blockage. In order to enhance data rate of the cell-edge UE, maintain the seamless connectivity and avoid the connection interruption caused by channel blockage in multi-AP VLC networks, a combination of the coordinated multi-channel transmission (CMcT) and link handover, denoted as the CMcT HO scheme is proposed in the paper.

When an UE moves into an overlapping area of two or more APs, the UE can implement the CMcT method before doing link handover to another AP. Different with the ComP-JT scheme, the proposed CMcT sends downlink data to the UE from two APs in different time slots. Link handover and CMcT decisions are carried out based on the UE's received signal power, UE's SNR and the load ratio of APs. The remainder of the paper is organized as follows. Section 2 presents the multi-AP VLC system model. Section 3 describes the operation of the proposed CMcT HO scheme. Simulation results are presented and discussed in Section 4. Finally, the conclusions are given in the Section 5.

2 System model

2.1 System description

As shown in Figure 1, a multi-AP VLC network includes a Coordinator, N_{CAP} ceiling-AP, N_{DAP} desk-AP) and N_{ue} UE.

Each ceiling-AP is assigned an identity CAP_{ID}, where $CAP_{ID} \in \{1, 2, \ldots, N_{CAP}\}$. Ceiling-APs (CAP) are installed in a grid layout on the ceiling as it is commonly used in practice to provide uniform illumination. The distance between the ceiling-AP plane and the floor is h_{CAP} (m).

Each desk-AP is assigned an identity DAP_{ID}, where $DAP_{ID} \in \{N_{CAP}+1, N_{CAP}+2, \ldots, N_{CAP}+N_{DAP}\}$. Desk-APs (DAP) are installed on desks at random locations and there is not overlapping area between any two DAPs. The distance between desk-AP plane and the floor is h_{DAP} (m). All CAPs and DAPs are connected to the Internet via the Coordinator which is responsible for mobility management and downlink resource allocation to UEs [2, 11, 21]. There are two types of UE including stationary-UE and mobile-UE which have random initialized location in the room area. Mobile UEs move around the room following the random waypoint (RWP) model [24]. Each UE is assigned a UE's identity u, where $u \in \{1, 2, \ldots, N_{ue}\}$. Each UE has the height from the floor h_{UE} (m). An UE uses a photo detector (PD) which is oriented perpendicular to the floor and vertically upward. Assume all UEs use RF as the uplink channels [25] and VLC links for downloading data. For the downlink transmission, the fractional frequency reuse (FFR) technique [6, 19, 23] and Direct-current optical orthogonal frequency division multiplexing (DCO-OFDM) are deployed [6]. Five frequency bands are used where four different frequency bands are allocated to four neighboring CAPs in the square layout and the remaining band is allocated to DAPs. This reduces the co-channel interference (CCI) affect to UEs in overlapping areas of APs. Each AP (CAP or DAP) provides a shared channel of K subcarriers which exploits Time Division Multiple Access (TDMA) for downlink multiple access. An AP exploits a broadcast channel to transmit pilot signals which carry the identity of the AP (CAP_{ID} or DAP_{ID}) and subcarriers of training channels. An UE scans broadcast channels of its serving AP and neighbor APs periodically to measure the RSS and detect AP's identity (CAP_{ID} or DAP_{ID}). An AP has a training channel which uses predefined subcarriers in the frequency band of the AP. When an UE resides in the overlapped area of the adjacent APs, the UE measures the training channel of each adjacent AP, which is distinguished by particular predefined subcarriers, in a periodical time slot to estimate the downlink SNR of the adjacent AP. The UE creates a downlink SNR estimation report and sends it to the serving AP and the serving AP sends the report to the Coordinator.

2.2 Downlink channel

Figure 2 illustrates two types of VLC downlink channels: Line-of-sight (LOS) (from LED to UE directly) and Non-line-of-sight (NLOS) (due to the reflection of the floor, ceiling, and walls) [25]. Because the received signal power of NLOS paths is much lower than that of LOS paths, we can ignore NLOS paths. The LOS channel is modeled using the channel direct-current (DC) gain which is expressed as follow [26]:

$$G = \begin{cases} \dfrac{(m+1)A}{2\pi d^2} \cos^m(\phi) T_s(\psi) g(\psi) \cos(\psi), \ 0 \le \psi \le \psi_c \\ 0, \ \psi > \psi_c \end{cases} \tag{1}$$

where, A is the physical area of the Photo Detector (PD). d is the Euclidean distance between an AP to the PD of UE. ψ is the incidence angle at the receiver. ϕ is the angle of irradiance. Assume that all APs are directed downwards and all UEs are directed upwards. Then, we have ψ equals ϕ. $T_s(\psi)$ is the gain of an optical filter. m is the Lambertian index that is given by

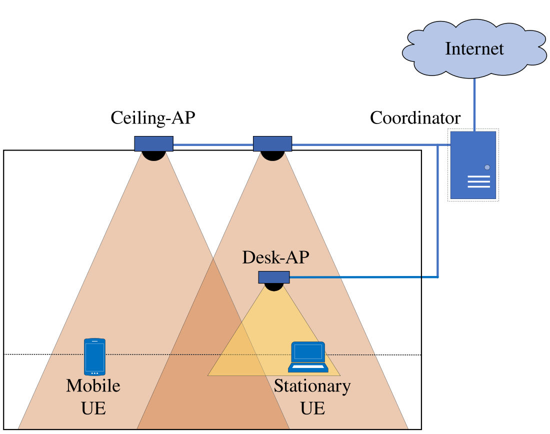


Figure 1: Multi-AP VLC network model.

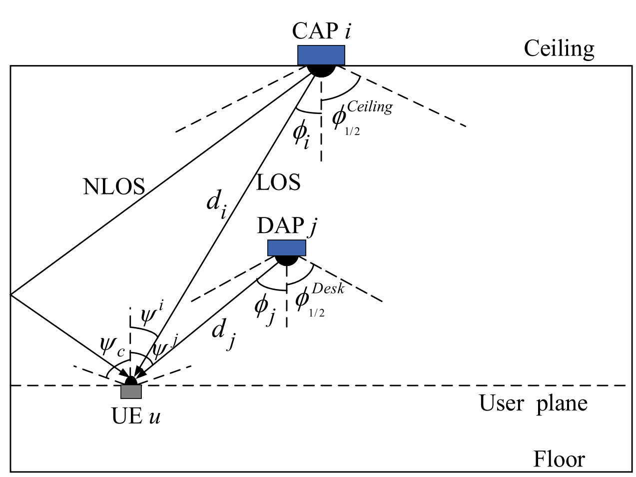


Figure 2: VLC downlink channel model.

$$m = \frac{-ln(2)}{ln(\cos(\Phi_{1/2}))} \tag{2}$$

where $\Phi_{1/2}$ is the half-intensity radiance angle of LED chip. ψ_c denotes the width of the field of view (FOV) at the receiver. $g(\psi)$ is the gain of an optical concentrator which can be calculated as:

$$g(\psi) = \begin{cases} \dfrac{n^2}{\sin^2(\psi_c)}, & 0 \le \psi \le \psi_c \\ 0, & \psi > \psi_c \end{cases} \tag{3}$$

where n is the refractive index of the air.

2.3 SNR analysis

The electrical signal power transmitted by AP_i on the subcarrier k is defined below [27]:

$$P_{elec,i,k} = \frac{P_{opt}^2}{(K-2)\rho^2} \tag{4}$$

$$\rho = \frac{x_{DC}}{\sqrt{\sum_{k=0}^{K-1} E[x_k^2(t)]}} \tag{5}$$

where, P_{opt} is the average transmitted optical power. x_{DC} is the DC-bias. $x_k(t)$ is the OFDM symbol on subcarrier k. K is the total number of subcarriers. $(K-2)$ is the number of subcarriers carrying the signal [27]. $E[.]$ is the expectation operator.

The average received signal power of UE_u from AP_i on the subcarrier k is determined by the following formula:

$$P_{i,u,k} = R_{pd}^2 G_{i,u}^2 P_{elec,i,k} \tag{6}$$

where, $G_{i,u}$ is the DC channel gain from AP_i to UE_u. R_{pd} is the efficiency of converting the light to the electrical signal.

In the VLC network model, the fractional frequency reuse (FFR) technique is used which allocate different spectrum to APs i. e. the CCI to UEs can be negligible. The SNR of UE_u on the subcarrier k from AP_i is determined as follows:

$$SNR_{i,u,k} = \frac{R_{pd}^2 G_{i,u}^2 P_{elec,i,k}}{\sigma_k^2} \tag{7}$$

where, σ_k^2 is the received noise power due to the shot noise on the subcarrier k. The noise power is defined by [28]:

$$\sigma_k^2 = 2qI_{bg}B_{sc} + \frac{4K_B T_A B_{sc}}{R_F} \tag{8}$$

where, I_{bg} is the background current caused by the background light. The electronic charge is $q = 1.6 \cdot 10^{-19}$ C. K_B is the Boltzmann constant. T_A is the absolute temperature. R_F is the gain of the signal when passing through a transimpedance amplifier (TIA). B_{sc} is the bandwidth of a subcarrier which is determined as follows:

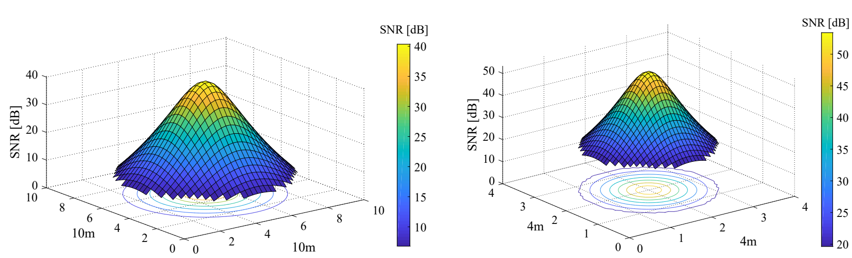
$$B_{sc} = \frac{W}{K} \tag{9}$$

where W is the total bandwidth. K is the total number of subcarriers.

Figure 3 illustrates UE's SNR distribution received from a ceiling-AP and a desk-AP. The system parameters are shown in Table 3. Figure 3(a) shows that the SNR values of UEs received from the ceiling-AP has the range of 6.6–40.1 dB. Figure 3(b) shows that the SNR received from the desk-AP has the range of 19.9–53.3 dB. The SNR has a large decrease from the cell center to the cell edge in both cases. That means UE's data rates are decreased from the cell center to the cell edge. The SNR received from the desk-AP is much higher than those from the ceiling-AP but the coverage area of desk-AP is much smaller. When the incidence angle at the UE's receiver is more than the FOV width of the receiver, the received power value of UEs is zero as shown in Equation (1).

2.4 LoS downlink channel blockage

Because VLC communications exploits LoS transmission, it is sensitive to the blockage of objects and suffering shadowing. With respect to the channel blockage, there are three key elements: the occurrence rate, the occupation rate, and the blockage degree [29]. For a pair of AP_i



(a) SNR distribution from ceiling-AP (b) SNR distribution from desk-AP

Figure 3: UE's SNR distribution.

and UE_u, the occurrence rate (denoted by $\lambda_{i,u}$) is described as the number of LOS downlink channel blockages happening per a time unit. The occupation rate (denoted by $\eta_{i,u}$) is defined as the proportion of time during which a UE experiences the downlink channel blockages. The blockage degree (denoted by $\xi_{i,u}$) is used to indicate the extent to which the downlink channel blockage affects the channel quality. It is a fraction number between 0 and 1 when $\xi_{i,u}$ is 0, it means the downlink channel non-blockage, and when $\xi_{i,u}$ is 1, it means the downlink channel blockage. Therefore, Equations (6) and (7) is modified to:

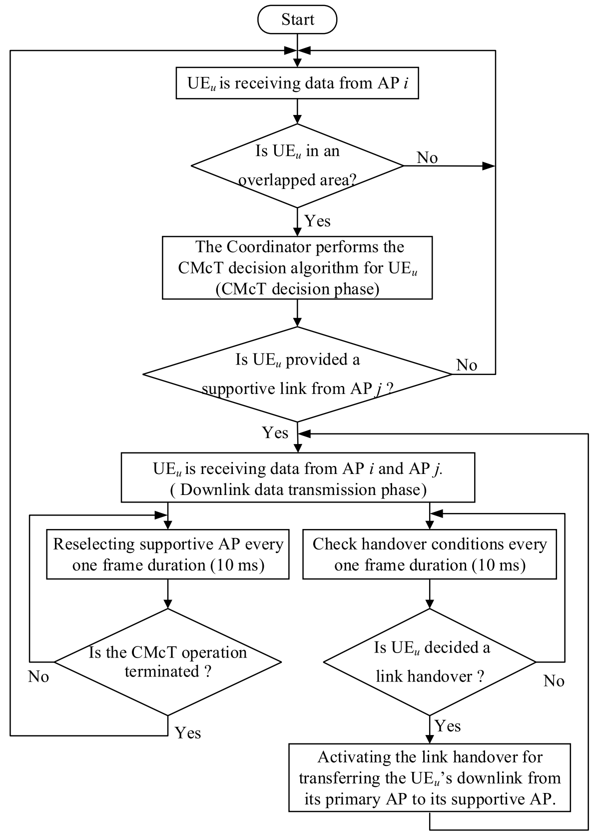
$$P_{i,u,k} = \left(1 - \xi_{i,u}\right) R_{pd}^2 G_{i,u}^2 P_{elec,i,k} \tag{10}$$

$$SNR_{i,u,k} = \left(1 - \xi_{i,u}\right) \frac{R_{pd}^2 G_{i,u}^2 P_{elec,i,k}}{\sigma_k^2} \tag{11}$$

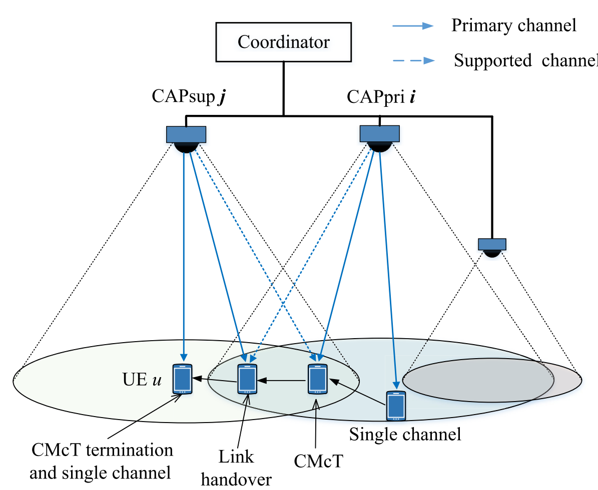
3 Proactive link handover exploiting coordinated multi-channel transmission

When an UE moves through APs, it has to perform a link handover scheme to keep continuous communications. We design a new proactive link handover (CMcT HO) scheme exploiting the CMcT for multi-AP VLC networks aiming to provide seamless communications, improve QoS (high throughput, low packet latency) and reduce the number of link handovers.

Figure 4(a) shows a flowchart of the proposed proactive link handover procedure. The proposed procedure is divided into two phases: the CMcT phase and link handover phase which are described in Section 3.1 and Section 3.2, respectively. When an UE resides in an overlapped area of APs, by exploiting CMcT scheme, the UE receives downlink data from its serving AP and the supportive AP simultaneously. The CMcT achieves load sharing between APs i. e. low-load APs will support data transmission for UEs currently served by high-load APs. It also enhances the data rate and provides the alternative link for the UE, thereby reduces the risk of disconnection of UE due to random shadowing of obstructions. When the link handover conditions are satisfied, the Coordinator activates the link handover for transferring the UE's downlink from its primary AP to its supportive AP and the previous primary AP becomes the new supportive AP. The CMcT is terminated when the UE moves out of the coverage area of the supportive AP.



(a) Flowchart of the proactive link handover scheme



(b) Illustration of the proactive link handover scheme

Figure 4: Proactive link handover scheme for multi-AP VLC networks.

As shown in Figure 4(b), when UE_u moves into the overlapping area of CAP i and CAP j, UE_u exploits the multi-channel downlink transmission. UE_u has the primary downlink channel received from its serving CAP i (known as primary AP – AP^{pri}) and the secondary downlink channel from the most appropriate neighbor CAP *j* (known as supportive AP – AP^{sup}). When UE_u moves out the coverage of the serving CAP *i* into the coverage of CAP *j*, the link handover decision is made to activate the link handover for transferring the UE's downlink from its primary CAP *i* to its supportive CAP *j* and CAP *i* becomes the new supportive AP.

An AP_i (ceiling-AP or desk-AP) classifies its connected UEs to two sets including primary-UEs ($Set\_UE_i^{pri}$) for those the AP_i is their serving AP and supported-UEs ($Set\_UE_i^{sup}$) for those the AP_i is their supportive AP. The Coordinator determines AP assignment and mobility management for all UEs. Consider UE_u is downloading data from the serving AP_i. By using the training and broadcast channels, UE_u periodically estimates SNR and RSS information of AP_i and neighbor APs and send them to the Coordinator in measurement reports. The RSS and SNR are estimated by UE_u based on Equations (10) and (11) respectively.

3.1 Coodinated multi-channel transmission

Consider mobile UE_u who is moving in the VLC network space. When the Coordinator receives a measurement report of UE_u and recognizes that UE_u is in an overlapped area of two or more APs, the Coordinator performs the CMcT scheme which consists of three phases. First, the Coordinator performs the CMcT decision algorithm to check whether UE_u can receive downlink data from two APs simultaneously. If using the CMcT is feasible, the Coordinator will determine which AP is the supportive AP of UE_u. In the second phase of downlink data transmission, the Coordinator performs the resource allocation algorithm to allocate downlink time slots to UEs in each AP. In the third phase, the Coordinator performs either the reselection of the supportive AP or the CMcT termination when the current $AP^{sup,u}$ of UE_u is not available anymore.

3.1.1 CMcT decision phase

Consider UE_u is downloading data from AP_i (known as $AP_i^{pri,u}$ of UE_u), which can be either ceiling-AP or desk-AP. When the Coordinator receives the measurement report of UE_u, it checks the set of neighbor APs in the measurement report ($SetAP\_report^u$). If the set $SetAP\_report^u$ is empty, UE_u is not able to have coordinated multi-channel transmission. Otherwise, the CMcT decision algorithm is performed by following steps:

Step 1: The Coordinator creates a list of neighbor APs which can provide downlink transmission or redundant link to UE_u ($List\_AP^u$).

An AP *j* in $SetAP\_report^u$ is added into $List\_AP^u$ if the following condition is satisfied:

$$SNR_{current,j,u} \geq SNR_{min,tran} \tag{12}$$

where, $SNR_{min,tran}$ is the SNR value which is required to transmit downlink data at the lowest modulation scheme. Table 2 shows the required SNR of different modulation schemes in VLC networks, thus we can take $SNR_{min,tran}$ of 13.4 dB. $SNR_{current,j,u}$ is the current SNR of UE_u from the neighbor AP_j.

If $List\_AP^u$ is empty, finish the CMcT decision phase.

Step 2: The Coordinator selects a $AP^{sup,u}$ for UE_u.

Each AP_j in the $List\_AP^u$ $\{AP_1, AP_2, \ldots, AP_n\}$ has two parameters including $SNR_{current,j,u}$ and $R_{load,j}$ which is the current load ratio of the AP_j.

The AP_j which is selected as the supportive AP of UE_u satisfies two following conditions:

– Its current load ratio is less than the defined low-load threshold of APs ($R_{thr,lowload}$):

$$R_{load,j} \leq R_{thr,lowload} \tag{13}$$

– Among these APs satisfying Equation (13), the supportive AP of UE_u ($AP^{sup,u}$) is the AP which has highest $SNR_{current,j,u}$.

$R_{load,j}$ is the current load ratio of the AP_j is defined as follows:

$$R_{load,j} = \frac{N_j^{pri} + N_j^{sup}}{N_{max}} \tag{14}$$

where, N_j^{pri} and N_j^{sup} is the number of UEs in the $Set\_UE_j^{pri}$ and $Set\_UE_j^{sup}$ of AP_j, respectively. N_{max} is the number of time slots of a time frame.

If all APs in $List\_AP^u$ don't satisfy Equation (13), $AP^{sup,u}$ is the AP in the list $List\_AP^u$ which has the highest $SNR_{current,j,u}$.

After selecting the supportive AP of UE_u, add UE_u into the Set_UE^{sup} of $AP^{sup,u}$ and synchronize the connection between UE_u and $AP^{sup,u}$.

3.1.2 Downlink data transmission phase

The time frame structure is shown in Figure 5 where a time frame of an AP consists of *pri_UE* subframe (white slots) and *sup_UE* subframe (grey slots) for allocating to primary and supportive UEs, respectively. At the beginning of each

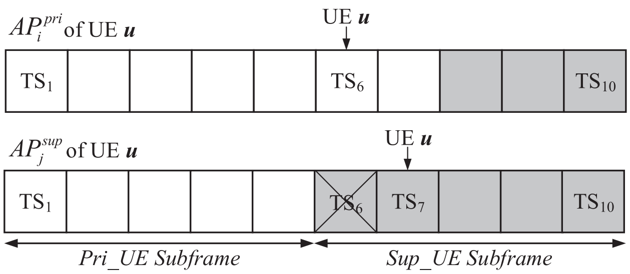


Figure 5: Time frame structure of the CMcT.

time frame, the Coordinator performs a resource allocation algorithm to calculate the number of time slots of the subframes and allocate time slots to UEs of the *Set_UE*^{pri} and *Set_UE*^{sup}. After that, the AP will transmit data to a UE in the allocated time slots.

Assume UE_u receives downlink data from the primary AP_i ($AP_i^{pri,u}$) and the supportive AP_j ($AP_j^{sup,u}$). To avoid the data collision, $AP_i^{pri,u}$ and $AP_j^{sup,u}$ have to send data to UE_u in different time slots. As shown in Figure 5, UE_u is allocated data transmission at the time slot TS6 in *pri_UE* subframe of $AP_i^{pri,u}$ and UE_u must not be allocated the time slot TS6 in *sup_UE* subframe of $AP_j^{sup,u}$.

When performing time slot allocation of an AP_j, the resource allocation algorithm has following steps:

Step 1: Select which supportive UEs of AP_j will be allocated time slots of the next time frame.

As the example given above, consider UE_u belonging to the $Set\_UE_j^{sup}$ of the AP_j whereas AP_i is the primary AP of UE_u. The UE_u is added to the set of selected supportive UEs of AP_j ($Selected\_UE_j^{sup}$), who will be allocated time slot in the *sup_UE* subframe of AP_j , when one of two cases happens:

– The current SNR of the primary link of UE_u is less than the minimum quality i. e.

$$SNR_{current,i,u} < SNR_{min,tran} \tag{15}$$

– When the current load ratio of the primary AP of UE_u (AP_i) is higher than the defined threshold as shown in Equation (16) and the current load ratio of the supportive AP of UE_u (AP_j) is less than the defined threshold as shown in Equation (17).

$$R_{load,i} > R_{thr,lowload} \tag{16}$$

$$R_{load,j} < R_{thr,lowload} \tag{17}$$

Step 2: The Coordinator calculates the number of time slots for the *pri_UE* subframe ($T_j^{pri\_UE}$) and the *sup_UE* subframe ($T_j^{sup\_UE}$) of the supportive AP_j according to the following formula:

$$T_j^{pri\_UE} = \left\lfloor T \times \frac{N_j^{packet,pri}}{N_j^{packet,pri} + N_j^{packet,sup}} \right\rfloor \tag{18}$$

$$T_j^{sup\_UE} = T - T_j^{pri\_UE} \tag{19}$$

where, T is the number of time slots of a time frame. $\lfloor\cdot\rfloor$ is the floor function. $N_j^{packet,pri}$ and $N_j^{packet,sup}$ are the total number of packets in the downlink queue of all UEs belonging to the $Set\_UE_j^{pri}$ and the $Selected\_UE_j^{sup}$, respectively which are determined by the following formula:

$$N_j^{packet,pri} = \sum_{v \in Set\_UE_j^{pri}} N_{v,j} \tag{20}$$

$$N_j^{packet,sup} = \sum_{u \in Selected\_UE_j^{sup}} N_{u,j} \tag{21}$$

where, $N_{v,j}$ and $N_{u,j}$ are the number of packets of UE_v and UE_u waiting in the downlink queues in the Coordinator, respectively.

Step 3: The Coordinator allocates time slots to UEs in the $Set\_UE_j^{pri}$ and the *Selected_UE*^{sup} of AP_j.

The Coordinator allocates time slots of the *pri_UE* subframe of AP_j to its primary UEs by Round Robin (RR) scheduling until either the *pri_UE* subframe is full or UE’s buffers are empty.

Supportive UEs in the *Selected_UE*^{sup} of AP_j are served in RR scheduling until either the *sup_UE* subframe of AP_j is full or UE’s buffers are empty. When UE_u of the *Selected_UE*^{sup} of AP_j is scheduled, which is the primary UE of $AP_i^{pri,u}$, if there are empty time slots in the *sup_UE* subframe of AP_j, the Coordinator will allocate one time slot of the *sup_UE* subframe of AP_j to UE_u when:

– If UE_u was not allocated a time slot in *pri_UE* subframe of $AP_i^{pri,u}$.
– If UE_u was allocated time slots in the *pri_UE* subframe of $AP_i^{pri,u}$, and if they are not collided with empty time slots of the *sup_UE* subframe of AP_j.

Otherwise, UE_u is not allocated time slots in the *sup_UE* subframe of AP_j.

3.1.3 Reselecting supportive AP or CMcT termination

When an UE moves, the quality of its supportive channel might vary and the channel can have blockage. If the UE moves out of the coverage area of the current supportive

AP and there is not any candidate for becoming its new supportive AP, the CMcT operation is terminated. Otherwise, the Coordinator will perform reselection of supportive AP.

To avoid repeated reselection of the supportive AP, we use an update time (T_{update}) to decide whether to update the supportive channel or not. Suppose that UE_u currently has the supportive channel from AP_j. After the Coordinator received the measurement report of UE_u, the Coordinator might find another AP_k ($k \neq j$) as a better candidate of the new supportive AP. It starts a time counter t_{update} which is counted as long as AP_k is still being selected as the candidate of the new supportive AP. When the time counter reaches the update time ($t_{update} \geq T_{update}$), it changes the supportive channel from AP_j to AP_k, i. e. the Coordinator asks AP_j to release the supportive channel for UE_u and synchronize the connection between UE_u and AP_k. If the Coordinator does not find any new supportive AP, the current supportive channel is remained. In the case the current supportive AP is blocked for a short time while the update time is not expiring, the Coordinator waits until the update time is expired and performs the reselection again.

3.2 CMcT link handover scheme

When UE_u moves to an overlapped area of APs, UE_u maintains primary and supportive downlink channels from AP_i and AP_j, respectively. When the Coordinator decides that UE_u needs a link handover from the primary AP_i to the supportive AP_j, the supportive AP_j becomes the new primary AP and AP_i becomes the new supportive AP.

The proposed proactive link handover procedure is implemented in two cases:

- Handover for the unblocked primary channel: the proactive link handover is performed because the UE moves to another AP.
- Handover for the blocked primary channel: UE's primary downlink channel is being blocked. Therefore, the UE must need a link handover.

In order to identify if the primary channel is blocked, the Coordinator periodically monitor the history of the RSS value as below:

$$P^{pri}_{previous} - P^{pri}_{current} \geq \rho \tag{22}$$

where, $P^{pri}_{current}$ and $P^{pri}_{previous}$ is the current and previous RSS values of the UE received from its primary AP, respectively. ρ is a hysteresis margin to determine whether the downlink channel is blocked or unblocked.

3.2.1 Handover procedure for unblocked primary channels

Due to the multi-AP VLC network has both ceiling-APs (uniform lighting) and desk-APs (spotlighting), the Coordinator decides link handover for UE_u according to three scenarios below:

Scenario 1: The primary AP_i ($AP_i^{pri,u}$) and the supportive AP_j ($AP_j^{sup,u}$) of UE_u are both ceiling-APs.

When the UE moves from it is serving ceiling-AP coverage to another ceiling-AP (i. e. the supportive AP), the RSS value received from the primary AP gradually decreases, while these from the supportive AP gradually increase. The link handover decision is performed if the following condition is satisfied:

$$P^{sup}_{current,j,u} - P^{pri}_{current,i,u} > \delta_{HOM} \tag{23}$$

where, $P^{pri}_{current,j,u}$ and $P^{sup}_{current,i,u}$ is the current RSS value of UE_u from its primary AP_i and supportive AP_j, respectively. δ_{HOM} is the value of link handover margin (HOM). The HOM value is a constant variable that represents the threshold for the difference in RSS between the primary and the target APs. HOM is used to solve the ping-pong effect and decide the most appropriate target AP that a UE can be handed over to.

Scenario 2: The primary AP_i of UE_u is a ceiling-AP and the supportive AP_j of UE_u is a desk-AP.

In this scenario, due to the desk-AP has a small coverage area and high SNR, if the Coordinator only uses Equation (23) to decide link handover, UE can perform unnecessary handover to the DAP if UE only pass the coverage of the DAP in a very short time. In order to avoid this problem, a handover trigger time (T_{HO}) is used. The Coordinator starts a timer (t_{HO}) when Equation (23) is satisfied. The time counter continues as long as Equation (23) is satisfied, and otherwise is reset. When $t_{HO} \geq T_{HO}$, a link handover decision is made to transfer UE_u from the primary AP_i to the supportive AP_j.

Scenario 3: The primary AP_i of UE_u is a desk-AP and the supportive AP_j of UE_u is a ceiling-AP.

When UE_u resides in the primary DAP's coverage, UE_u always achieves high RSS values. However, when it moves out of the DAP's coverage, its RSS suddenly drops, leading to temporary disconnections. In order to avoid this, in this scenario, the link handover is performed if the following condition is satisfied:

$$P^{pri}_{current,i,u} < P_{min,desk} + \delta_{HOM} \tag{24}$$

where, $P_{min,desk}$ is the smallest RSS value that the UE can received from the desk-AP. $P_{min,desk}$ is determined based on formula (6) with UE's location satisfying the incidence angle ψ being equal the width of FOV ψ_c.

3.2.2 Handover procedure for blocked primary channels

The primary downlink channel of UE is blocked when the condition given in Equation (22) is satisfied. If the blocked primary link is switched to another available link immediately, it may lead to unnecessary link handovers and signaling load because the primary link might be blocked for a very short time in the case of random shadow. In order to avoid this problem, the handover trigger time (T_{HO}) is also used for link handover decision. The Coordinator starts a timer when Equation (22) is satisfied. The timer continues as long as Equation (22) is satisfied or it will be reset when the LoS primary channel is recovered. When the time counter reaches the T_{HO} value, the link handover decision is made to activate the link handover for transferring the UE's downlink from its primary AP to its supportive AP.

4 Simulation results and discussions

The simulation model includes a multi-CAP VLC network covering a 12 m × 12 m × 2.5 m (length, width and height) space as shown in Figure 6. The VLC network has nine ceiling-APs denoted as AP_1 to AP_9 and 10 desk-APs denoted as AP_{10} to AP_{19} providing optical downlink transmission and seamless lighting. All of APs (ceiling-APs and desk-APs) have the half-intensity radiance angle of 70°. The distance between two adjacent ceiling-APs is 4 m. Desk-APs are installed randomly on the desk-AP plane which is at 1.5 m height of the floor plane. The location of all APs is presented in Table 1.

The initialization position of UEs (i. e. both mobile-UEs and stationary-UEs) is uniformly distributed in the entire room area. Stationary UEs add fixed data traffic to the system whereas mobile UEs cause dynamic traffic to access points because they move randomly in the room area. In all simulation scenarios, the percentage of stationary and mobile UEs are 33 and 67%, respectively. For example, in the case of N_{UE} is 20, the stationary and mobile UE number is 7 and 13, respectively. The height of UE's PD receiver is 1 m. Mobile UEs move around the room following the RWP at the average speed of 0.5 m/s. Events of LoS downlink channel blockages for each UE are generated following the Poisson process with the mean arrival rate is termed the

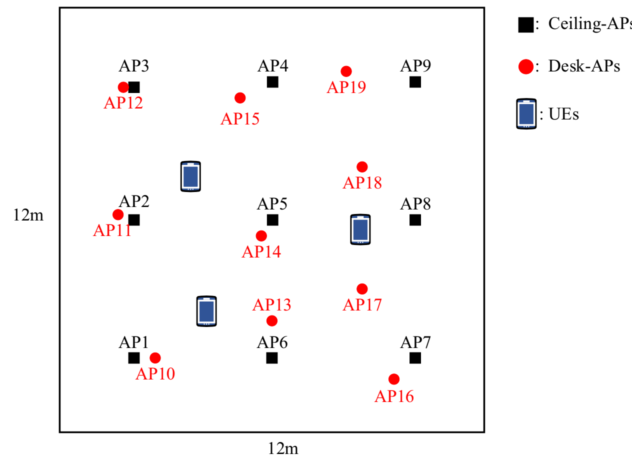


Figure 6: The layout of the simulated VLC network.

blockage occurrence rate [29]. For simplicity, we use the blockage interval parameter which is uniformly distributed between 0 and 1 s to replace the blockage occupation rate.

Table 2 presents the uncoded quadrature amplitude modulation (QAM) with a target BER of 10^{-3} in [21]. Downlink traffic of each UE is generated in a Poisson process which has packet size of 12.6 kbits and the mean inter-arrival time of 1.67 ms. Other simulation parameters are summarized in Table 3. In simulation experiments, we evaluate and compare performance of UE's throughput and packet delay of the CMcT HO scheme with those of the ComP-JT HO scheme [20] and the location-aware HO scheme [15].

The ComP-JT HO scheme performs link handover and CoMP-JT decisions based on the RSS report of mobile UEs which is updated to the Coodinator periodically. When a UE moves into an overlapped area of its serving AP and neighbor APs, the Coordinator chooses the neighbor AP which has the highest received power as the target AP. Then the CoMP joint transmission starts and the UE receives signals sent from both APs (the serving AP and the target AP) simultaneously. When the link handover condition is satisfied, the UE terminates its connection with the serving AP and connects to the target AP. The target AP

Table 1: Location of APs in the VLC network.

Access point	Location
$AP1$, $AP2$, $AP3$, $AP4$, $AP5$, $AP6$, $AP7$, $AP8$, $AP9$, $AP10$, $AP11$, $AP12$, $AP13$, $AP14$, $AP15$, $AP16$, $AP17$, $AP18$, $AP19$	(2, 2, 3), (2, 6, 3), (2, 10, 3), (6, 10, 3), (6, 6, 3), (6, 2, 3), (10, 2, 3), (10, 6, 3), (10, 10, 3), (2.4, 2, 1.5), (1.7, 6.3, 1.5), (1.8, 9.75, 1.5), (6, 3, 1.5), (5.7, 5.5, 1.5), (5.25, 9.7, 1.5), (9.5, 1.5, 1.5), (8.6, 4, 1.5), (8.6, 7.5, 1.5), (8.15, 10.3, 1.5)

Table 2: Uncoded QAM adaptive bit loading [21].

$SNR_{min,modulation}$	Modulation	Bits/symbol
13.4	8QAM	3
16.5	16QAM	4
19.6	32QAM	5
22.5	64QAM	6
25.5	128QAM	7
28.4	256QAM	8

becomes the new serving AP and starts serving the UE alone.

The location-aware HO scheme aims to reduce the scanning time in order to reduce the link switching delay. When a UE moves to the cell edge area of the serving AP, the RSS value is decreased. If the received signal from the serving AP becomes too weak (below a link switching threshold), the link switching procedure starts. First, the UE sends its location information to the serving AP (Time Difference of Arrival – TDOA method is used to estimate location of UE). Based on the location information received from the UE, the serving AP determines the neighbor APs to which the UE is approaching and sends addresses of the APs to the UE. The UE scans the RSS of neighbor APs and chooses the AP having the strongest RSS as the new serving AP and starts communicating with the new serving AP.

Table 3: Simulations parameters.

Parameters	Unit	Value
Simulation time	Seconds	4000
Time slot duration (T_S)	Milliseconds	1
Time frame duration	Milliseconds	10
Area of PD (A)	cm^2	1
Height of UEs (h_{UE})	m	1
FOV at a receiver (ψ_c)	Degree	70°
O/E conversion efficiency (R_{pd})	A/W	0.53
Gain of an optical filter ($T_s(\psi)$)		1
Refractive index of a lens at a PD (n)		1.5
Feedback resistance of TIA (R_F)	kΩ	6
Current due to background light (I_{bg})	μA	5100
Height of Ceiling-APs (h_{CAP})	m	2.5
Height of Desk-APs (h_{DAP})	m	1.5
Ceiling-AP power ($P_{t,CAP}$)	W	50
Desk-AP power ($P_{t,DAP}$)	W	25
Number of subcarriers in each AP		300
Bandwidth of 1 subcarrier	kHz	15
SNR threshold for data transmission ($SNR_{min,tran}$)	dB	13.4
Low load threshold value ($R_{thr,lowload}$)		0.4
Link handover margin (δ_{HOM})	dB	3
Time of update trigger (T_{update})	Seconds	0.1
Time of handover trigger (T_{HO})	Seconds	0.5
Hysteresis margin (ρ)	dB	7
The smallest RSS value of UE received from desk-AP ($P_{Min,Desk}$)	μW	0.263
Blockage occurrence rate (λ)	/minute	10

4.1 Performance comparison of handover schemes with different UE quantity

When using the CMcT HO scheme, a VLC-AP can share the input load with its neighbors and improve downlink data transmission rates of cell-edge UEs which are smoothly switched from the primary AP to the supportive AP. Because the connection between a UE and its primary AP can be still maintained after a handover is completed, our proposed scheme effectively reduces the data transmission interruption. Figure 7 shows the instantaneous throughput of a selected mobile-UE over a period of 60 s. In the simulation scenario, a mobile UE is moving in the simulated area in a random waypoint model with the mean velocity of 0.5 m/s. Because the mobile UE moves between APs, it will need to perform link handover. We observe the transmission interruption which the applied handover schemes might cause to the mobile UE by measuring the number of received packets of the mobile UE for every 0.1 s. Simulation results show that by using the CMcT HO scheme, the number of transmission interruption (the sample of the number of received packets is zero, denoted as zero-sample) of the the mobile UE is reduced significantly. The proposed CMcT HO scheme has nine zero-samples equal whereas the ComP-JT HO and Location-aware schemes have 56 and 63 zero-samples, respectively.

Figure 8 shows a comparison of the average mobile-UE's throughput with different UE's quantity. The proposed CMcT HO scheme always achieves a higher throughput than two other schemes. This gain becomes more significant as the number of UEs increases. For example, when a number of UEs in the room is 20, the average throughput is about 7.35, 6.84 and 6.45 Mbps in the CMcT HO, ComP-JT HO and Location-aware HO schemes, respectively. In the case the number of UEs in the room is 60, the average throughput achieved about 5.71, 4.86 and 4.48 Mbps for CMcT HO, ComP-JT HO and Location-aware HO schemes respectively.

Figure 9 shows the cumulative distribution function (CDF) of stationary-UE's throughput with two scenarios N_{ue} = 30 and N_{ue} = 50. The results show that the CMcT HO scheme can provide higher throughput of stationary-UEs than the ComP-JT HO and Location-aware HO schemes. In the case N_{ue} = 30, the percentage of throughput samples

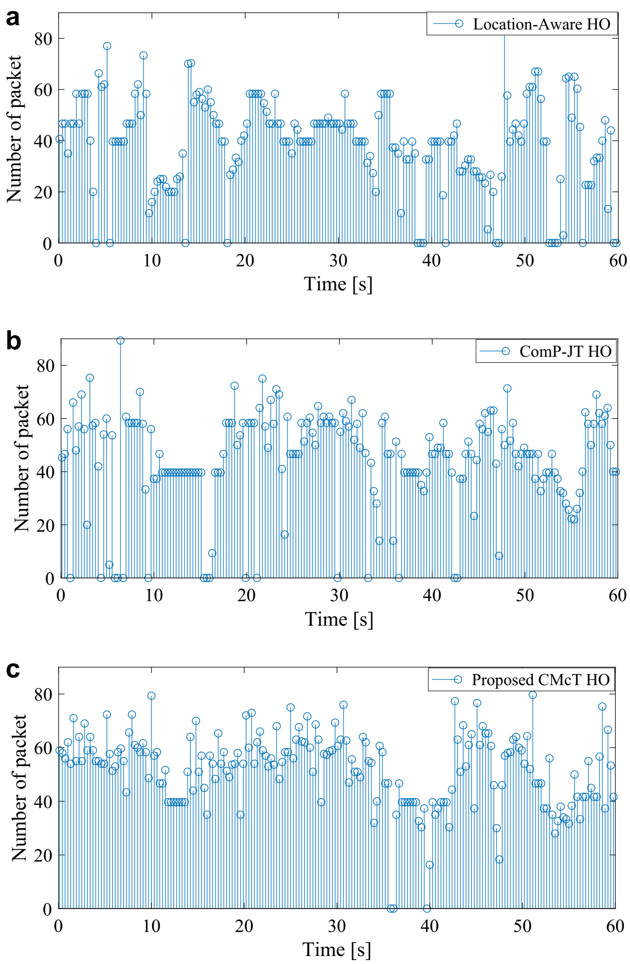


Figure 7: The instantaneous throughput of a mobile-UE over a period of 60 s.

higher than 6.5 Mbps in the CMcT HO scheme is 97.5% while it is only 76 and 69.5% in ComP-JT HO scheme and Location-aware HO scheme, respectively. When $N_{ue} = 50$, there are 78.5, 67 and 57% UEs have download throughput higher than 5.5 Mbps in the CMcT HO scheme, the ComP-JT HO scheme and the Location-aware HO scheme, respectively.

Because the UE's data rate is increased and the link handover delay is reduced, the proposed CMcT HO scheme can provide smaller packet delay than those of ComP-JT HO and Location-aware HO schemes. For example, Figure 10 shows the comparison of the average mobile-UE's packet delay among three schemes used in the simulation with different number of UEs. When there are 20 UEs in the room, the proposed scheme can improve up to 56.9 and 91.6% in the average packet delay when compared to the ComP-JT HO and Location-aware HO schemes, respectively, i. e. the average packet delay is about 0.0144, 0.0226 and 0.0276 s in the CMcT

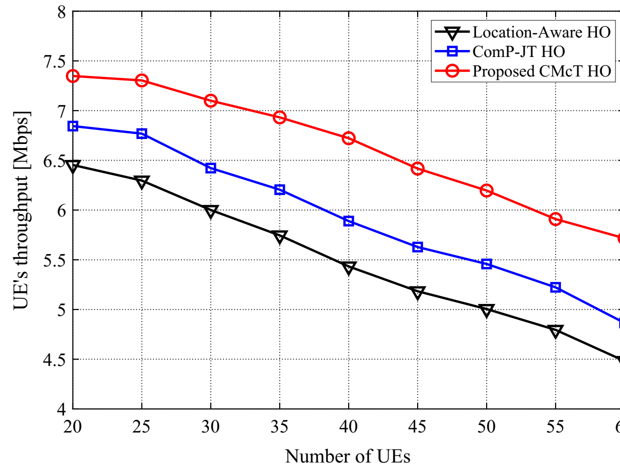


Figure 8: Mobile-UE's throughput comparison when changing the number of UEs.

HO, ComP-JT HO and Location-aware HO schemes, respectively. When the number of UEs in the room is 60, the CMcT HO scheme can improve the packet delay over the ComP-JT HO and Location-aware HO schemes by 41.1 and 60.4%.

Figure 11 shows the CDF of stationary-UE's packet delay when N_{ue} is 30 and N_{ue} is 50. The CMcT HO scheme can provide lower delay packet of stationary-UEs than ComP-JT HO and the Location-aware HO schemes. For example, when N_{ue} is 30, the percentage of delay samples lower than 0.03 s in the CMcT HO scheme is 95% while it is only 73.2 and 66.5% in ComP-JT HO and Location-aware HO schemes, respectively. When N_{ue} is 50, there are 77.5, 67.5 and 59.5% UEs having the packet delay lower than 0.06 s in

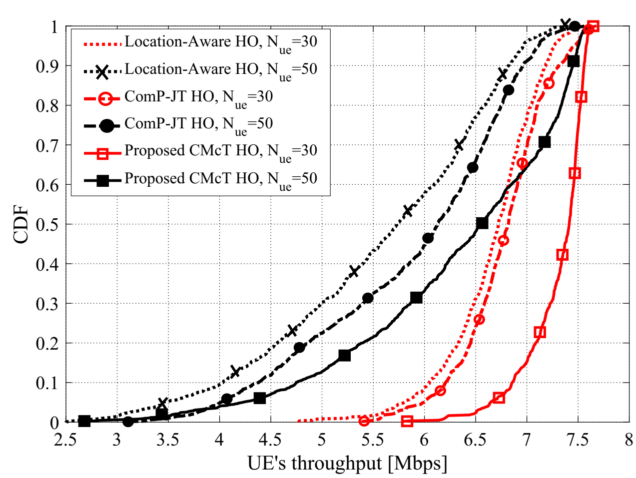


Figure 9: Stationary-UE's throughput comparison with number of UEs equal 30 and 50.

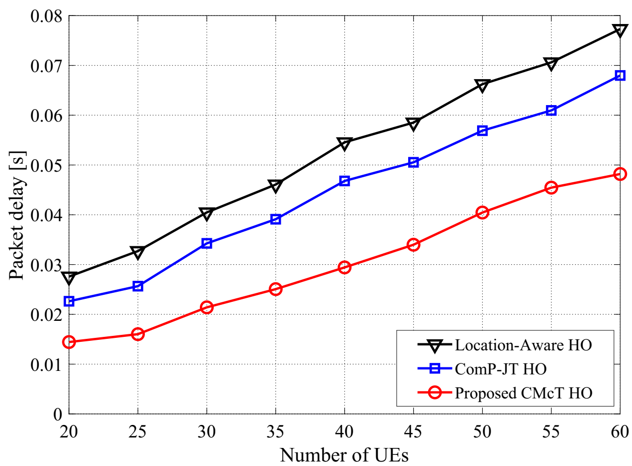


Figure 10: Mobile-UE's packet delay comparison when changing the number of UEs.

the CMcT HO, ComP-JT HO and Location-aware HO schemes, respectively.

4.2 The impact of random downlink channel blockages

In the simulation experiment, we study the impact of random light-path blockages on the link handover rate and user throughput. Simulation parameters also are given in Table 3 and the number of mobile UEs in the room is 30.

Figure 12 shows a comparison of the average link handover rate of the three link handover schemes when changing the blockage occurrence rate. The simulation results show that deploying the CMcT HO scheme can reduce the link handover rate significantly. The link handover rate is 0.32/s when the blockage occurrence rate is 30 times per minute. Meanwhile, the link handover rate reaches up to 0.49/s and 0.9/s in the Location-aware HO scheme and ComP-JT HO scheme, respectively.

Figure 13 shows the comparison of the average mobile-UE's throughput with different blockage occurrence rates. The average throughput decreases when the occurrence rate increases. However, the CMcT HO scheme achieves a higher average throughput and has a smaller throughput reduction than the ComP-JT HO scheme, and the Location-aware HO scheme. When the blockage occurrence rate increases from 6 to 30 times per minute, the user throughput decreases by 0.463, 0.794 and 1.071 Mbps in the CMcT HO scheme, the ComP-JT HO scheme and the Location-aware HO scheme , respectively.

In summary, the CMcT HO scheme outperforms the ComP-JT HO and Location-aware HO schemes in terms of user throughput and packet delay because the CMcT HO scheme applies coordinated multiple channel transmission, proactive handover and methods to avoid unnecessary handover. For the ComP-JT HO scheme, it uses the link HOM to decide link handover, from which UEs can be easily switched to a desk-AP if the UE move into the its coverage. However, it can cause unnecessary link handovers if UEs only pass through the desk-AP coverage for a very short period of time. Because the ComP-JT can improve SNR of cell-edge UEs, the ComP-JT HO scheme achieves better performance than the Location-aware HO scheme. In the Location-aware HO scheme, when the RSS value of an UE received from it is primary AP is less than the link handover threshold, the Coordinator will select a target AP based on UE's location information and SNR, then a link

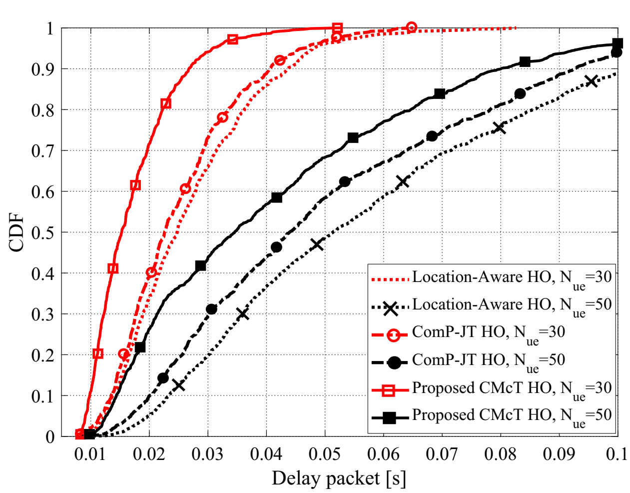


Figure 11: Stationary-UE's packet delay comparison with number of UEs equal 30 and 50.

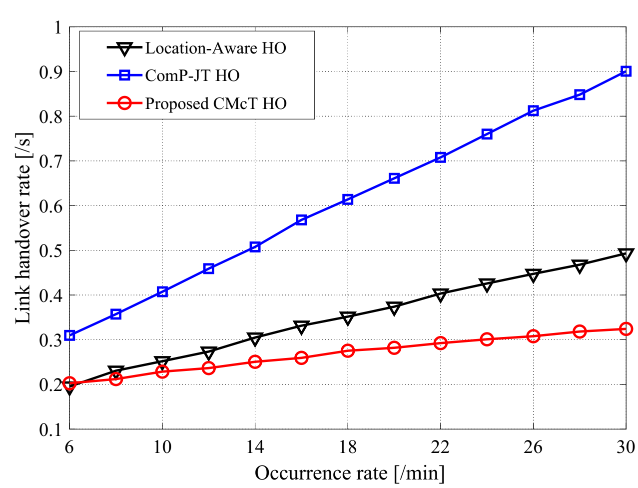


Figure 12: Link handover rate comparison with different channel blockage occurrence rates.

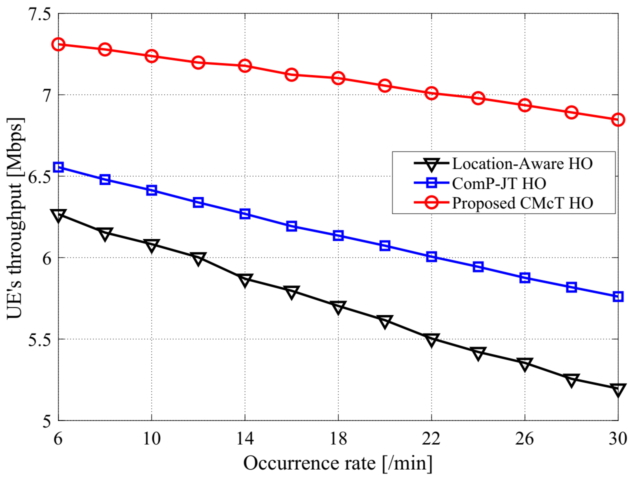


Figure 13: Mobile-UE's throughput comparison with different channel blockage occurrence rates.

handover is performed to switch the link from the serving AP to the target AP. When using the Location-aware HO scheme, UEs are difficult to switch to a desk-AP because the desk-AP coverage is random located within the ceiling-AP coverage. Because the scheme applies single-channel transmission, the data rate of UEs is significantly reduced when UEs enter the cell edge area. As a result, the Location-aware scheme achieves the lowest performance in all scenarios.

5 Conclusion

In this paper, we have proposed a proactive link handover scheme combined with coordinated multi-channel transmission for multi-AP VLC networks. In order to enhance the data rate and provide alternative/supportive links for UEs, the CMcT decision algorithm and the resource allocation algorithm are proposed to eliminate data collision of primary and supportive time slots. The proactive link handover scheme (the CMcT HO scheme) works effectively for handling link switching to mobile users. Simulation results proved that the proposed CMcT HO scheme can improve network performance including user throughput and packet delay and reduce unnecessary handovers. Future works include research on optimization of the system performance by setting adaptively parameters of the CMcT HO such as the threshold value and the link HOM.

Acknowledgment: This work has been supported by Vietnam National University, Hanoi under Project QG.18.35 "Research on interference mitigation and performance enhancement and development of a simulation tool for beam-steering visible light communications networks".

Author contribution: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.
Research funding: This research was funded by Vietnam National University, Hanoi.
Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References

1. Ghassemlooy Z, Popoola W, Rajbhandari S. Optical wireless communications: system and channel modelling with MATLAB. Boca Raton, FL: Taylor & Francis Group; 2012.
2. IEEE Standard, 802.15.7. IEEE standard for local and metropolitan area network– Part 15.7: Short-range wireless optical communication using visible light; 2019.
3. Karunatilaka D, Zafar F, Kalavally V, Parthiban R. LED based indoor visible light communications: state of the art. IEEE Commun Surv Tutorials 2015;17:1649–78.
4. Tsonev D, Chun H, Rajbhandari S, McKendry JD, Videv S, Gu E, et al. A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride LED. IEEE Photon Technol Lett 2014;26:637–40.
5. Huang X, Shi J, Li J, Wang Y, Wang Y, Chi N. 750 Mbit/s visible light communications employing 64QAM-OFDM based on amplitude equalization circuit. In: 2015 optical fiber communications conference and exhibition (OFC); 2015: p. 1–3.
6. Chen C, Videv S, Tsonev D, Haas H. Fractional frequency reuse in DCO-OFDM-based optical attocell networks. J Lightwave Technol 2015;33:3986–4000.
7. Chen C, Tsonev D, Haas H. Joint transmission in indoor visible light communication downlink cellular networks. In: Proc globecom workshops (GC wkshps); 2013: p. 1127–32.
8. Hanzo L, Haas H, Imre S, O'Brien D, Rupp M, Gyongyosi L. Wireless myths, realities, and futures: from 3G/4G to optical and quantum wireless. Proc IEEE 2012;100:1853–88.
9. Wang Y, Videv S, Haas H. Dynamic load balancing with handover in hybrid Li-Fi and Wi-Fi networks. In: Proc IEEE 25th international symposium on personal indoor and mobile radio communications (PIMRC); 2014: p. 548–52.
10. Borogovac T, Rahaim M, Carruthers JB. Spotlighting for visible light communications and illumination. In: 2010 IEEE globecom workshops (GC wkshps); 2010: p. 1077–81.
11. Kizilirmak RC, Narmanlioglu O, Uysal M. Centralized light access network (c-LiAN): a novel paradigm for next generation indoor VLC networks. IEEE Access 2017;5:19703–10.
12. Pollini GP. Trends in handover design. IEEE Commun Mag 1996;34:82–90.
13. Nguyen T, Chowdhury MZ, Jang YM. A novel link switching scheme using pre-scanning and RSS prediction in visible light communication networks. EURASIP J Wirel Commun Netw 2013;2013:293–309.
14. Wu X, Haas H. Handover skipping for LiFi. IEEE Access 2019;7:38369–78.
15. Nguyen T, Chowdhury MZ, Jang YM. Location-aware fast link switching scheme for visible light communication networks. J Korean Inst Commun Inf Sci 2012;37C:888–93.

16. Xiong J, Huang Z, Zhuang K, Ji Y. A cooperative positioning with kalman filters and handover mechanism for indoor microcellular visible light communication network. Opt Rev 2016;23:683–88.
17. Bui TC, Kiravittaya S, Nguyen NH, Nguyen NT, Spirinmanwat K. LEDs configuration method for supporting handover in visible light communication. In: The 2014 IEEE region 10 conference (TENCON 2014); 2014: p. 1–6.
18. Soltani MD, Kazemi H, Safari M, Haas H. Handover modeling for indoor Li-Fi cellular networks: The effects of receiver mobility and rotation. In: Proc IEEE wireless communications and networking conference (WCNC), San Fransisco, CA, USA. 2017: p. 1–6.
19. Dinc E, Ergul O, Akan OB. Soft handover in OFDMA based visible light communication networks. In: Proc 82nd Vehicular Tech Conf (VTC Fall); 2015: p. 1–5.
20. Demir MS, Miramirkhani F, Uysal M. Handover in VLC networks with coordinated multipoint transmission. In: Proc IEEE int black sea conf commun netw (BlackSeaCom); 2017: p. 1–5.
21. Chen C, Haas H. Performance evaluation of downlink cooperative multipoint joint transmission in LiFi systems. In: 2017 IEEE globecom workshops (GC wkshps); 2017: p. 1–6.
22. Guzman GB, Serrano AL, Jimenez VPG. Cooperative optical wireless transmission for improving performance in indoor scenarios for visible light communications. IEEE Trans Consum Electron 2015;61:393–401.
23. Chen C, Serafimovski N, Haas H. Fractional frequency reuse in optical wireless cellular networks. In: 2013 IEEE 24th annual international symposium on personal, indoor, and mobile radio communications (PIMRC); 2013: p. 3594–8.
24. Bettstetter C, Hartenstein H, Perez-Costa X. Stochastic properties of the random waypoint mobility model. ACM Wireless Netw 2004;10:555–67.
25. Shao S, Khreishah A, Rahaim MB, Elgala H, Ayyash M, Little T. An indoor hybrid WIFI-VLC internet access system. In: Proceedings IEEE 11th international conference MASS; 2014: p. 569–74.
26. Komine T, Nakagawa M. Fundamental analysis for visible light communication system using LED lights. IEEE Trans Consum Electron 2004;50:100–107.
27. Cheng C, Ijaz M, Tsonev D, Haas H. Analysis of downlink transmission in DCO-OFDM-based optical attocell networks. In: 2014 IEEE global communications conference; 2014: p. 2072–7.
28. Ghimire B, Haas H. Self-organising interference coordination in optical wireless networks. EURASIP J Wirel Commun Netw 2012;1: 1–15.
29. Wu X, Haas H. Access point assignment in hybrid LiFi and WiFi networks in consideration of LiFi channel blockage. IEEE SPAWC 2017: 1–5. https://doi.org/10.1109/SPAWC.2017.8227704.