Coordinated Multi-channel Transmission Scheme for Indoor Multiple Access Points VLC Networks

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***Abstract*- Visible Light Communications (VLC) is considered as an effective complementary solution for indoor wireless communications to achieve high-speed and secure data transmission. Instead of using RF bandwidth, VLC uses the visible light spectrum to perform lighting and communications functions simultaneously. In a large indoor environment, a multiple ceiling access point VLC network (multi-CAP VLC) is deployed to achieve seamless coverage and high spectral efficiency. In the multi-CAP VLC network, random movement of user equipment (UE) leads to an uneven load distribution between CAPs. Furthermore, the quality of service of cell-edge users who reside at cell edge areas is decreased due to the high attenuation of the received signal. In the paper, to improve the QoS of cell-edge UEs, we propose a coordinated multi-channel transmission scheme (CMcT) for indoor multi-CAP VLC networks. The CMcT performs a coordinated downlink data transmission from different CAPs to a UE simultaneously. Performance results obtained by computer simulation show that the CMcT scheme can significantly improve user throughput and packet delay comparing with those of the single-channel transmission scheme.**

Keywords— Visible light communications, multi-channel transmission, time slot scheduling.

I. INTRODUCTION

The development of mobile networks has led to a huge data demand in wireless communications. However, the radio frequency (RF) spectrum for wireless communications is a finite resource and is not sufficient to meet future demands. With the rapid development of recent material technologies, the light-emitting diode (LED) technology has led to great interests in the application and research of indoor Visible Light Communications (VLC) [1]. 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 radiofrequency sensitive electronic devices [2] and simultaneously be able to provide high point-to-point data rate [3].

VLC systems are often based on intensity modulation and direct detection (IM-DD). At the transmitter side, VLC systems use intensity modulation (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 to be use for IM/DD VLC systems because of its advantages. In [4], a VLC system using OFDM achieves high spectral efficiency, immunities to channel frequency selectivity and mitigates the multipath-induced inter-symbol interference (ISI). In [5], a multiple access scheme was proposed for optical attocell networks using OFDM by dividing time and frequency resources among multiple users.

Because a CAP has small coverage, in order to satisfy communications and lighting requirements to multiple UEs in a large indoor environment, the atto-cell VLC network model was proposed in [5,6]. This atto-cell network is also known as multi-CAP VLC network, which is deployed by installing multiple LED access points on the room ceiling in an appropriate layout. In order to enhance the data rate of multi-CAP VLC networks, the coordinated multipoint joint transmission (ComP-JT) technique of wireless communications is adapted to a multi-CAP VLC to increase SINR for UEs at cell edge area [6-8]. When using ComP-JT in the VLC system, downlink signal sent to a single UE is simultaneously transmitted from multiple CAPs using the same optical bandwidth to improve the data transfer rate and also reduce the impact of blockages on UEs. However, in [6], the requirement of a special multi-light beam structure at the transmitter makes ComP-JT difficult to apply with conventional diffuse light sources. Using coordinated transmission at the physical layer requires high transmission time synchronization between CAPs resulting in the complex design of VLC systems. In other research [5,9,10], fractional frequency reuse (FFR) was proposed to mitigate co-channel interference (CCI) between neighbor CAPs for improving downlink data rate for cell-edge UEs. However, exploiting FFR decreases the spectrum efficiency when CAPs have different input load.

In this paper, in order to enhance data rate of cell-edge UEs, a coordinated multi-channel transmission scheme (CMcT) is proposed for indoor multi-CAP VLC networks which exploit fractional frequency reuse (FFR). When an UE exploits the CMcT scheme, UEs can receive downlink data sent from two CAPs in different time slots. We propose a time slot scheduling algorithm to avoid the collision of downlink signals sent from CAPs. The remainder of the paper is organized as follows. Section II presents the multi-CAP VLC system model. Section III describes the operation of the proposed coordinated multi-channel transmission scheme (CMcT). Simulation results are presented and discussed in section IV. Finally, the conclusions are given in the last section.

II. SYSTEM MODEL

A. System description

As shown in Fig.1, the system includes a Coordinator, N_{CAP} ceiling access point (CAP) and N_{UE} UE. Each CAP is assigned an identity (CAP-ID) $\boldsymbol{i}$, where $\boldsymbol{i}$ = 1, 2,…, N_{CAP}. CAPs are installed in a grid layout on the ceiling. The distance between ceiling (CAP plane) and the floor is h_{CAP} (m). All CAPs are connected to the Internet via the Coordinator which is responsible for mobility management and downlink resource allocation to UEs [7,11]. There are two types of UE including stationary UE and mobile UE those are randomly distributed in-room area. Each UE is assigned a UE's identity $\boldsymbol{u}$, where $\boldsymbol{u} = 1, 2,\ldots, N_{UE}$. 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. We consider that uplink channels of UEs use RF [12]. For the downlink transmission, fractional frequency reuse (FFR) technique and Direct-current optical orthogonal frequency division multiplexing (DCO-OFDM) are deployed [5]. Fig.2 shows an example of using FFR of four frequency bands where four neighbor CAPs are allocated to four different frequency bands. This reduces CCI affect to UEs in overlapping areas of CAP. A CAP provides a shared channel of K subcarriers which exploits TDMA for downlink multiple access. A CAP exploits a broadcasting channel to transmit pilot signals which carry the identity of the CAP (CAP-ID). An UE scans broadcasting channels of its serving CAP and neighbor CAPs periodically to measure the received signal strength (RSS) and detect CAP-ID. A CAP uses a training channel which UE can use to estimate the SNR of the downlink channel of the CAP.

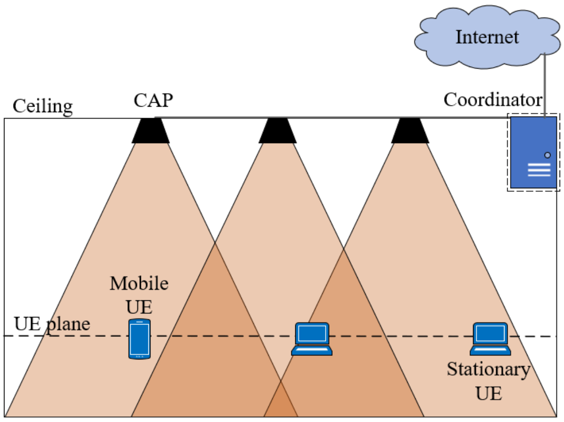

Figure 1 Multi-CAP VLC network model

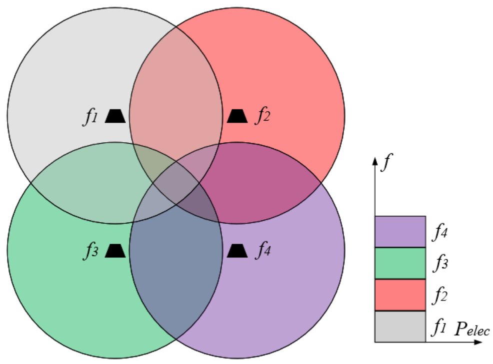

Figure 2 Example of deploying FFR for multi-CAP VLC networks

B. Downlink Channel

There are 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) [13]. However, 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 follows [13]:

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

Where, A is the physical area of the Photo Detector (PD); d is the Euclidean distance between a CAP to the PD of UE; ψ is the incidence angle at receiver; ϕ is the angle of irradiance; $T_s(\psi)$ is the gain of an optical filter used; m is the Lambertian index that is given by $-\ln(2)/\ln(\cos(\phi_{1/2}))$, 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 can be calculated as:

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

Where n is the refractive index of the air.

The electrical signal power transmitted by CAP $\boldsymbol{i}$ on subcarrier $\boldsymbol{k}$ is defined below [14]:

$$P_{elec,i,k} = \frac{P_{opt}^2}{(K-2)\rho^2} \quad (3)$$

$$\rho = x_{DC} / \sqrt{\sum_{k=0}^{K-1} \mathrm{E}[x_k^2(t)]} \quad (4)$$

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

The average received signal power of UE $\boldsymbol{u}$ from CAP $\boldsymbol{i}$ on subcarrier $\boldsymbol{k}$ is determined by the following formula:

$$P_{i,u,k} = R_{pd}^2 G_{i,u}^2 P_{elec,i,k} \quad (5)$$

Where, $G_{i,u}$ is the DC channel gain from CAP $\boldsymbol{i}$ to UE $\boldsymbol{u}$; R_{pd} is the efficiency of converting the light to the electrical signal.

In order to evaluate the downlink signal quality, the SNR of UE $\boldsymbol{u}$ on subcarrier $\boldsymbol{k}$ from CAP $\boldsymbol{i}$ is determined as follows:

$$SNR_{i,u,k} = \frac{R_{pd}^2 G_{i,u}^2 P_{elec,i,k}}{\sigma_k^2} \quad (6)$$

Where, σ_k^2 is the received noise power due to mainly shot noise on subcarrier $\boldsymbol{k}$. The noise power σ_k^2 is defined by [15]:

$$\sigma_k^2 = 2qI_{bg}B_{sc} + \frac{4K_B T_A B_{sc}}{R_F} \quad (7)$$

Where, I_{bg} is the background current caused by the background light; $B_{sc} = W/K$ is the bandwidth of subcarrier, where W is the total bandwidth; the electronic charge is q = 1,6 × 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 trans-impedance amplifier (TIA).

III. Coordinated Multi-channel Transmission Scheme

When an UE resides in an overlapped area of CAPs, the UE can receive downlink data from the two most appropriate CAPs simultaneously. The CMcT scheme is proposed for multi-CAP VLC networks to achieve the following objectives:

- Support load sharing between CAPs: low-load CAPs will support data transmission for UEs served by high-load CAPs.
- Enhance the data rate for cell-edge UEs.
- Provide redundant links for the cell-edge UE, thereby reducing the risk of disconnection of UE due to random shadowing of obstructions.

As shown in Fig.3, when an UE be performed multichannel downlink transmission, the UE has the primary downlink channel received from its serving CAP (known as primary CAP - CAP_{pri}). The secondary downlink channel is received from the most appropriate neighbor CAP (known as supportive CAP - CAP_{sup}). A CAP also classifies its connected UEs to two categories: primary-UEs (UE_{pri}) for those the CAP is their serving CAP and supported-UEs (UE_{sup}) for those the CAP is their supportive CAP.

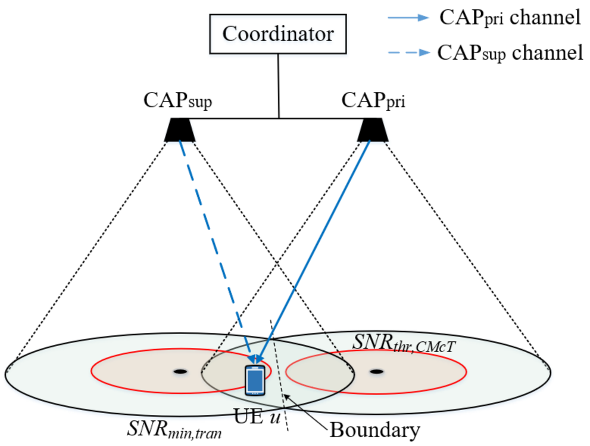

Figure 3 Coordinated multi-channel transmission for multi-CAP VLC networks

When the Coordinator receives a measurement report of UE ***u*** and reorganizes that UE ***u*** is in the overlapped area of two or more CAPs, the Coordinator performs the CMcT scheme which consists of three phases. First, the Coordinator performs the CMcT decision algorithm for an UE to check whether the UE can receive downlink data from two CAPs simultaneously. If using the CMcT is feasible, the Coordinator will determine which CAP will be the CAP_{sup} of the UE. In the second phase of multi-channel downlink data transmission, the Coordinator performs the time slots allocation algorithm to allocate downlink time slots to UEs in each CAP (including UE_{pri} and UE_{sup}). In the third phase, the Coordinator performs the CMcT termination when conditions to apply the CMcT scheme are not possible.

A. CMcT decision

Consider an UE ***u*** is downloading data from CAP ***i*** (known as $CAP_{pri,i}$ of UE ***u***). By using the training and broadcasting channels, UE ***u*** estimates SNR and detects CAP-ID of neighbor CAPs then send it to the Coordinator in the measurement report. If the set of neighbor CAPs in the measurement report is empty, UE ***u*** is not able to have multi-channel transmission. Otherwise, the CMcT decision algorithm is performed if one of the following criteria are met:

$$\left[\begin{array}{l} SNR_{u,i} < SNR_{thr,CMcT} \\ R_{load,i} \geq R_{thr,highload} \end{array}\right. \tag{8}$$

Where $R_{thr,highload}$ is the high load threshold value of the CAP. $R_{load,i}$ is the current load ratio of the $CAP_{pri,i}$ of the UE ***u***. $SNR_{thr,CMcT}$ is the SNR's threshold value which can use as the SNR value around the boundary of two neighboring cells.

$SNR_{thr,CMcT}$ is determined depending on the layout configuration and system parameters. For example, as shown in Fig.4, when we deploy four CAPs in a 6m×6m×2.5m space, the SNR values of UEs in the range of 14.5 dB to 38.2 dB. The SNR at the boundary of two neighboring cells is about 25.5 dB.

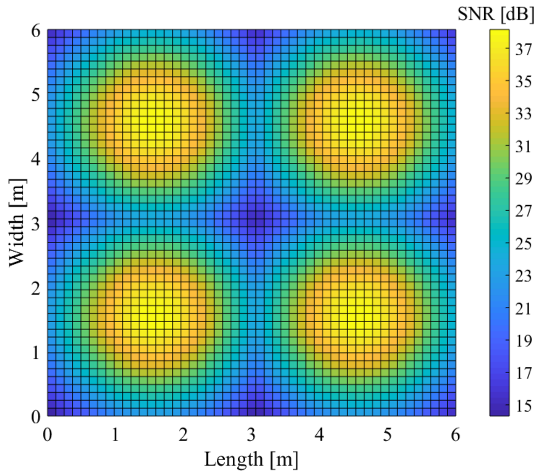

Figure 4 SNR distribution on the UE plane with four CAPs

The load ratio of CAP ***i*** is defined as follows:

$$R_{load,i} = \frac{|U_{pri,i}| + |U_{sup,i}|}{N_{\text{ue,max}}} \tag{9}$$

Where, $|U_{pri,i}|$ and $|U_{sup,i}|$ is the number of UEs in the set $U_{pri,i}$ and $U_{sup,i}$ of the CAP ***i***, respectively. $N_{ue,max}$ is the maximum number of UEs that each CAP can serve simultaneously during a time frame. If each UE consumed one time slots in each time frame, $N_{ue,max}$ is equal to the number of time slots of a time frame.

The CMcT decision phase has following steps:

Step 1: Create a set of neighbor CAPs which can provide downlink transmission to UE ***u*** ($SetCAP_u$).

- The Coordinator adds the CAP *j* into $SetCAP_u$ if following conditions are satisfied:

$$SNR_{u,j} \geq SNR_{min,tran} \tag{10}$$

$$R_{load,j} < R_{thr,highload} \tag{11}$$

Where, $SNR_{min,tran}$ is the SNR threshold value which is required to transmit downlink data at the lowest modulation scheme; $SNR_{u,j}$ is the SNR of the UE ***u*** from the neighbor CAP *j*; $R_{load,j}$ is the load ratio value of the CAP *j*.

- If $SetCAP_u$ is empty, finish the CMcT decision phase.

Step 2: Select CAP_{sup} for UE ***u***.

- The Coordinator determines CAP_{sup} according to the following formula:

$$CAP_{sup} = \underset{j \in SetCAP_u}{\arg\max}\, SNR_{u,j} \tag{12}$$

- Add UE ***u*** into the set U_{sup} of CAP_{sup} and synchronize the connection between UE ***u*** and CAP_{sup}.

B. Multi-channel downlink data transmission

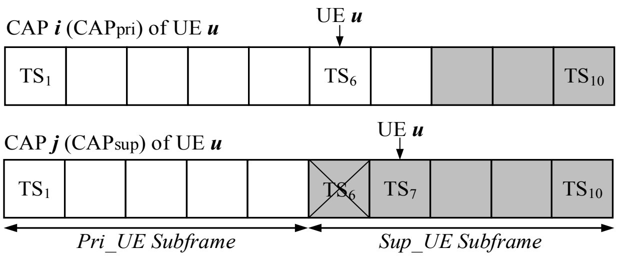

Figure 5 Time frame structure for CMcT

The time frame structure is shown in Fig.5 where a time frame of a CAP consists of *pri_UE subframe* (white slots) and *sup_UE subframe* (grey slots) for allocating to primary and supportive UEs, respectively. The ratio of the number of time slots of *pri_UE subframe* to that of *sup_UE subframe* is defined as follows:

$$R_{subf}^{i} = \frac{\sum_{u \in U_{pri,i}} N_{packet,u,i}}{\sum_{v \in U_{sup,i}} N_{packet,v,i}} \quad (13)$$

Where, $N_{packet,u,i}$ and $N_{packet,u,i}$ are the number of packets of UE u and UE v waiting in queues in the Coordinator.

The number of time slots of the *pri_UE subframe* ($T_{pri,subf}$) and the *sup_UE subframe* ($T_{sup,subf}$) of CAP ***i*** is determined as follows:

$$T_{pri\_subf}^{i} = \left\lfloor \frac{T \times R_{subf}^{i}}{1 + R_{subf}^{i}} \right\rfloor \quad (14)$$

$$T_{sup\_subf}^{i} = T - T_{pri\_subf}^{i} \quad (15)$$

Where, T is the number of time slots of a time frame; $\lfloor . \rfloor$ is the floor function.

In this phase, UE ***u*** receives downlink data from primary CAP ***i*** ($CAP_{pri,i}$) and supportive CAP ***j*** ($CAP_{sup,j}$). To avoid the collision of the two CAPs, $CAP_{pri,i}$ and $CAP_{sup,j}$ have to send data to UE ***u*** in different time slots. As the example in Fig.5, UE ***u*** is allocated data transmission at time slots TS_6 in *pri_UE subframe* of $CAP_{pri,i}$. In order to avoid colision, UE ***u*** is not allocated time slots TS_6 in *sup_UE subframe* of $CAP_{sup,j}$. The beginning of each time frame, the Coordinator performs the following time slot allocation algorithm for all CAPs, as described below:

Step 1: For each CAP, the Coordinator allocates time slots to primary UEs in *pri_UE subframe* in the Round Robin (RR) scheduling until either the *pri_UE subframe* is full or UE's buffers are empty.

Step 2: To allocate time slots to supportive UE of CAPs in their *sup_UE subframe*, the Coordinator performs following process: in each CAP, its supportive UEs are scheduled in Round Robin scheduling until either the *sup_UE subframe* is full or UE's buffers are empty. For an UE ***u*** which is the primary UE of CAP ***i*** and the supportive UE of CAP ***j***, if there are empty time slots in *sup_UE subframe* of CAP ***j***, the Coordinator will:

- If UE ***u*** was not allocated time slots in *pri_UE subframe* of CAP ***i***, UE ***u*** is allocated one empty time slot in the *sup_UE subframe* of CAP ***j***.
- If UE u was allocated time slots in the pri_UE subframe of CAP i, and if they do not collide with empty time slots of the sup_UE subframe of CAP j , UE u is allocated one empty time slot in the sup_UE subframe of CAP j.
- Otherwise, UE u is not allocated time slots in the sup_UE subframe of CAP j.

C. CMcT termination

The CMcT scheme applied to an UE is terminated in three cases. First, when the UE moves out the coverage area of the supportive CAP, the SNR received from CAP_{sup} is below the SNR threshold of data transmission ($SNR_{min,tran}$). Second, when the UE moves out the coverage area of the primary CAP, the UE needs to handover to another CAP. Third, when the supportive CAP has high loads, it will terminate the CMcT scheme of its supportive UEs. In each case, the Coordinator asks the supportive CAP to release the supportive channel for the UE and finish the CMcT scheme.

IV. Simulation Results And Discussions

The simulation model includes a multi-CAP VLC network covering a 12m×12m×2.5m space as shown in Fig.6. CAPs have the half-intensity radiance angle of 60^0. The distance between two neighbor CAPs is 3m. There are 16 CAPs to ensure seamless lighting and communications coverage. The height of UE's PD receiver is h_{UE} = 1m. The VLC downlink channel model is LOS which is assumed flat and invariant over time. Other simulation parameters are listed in Table 1. Table 2 presents the uncoded quadrature amplitude modulation (QAM) with a target BER of 10^{-3} in [7], where SNR_{target} is the smallest SNR value to achieve a level of modulation. In the simulation model, we consider that half of the CAPs (8 CAPs have CAP-ID ***i*** = 2, 4,…, 16) have a low mean new connection rate ($R_{lowcall}$) and other half have a high mean new connection rate ($R_{highcall}$) as shown in Fig.6. The connection duration is exponentially distributed with a mean duration of 180 seconds. New connections are generated for both stationary and mobile UEs, where the ratio between stationary and mobile UEs is 3:2.

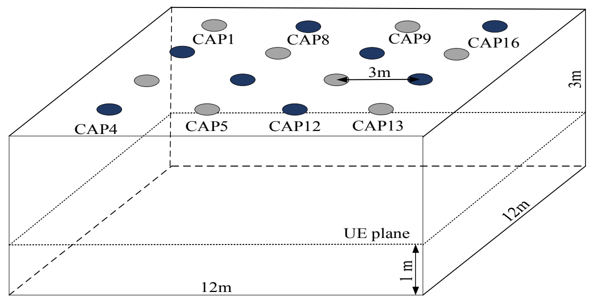

Figure 6 the layout of the simulation VLC network

Table 1 Simulations Parameters

Parameters	Value
Simulation time	3000[s]
Time slot duration (t_s)	0.001[s]
Time frame duration	0.01[s]
Area of PD (A)	1[cm^2]
FOV at a receiver (ψ_c)	70^0
O/E conversion efficiency (R_{pd})	0.26 [A/W]
Speed of UE movement (v)	0.5 [m/s]
Gain of an optical filter ($T_s(\psi)$)	1
CAP power (P_t)	25 [W]
Refractive index of a lens at a PD (n)	1.5
Number of subcarriers in each CAP	300
Bandwidth of 1 subcarrier	15 [KHz]
SNR threshold for CMcT ($SNR_{thr,CMcT}$)	25.5[dB]
SNR threshold for data transmission ($SNR_{min,tran}$)	13.4 [dB]

High load threshold value ($R_{thr,highload}$)	0.8
RSS threshold for link switching	-33.85 [dBm]

Table 2 Uncoded QAM Adaptive Bit Loading[7]

SNR_{target} [dB]	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

Table 3 Simulation Scenarios Parameters

Scenario	$R_{lowcall}$ (Connections/minute)	$R_{highcall}$ (Connections/minute)
1	1	2
2	1	4

The performance of UE's throughput is shown in Fig.7 which present its statistical cumulative distribution function (CDF). When the VLC system using the CMcT scheme, CAP can share input load with their neighbors and improve downlink data transmission rates of cell-edge UEs. Fig.7 shows that the CMcT scheme can provide higher user throughput than that of a single-channel scheme. For example, in the simulation scenario 1, the percentage of throughput samples higher than 3.5 Mbps in the CMcT scheme is 92.5 % while it is only 50% in the single-channel scheme. For the simulation scenario 2, there are 72% UEs and 56% UEs have download throughput higher than 3 Mbps in the CMcT scheme and the single-channel scheme, respectively.

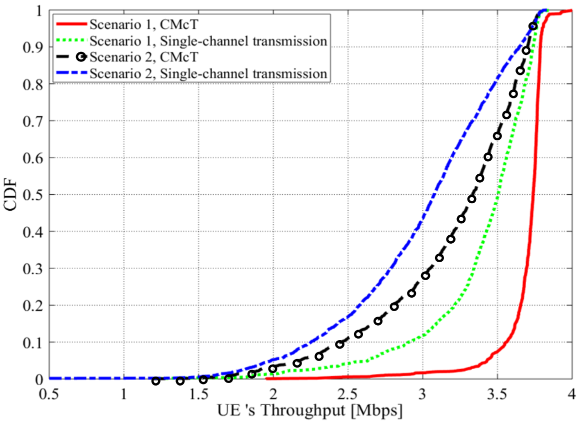

Figure 7 Throughput evaluation and comparison

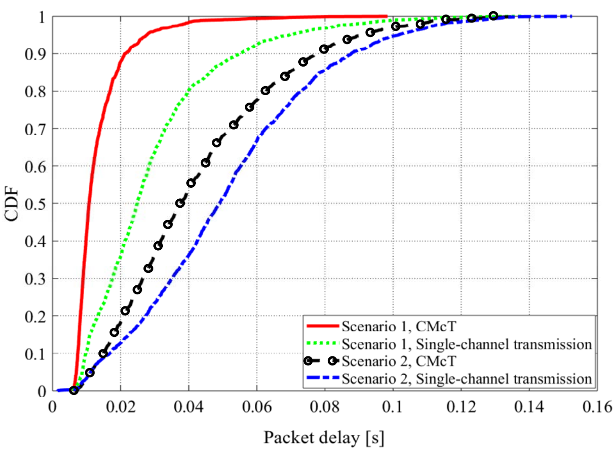

Figure 8 Packet delay evaluation and comparison

Fig.8 shows that the packet delay obtained when deploying the CMcT scheme can significantly be reduced. The CMcT scheme provides 98.5% and 54% delay samples smaller than 0.04s in the simulation scenario 1 and 2, respectively. The percentage of delay samples smaller than 0.04s of the single-channel scheme in scenario 1 and 2 are 80% and 36%, respectively.

In the simulation scenario 2, because the new connections rate is higher than that of the simulation scenario 1, more CAPs will have high loads. Therefore, high load CAPs might not be able to support the cell-edge UEs of their neighbor CAPs, resulting in performance degradation.

V. CONCLUSION

In this paper, we proposed the coordinated multi-channel transmission scheme for indoor multi-CAP VLC networks. We have designed the CMcT decision algorithm to select supportive CAPs and the time slot allocation algorithm in order to eliminate data collision of primary and supportive time slots. Simulation results proved that the proposed CMcT scheme can improve resource utilization efficiency and UE's QoS in terms of throughput and packet delay. Future works include the study of the combination of the CMcT scheme with handover protocols for improving handover performance when VLC networks have high mobility users.

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