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Visible light communications heterogeneous network (VLC-HetNet): new model and protocols for mobile scenario

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Abstract In order to resolve the crowded radio spectrum of wireless communication systems, visible light communications (VLC), which uses a vast unregulated and free light spectrum, has emerged to be a viable solution. However, duplex communication, user mobility, multi-user access and transmission mechanisms are becoming challenging tasks in VLC network. In this article, we propose a new VLC heterogeneous network (VLC-HetNet) model which merges VLC and radio frequency (RF) network. VLC channel is only used for downlink transmission, while RF channels are served for uplinks in any situation, or for downlinks only without VLC hotspots coverage. New VLC frame, multi-user access mechanism, horizontal and vertical handover protocols are presented to support the VLC-HetNet model, especially for solving the problems at multi-user mobility scenario. Simulation results show improvements in capacity performance of the VLC-HetNet, when compared to RF system. Besides, the average vertical handover number and VLC downlink dwelling time ratio have been analysed.

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1 Introduction

Recent proliferation of wireless technologies and choices available to user applications have triggered a tremendous wireless demand, and the global mobile data traffic will increase 13-fold between 2012 and 2017 [1]. Therefore, wireless network providers face an enormous challenge to increase their network capacity, in order to cope with the increasing traffic demand. However, this pushes the radio frequency (RF)-based wireless technologies to their limits, and the spectrum allocation charts show that most of the spectrum is already allocated under license [2]. Visible light communications (VLC) utilize off-the-shelf light emitting diodes (LEDs) as signal transmitters and off-the-shelf p-intrinsic-n (PIN) photodiodes (PDs) or avalanche photo-diodes (APDs) as signal receivers. Furthermore, VLC uses light in the wavelength interval of 375–780 nm, and it is emerging as a solution to overcome the crowded radio spectrum for wireless communication systems.

VLC has several advantages over RF communications. Firstly, it uses a vast unregulated and free spectrum without electromagnetic interference to support data communication and illumination in indoor environments where new energy-efficient LED materials and devices will replace old incandescent and fluorescent lighting [3]. Due to the broader spectral bands in the optical domain, VLC could be exploited for high rate transmission and system capacity. Secondly, the installation of VLC is low cost. The intensity modulation and demodulation techniques are implemented in low cost LED bulbs as VLC transmitter and photodiode as VLC receiver (RX). Besides, powerline communication

system, the backup network of VLC, can utilize the existing power grid rather than establishing a new network. Therefore, it is much more economical than the traditional wireless network which is backed up with the fiber optical communication system. Thirdly, the optical signal cannot penetrate opaque obstacle and hence, spatial confinement of the light beams provides inherent security eliminating interception or eavesdropping. Lastly, VLC does not have the electromagnetic compatibility problem, and it does not pose any health risk and are therefore safe for most applications.

Although VLC has several superiorities over RF system at indoor scenarios, some challenging tasks are still needed to be resolved. Firstly, VLC using illumination sources is naturally suited to broadcast applications, while providing an optical uplink to the distributed transmitter structures can be problematic [4–6]. Because it will interfere with the downlink signal and the receiver must point to the direction of the VLC transmitter even when the mobile terminals (MT) move. Infrared technologies are usually for uplink transmission [3, 7–9], but it can be easily blocked. Secondly, optical channel is easily influenced by the blockage of objects and suffers from shadowing. As a result, it is necessary to have link recovery as well as handover mechanisms at mobile scenarios [10, 11]. Thirdly, the VLC coverage is constrained within the opaque space which is different from the characteristics of RF. So the seamless coverage can be problematic.

In order to overcome the disadvantages of VLC technology, the combination schemes of VLC and RF are presented in recent literature sources under indoor scenarios. Hou and O'Brien [11] proposed a fuzzy-logic-based decision-making algorithm for vertical handover in the integrated system of optical wireless and RF technologies. In this system, the optical link is subject to blocking, and depending on the duration of the blocking, the system performs a vertical handover to an RF LAN. Rahaim et al. [12] proposed an indoor hybrid system that integrates WiFi and VLC luminaries in which VLC is only used for broadcasting. A simplified vertical handover mechanism was presented and the downlink throughput have been analysed. However, user mobility has not been considered. Chowdhury and Katz [13] analysed the performances of hybrid wireless local area network (WLAN)-VLC hotspot considering data download on moving scenario, while detailed access, horizontal and vertical handover protocols were not proposed. For a big house with multiple rooms, [14] introduced a VLC network coordinator, which is defined by IEEE Standard 802.15.7, for providing the bi-directional interfaces between uplink Wi-Fi access and downlink LED transmission. In [14], handover has been only used when the users are crossing different rooms. However, due to the limited coverage of one LED lamp,

horizontal or vertical handover in one room is necessary especially when multiple users transmit or receive data via VLC.

Although the total gain of indoor VLC channel consists of line-of-sight (LOS) and diffuse gains, the optical power by first order reflections is about more than 100 dB less than the path loss of the LOS transmission [15–17]. Since the path loss of higher order reflections is even larger, the effects of the diffuse paths can be neglected. Due to the VLC channel characteristics, every LED bulb has a limited coverage and the overlapped areas among different adjacent ones are also limited. As a result, under user mobility scenario, VLC transmitters have to locate the MTs for downlink transmissions. However, VLC uplink channels may not exist for providing any location feedback. Due to that, the user access mechanism of VLC network must provide uplink channels for access requests and feedbacks, while offering upper layer support for localizing MTs and coordination between VLC and RF networks. As for the handover issue, the larger overlapping area between cells allows the network elements enough time to initiate and complete it successfully in traditional RF networks (e.g., GSM, UMTS etc.). Nevertheless, VLC is not the same. The small overlapping area requires the short handover delay. Another problem of VLC handover is the intermittent shadowing. Objects such as furniture can cause shadowing, and also human wandering can block signal. Signal to noise ratio (SNR) can drop and rise up again in a few centimetres. The frequent handovers may probably terminate the connections or delay the data transmission.

In order to overcome the problems mentioned above under mobile scenarios, we propose an indoor heterogeneous network (HetNet) with the combination of VLC and RF. The HetNet contains multiple LED bulbs covering the indoor downlink transmission, and one VLC control center (VLC-CC) to manage the coordination between RF base station (BS) and VLC, also allocates resources for multiple accessing MTs. In this paper, we firstly design a VLC frame and propose a new access mechanism for multiple MTs. Secondly, a novel handover scheme named as dynamic hybrid handover protocol (DHHO) is presented, which is combined with horizontal and vertical handover mechanisms accounting for indoor moving seamlessly. Thirdly, we evaluate the system capacity, average vertical handover number and VLC downlink dwelling time ratio (the ratio between downlink data transmission in VLC network and the total downlink transmission time) compared with the traditional immediate vertical handover (IVHO) scheme [11].

The remainder of this paper is outlined as follows. In Sect. 2, we propose a new VLC-HetNet framework and give the network settings. Section 3 illustrates the VLC frame and multiple user access protocol. Section 4

introduces the proposed DHHO scheme which is combined with horizontal handover protocol among adjacent VLC hotspots and vertical handover protocol from VLC to RF or RF to VLC network. In Sect. 5, we simulate the network capacity, handover performance and VLC dwelling time ratio. Finally, conclusions are drawn in Sect. 6.

2 Network deployment

In terms of network deployment, the indoor VLC-HetNet contains RF-BS, VLC-CC, LED bulbs and MTs as shown in Fig. 1. RF-BS provides the RF signal coverage and the uplink sub-channels for MTs of the whole area. MTs access to the VLC-HetNet successfully only if they are accepted by the RF-BS. VLC-CC connects to the LED bulbs which are installed at indoor scenarios via powerline, it is aware of the LED bulbs' locations in the room and responsible for the resource allocations of multiple MTs. Every LED bulb is mounted on the ceiling of the room, contains an array of LEDs as transmitters using white light and for illumination. It has a unique ID which can be used to locate MTs by VLC-CC. The details will be shown in Sect. 3. The VLC transmitter (LED bulb) uses a Lambertian optical source, of which the brightness to an observer is the same regardless of the observer's angle of view [18]. As a result, the projection on the ground can be considered as a circle and the coverage area of LED bulb is called as "hotspot" in this paper. VLC link is exclusively used for rapid downlink transmission. MTs are equipped with two kinds of transceivers, one for RF and the other is for light detection.

The key problems of establishing this VLC-HetNet are to solve access and handover issues. As for the access mechanism, the MT has to apply for uplink channels from RF-BS due to the unidirectional VLC link. Prior to downlink transmission, VLC-CC has to find out the serving hotspot of the MT and distribute the downlink contents to it. The optical channel conditions that are detected by the MT are reported to the VLC-CC via RF-BS relay. According to that, VLC-CC can allocate time resources for the downlink transmissions of the MT. The issues of localizing MT and the coordination mechanism between VLC and RF-BS are key challenges in the access protocol.

As for the handover issue, the MT may move across different hotspots and it triggers the horizontal handover. However, the VLC detector cannot receive VLC signal when MT enters into the overlapped area of adjacent hotspots due to the interference. The vertical handover depends on the duration of staying in the overlapped area. In order to keep the services continuous when the MT is moving at indoor scenarios, a novel protocol combined with horizontal and vertical handover mechanisms must be proposed. Details are discussed in Sect. 4.

3 VLC frame and access protocol

The VLC frame used for LED downlink transmission is shown in Fig. 2(a). It is broadcasted periodically and contains L slots. Every slot in the frame contains the "training sequence" which is used for synchronization and channel estimation, the "header" which provides details on the frame such as the frame length, modulation and coding scheme, and the data payload frame, the "resource allocation information" which gives the downlink transmission slots allocation to the target MT, the "LED ID" which identifies the serving hotspot (coverage area of the LED bulb) for MT, the "MT ID" which serves for finding the right receiving MT, and the "downlink data" used for downlink transmission. If an MT enters into the overlapped area of adjacent hotspots, the received "LED ID" will be the combinations of different IDs from adjacent hotspots,

Fig. 1 VLC-HetNet model
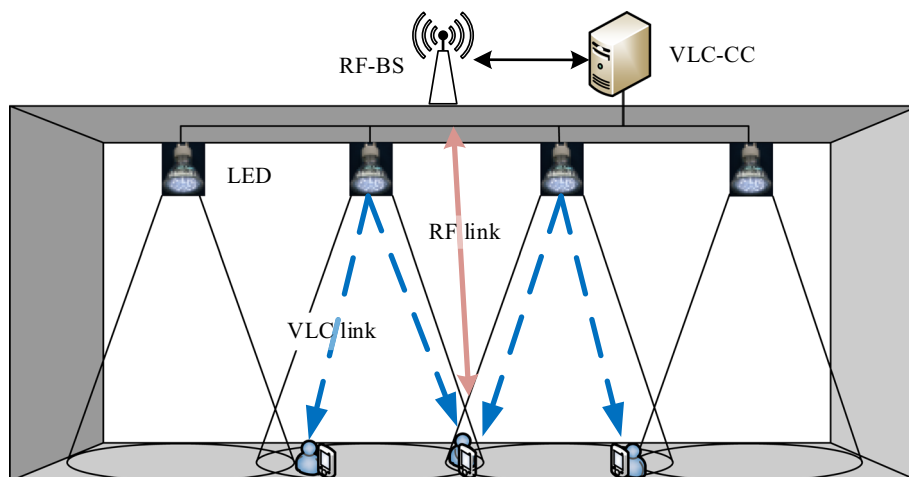
**Fig. 2 a** VLC frame, **b** one sample of conflicting pattern

(a)

(b)
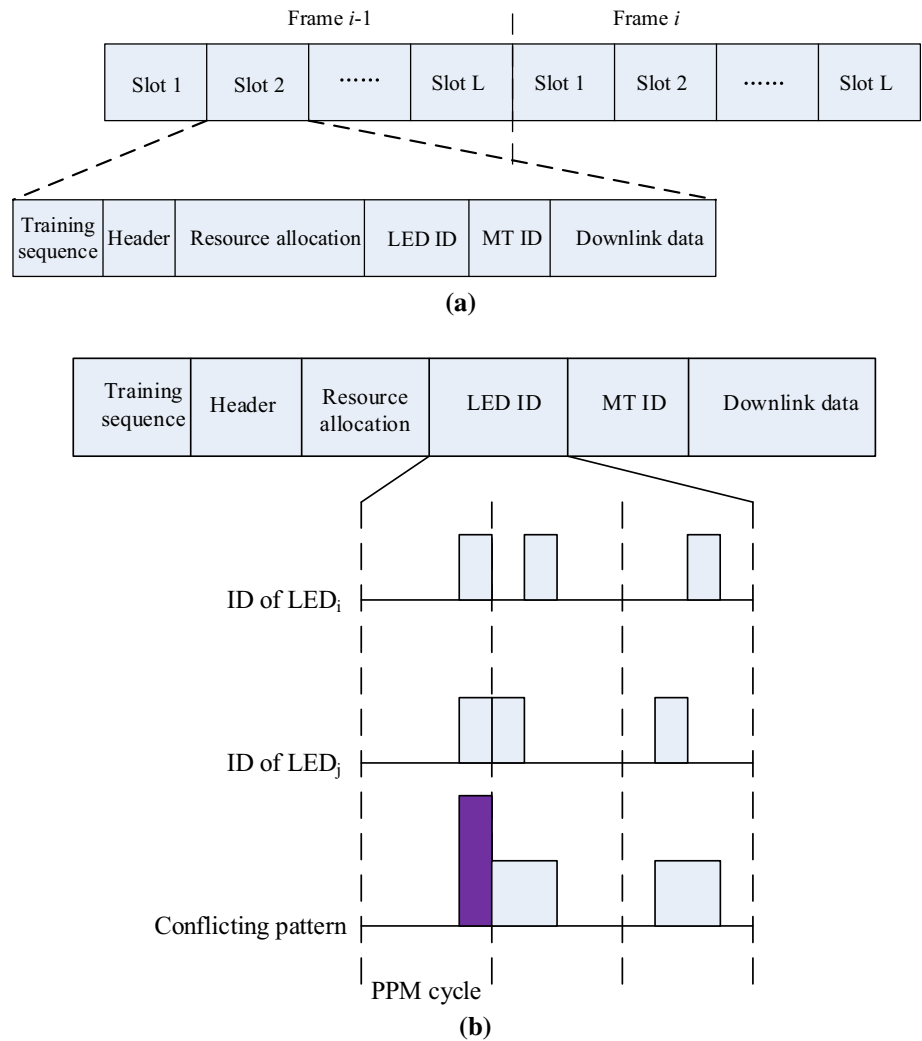
which is named as "conflicting pattern" here. However, the MT can be located via the "conflicting pattern" if it is unique. A sample of the LED "conflicting pattern" is shown in Fig. 2(b). Therefore, an ID coding rule for localizing purpose is designed as follows. First, we define the LED ID set as $\mathbf{C} = \{C_i, i = 1, 2, \ldots\}$ satisfying $C_i + C_j \notin \mathbf{C}$, where C_i is the ID of the i-th LED, C_j is the adjacent ID set of the i-th LED. Second, in order to resist reception error, the ID is designed as $C_i^* = max$ $min_{\forall C_k \in \mathbf{C}} d[(C_i + C_j) - C_k]$, where d [*] denotes the Euclidean distance. This criterion is to maximize the minimum Euclidean distance between the one in the ID set and the overlapped combination ID.

Based on the above, the accessing mechanism in Fig. 3 is as follows:

1. The MT sends accessing requests to RF-BS via RF link.
2. If RF-BS has some available spectrum resources, it will allocate the uplink channels for the MT and send feedbacks.

3. RF-BS informs the VLC-CC that it has accepted the accessing events of the MT.
4. The VLC receiver of the MT has detected the downlink VLC frame and estimated the optical channel conditions via "training sequence", also decoded the unique ID segment via the received "LED ID". The MT reports this information to RF-BS via RF.
5. Because all the uplinks are RF channels, there are no direct connections from the MT to VLC-CC. So, the RF-BS is responsible for relaying the channel conditions and the ID segments to VLC-CC.
6. Based on the ID encoding algorithm discussed above, the VLC-CC can locate the MT via the ID segment. It means that VLC-CC can find the serving hotspot of the MT and get ready for its VLC downlink transmission. If the MT is on the overlapped area, the ID segment is the unique "conflicting pattern". Because of the interference, the handover event may be triggered at this moment and it will be discussed in detail in Sect. 4.

**Fig. 3** Access protocols in VLC-HetNet
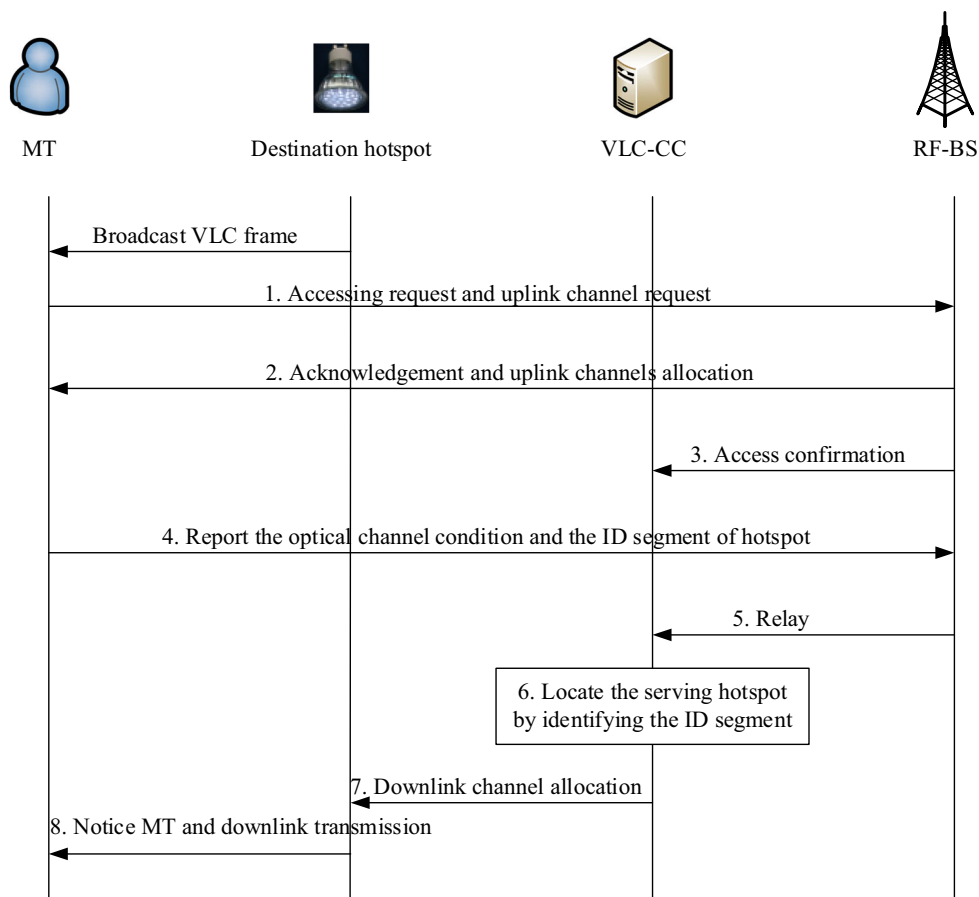
7. VLC-CC allocates the time slots for the MT.
8. The time allocation information must be transmitted on every slot of the VLC frame.

4 Handover protocol

As mentioned above, VLC is sensitive to the blockage of objects and suffering shadowing due to the high directionality of the optical channel. Therefore, it is necessary to design a handover mechanism to keep the service continuous. Besides, the movement of MT is another incentive to make a handover. When the MT passes through different hotspots, it may change the downlink transmission from one to another, known as horizontal handover. However, MT may change the downlink from VLC to RF and vice versa, which is named as vertical handover. In the VLC-HetNet, handover is the most important issue to provide the seamless traffic and heterogeneous support. In the following, we present a new protocol considering both horizontal and vertical handover, as shown in Fig. 4. The suffix of the step number in the protocol (a or b) denotes the different

branch of the decision part in the flowchart, e.g., the flow chart of the handover protocol can be $1 \rightarrow 2 \rightarrow 3 \rightarrow \ldots \rightarrow 11$, or $1 \rightarrow 2 \rightarrow \ldots \rightarrow 5(\rightarrow 6) \rightarrow a \rightarrow b \rightarrow c \rightarrow d \rightarrow 10 \rightarrow 11$ or $1 \rightarrow 2 \rightarrow \ldots \rightarrow 5(\rightarrow 6) \rightarrow a \rightarrow b \rightarrow c \rightarrow d \rightarrow 10 \rightarrow e \rightarrow f \rightarrow g$.

1. After accessing the RF network, the VLC RX of MT keeps on detecting the optical channel. Once VLC is detected, the MT is ready to access the VLC and request downlink channel resources. If VLC is not detected for a certain duration t_v, the MT will apply for downlink channels from RF network. The duration t_v is selected to avoid unnecessary handovers caused by fading and shadowing of the optical channel.
2. The MT sets a "Timer" which is fit to limit the waiting time for accessing to VLC system. It will switch to RF network upon time-out. The value of "Timer" is selected to avoid frequent handover and service termination.
3. The MT receives the broadcast VLC frame and decodes the "LED ID" part to obtain the ID of serving hotspot. Besides, the optical channel condition is estimated via "training sequence". This
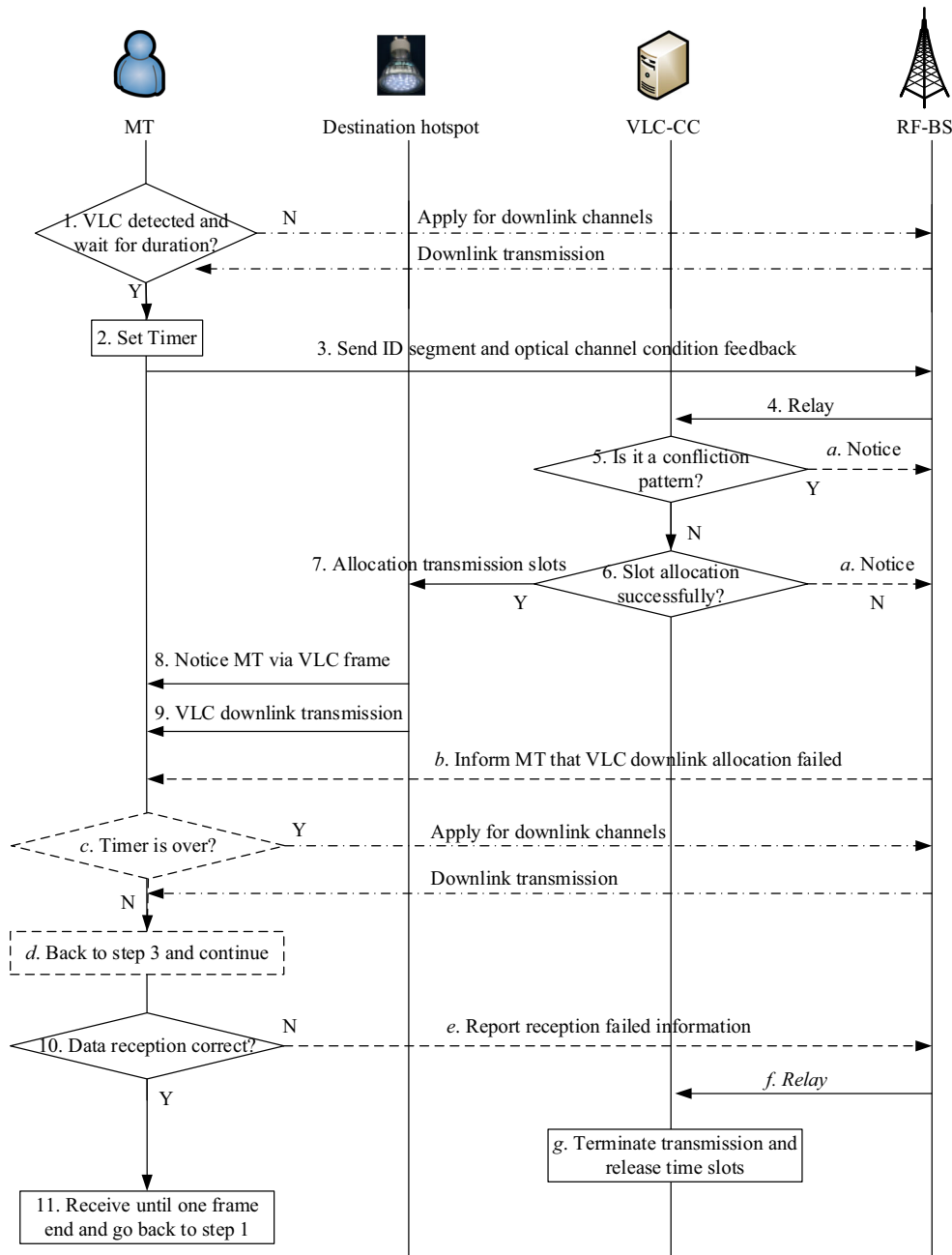
Fig. 4 DHHO scheme in VLC-HetNet

information will be sent to RF-BS via uplink channel.

4. As there is no direct link between VLC-CC and the MT, the RF-BS relay the information to VLC-CC.

5. If the MT is located at the overlapped area of the adjacent hotspots, the ID segment in "LED ID" is a

"conflicting pattern". In this case, it transfers to step *a*. Otherwise, it goes to step 6.

(a)   The VLC-CC notices the RF-BS that it receives a "conflicting pattern" or it cannot provide enough resources for the MT. Then, it goes to step *b*.

(b)   The RF-BS informs MT that VLC downlink allocation is failed due to the interference from the adjacent visible light channels. Then, it goes to step *c*.

(c)   Due to the mobility of MT, it will happen with a high probability that the MT moves outside of the overlapped area and it will be covered by another hotspot before the "Timer" expires. As a result, if the "Timer" is not expired, it goes back to step 3 and continue. This step completes the horizontal handover. Otherwise, the MT will apply for the downlink channels from RF-BS and the vertical handover happens.

6.   If all the slots in the serving hotspot are occupied, the VLC-CC will notice that the slot allocation has failed. And the MT will be ready for the vertical handover to RF network.

7.   The VLC-CC allocates the time slots for the MT and gets ready for the downlink data.

8.   The VLC-CC controls the serving LED bulb to send the slot allocation information to MT.

9.   The serving LED bulb starts the rapid downlink transmission via VLC.

10.   During the VLC downlink transmission, the MT may move outside the serving hotspot. Therefore, it is necessary to determine whether the reception data is correct. If yes, it goes to step 11. Otherwise, it jumps to step *e*.

11.   The MT receives until one frame ends and go back to step 1.

(e)   Once the MT has failed to receive data via VLC because of entering into the overlapped area or suffering shadowing. In this case, the MT must notice RF-BS of the failed reception. Then, it goes to step *f*.

(f)   The RF-BS informs the VLC-CC the information of failed reception. Then, it goes to step *g*.

(g)   VLC-CC terminates the downlink transmission and releases time slots for other MTs.

5 Simulation results and analysis

In this part, the proposed DHHO scheme is simulated in three aspects, i.e., capacity performance, successful handover number and VLC dwelling time ratio compared with the immediate vertical handover (IVHO). For IVHO scheme, vertical handover is immediately triggered when VLC channel is interrupted.

5.1 Simulation model

We use Matlab to simulate the system performances and run 10,000 independent tests for Figs. 7, 8, 9 and 10. The simulation scenario is constructed within a hall of 20 m × 5 m × 6 m (long, wide and height). VLC network with M hotspots provides the optical downlink transmission. The VLC coverage rate of the room is denoted as α, which is defined as the ratio of the effective VLC hotspots coverage and the overall room area. In addition, the overlapped area of the adjacent hotspots is not included in the effective VLC coverage domain due to the co-channel interference (CCI). We assume that the RF-BS covers the room completely with a certain data rate. OFDMA is assumed to be implemented in RF network. Besides, the number of RF uplink and downlink channels are denoted as N_u and N_d, respectively. The distribution of MTs is modelled as a homogeneous Poisson point process (HPPP) and it is assumed that the time between two consecutive demands of MTs for service in the system (or inter arrive time) is exponentially distributed [19]. We define ρ(x) as the spatial density of inter arrival time in s^{-1} m^{-2}, constant in time. The larger value of ρ(x) means higher capacity of the system. Because every MT sends uplink requests via OFDMA, we model this process as a queue M/M/N_u with a service rate μ which depends on the processing rate of RF-BS [20]. Similar to the uplink, the OFDMA downlink can also be considered as a queue M/M/N_d with service rate μ. As for the OFDMA downlink sub-channels, only when MTs are out of VLC hotspots coverage or fail to access to VLC network, are OFDMA downlink sub-channels utilized. The frequency response of the RF channel can be modelled as:

$$H = G_p G_m \tag{1}$$

where G_p and G_m denote the channel gain of path loss and Rayleigh flat-fading in frequency domain, respectively. The path loss model is described as:

$$|g_p(d)|^2 = L(d_0) + 10n \log_{10} \frac{d}{d_0} (dB) \tag{2}$$

where $g_p(d)$ is the amplitude channel gain in the time domain, d_0 is the reference distance, d is the distance between the transmitter and receiver. $L(d_0)$ is equal to 41.5 dB on 2 GHz, where $d_0 = 1$ m. n is set to 1.9 at indoor scenario [21]. $|g_m|^2$ is exponential distribution with mean $1/\gamma$ in which γ is assigned to 10 dB.

The user mobility model is considered as a constant speed of v m/s walking in a straight line through multiple hotspots. The user movement model is shown in Fig. 5 which is a specific scenario of Fig. 1, while the receiver held by the user is assumed to be parallel to the ceiling and 1 m height from the ground. That is to say, the receiver

Fig. 5 User movement model
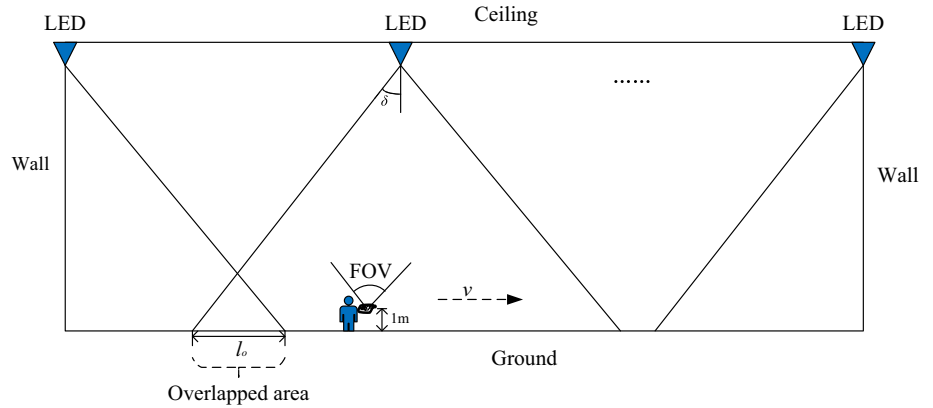
plane is assumed to be always parallel to the transmitting LED plane in our simulation. The distances between the adjacent LEDs are assumed to be the same. Besides, the maximum length of the overlapped area is denoted as l_o. The simulation parameters and definitions are shown in Table 1.

Every LED bulb has its unique ID, so as to be used for localizing MTs. In this simulation, pulse position modulation (PPM) is implemented in the "LED ID", which is illustrated in Fig. 6. If the detected signal at the VLC receiver has more than one PPM pulse, the user must be in the overlapped area and it can be localized by identifying the locations of the PPM pulses due to the conflicting pattern is unique. Therefore, it is easier for the MT to distinguish the overlapped area.

Table 1 Simulation parameters and definitions

|	
Size of simulation scenario	20 m × 5 m × 6 m (long, wide and height)
Spatial density of request arrival in unit time and area	ρ (s^{-1} m^{-2})
Number of uplink sub-channels in OFDMA network	N_u
Number of downlink sub-channels in OFDMA network	N_d
Overlapped length of the adjacent VLC hotspots	$l_o = 2$ m
Number of LED hotspots	$M = 5$
Ratio of downlink to uplink packet length	$N = 10$
Number of time slots in VLC downlink frame	L
Velocity of MT movement	v
Delay timing before vertical handover of DHHO scheme	Timer
LED half power angle	δ
Field-of-view (FOV) semi-angle of the receiver	δ

5.2 Capacity performance

Figure 7 shows the maximum spatial density against different number of downlink OFDMA sub-channels implementing IVHO and DHHO schemes. The maximum capacity of our proposed VLC-HetNet model is much larger than the pure OFDMA network because VLC channels could offload downlink data from the crowded OFDMA network. The VLC-HetNet could accommodate more users when N_d increases on condition that all the access requests have been successfully handled, i.e., the number of uplink sub-channels is sufficient. It means that more MTs can successfully handover to OFDMA network and establish OFDMA downlink sub-channels if the VLC network is interrupted or all the time slots in VLC frames are occupied. However, the achieved maximum spatial density decreases when N_d continues to increase. It is because that the decreasing N_u causes the VLC-HetNet cannot process more accessing requests from MTs and hence limit the system capacity. As shown in Fig. 7, N_d which makes ρ obtain its maximum, decreases with L. This is because VLC hotspots can accommodate more MTs when L increases, and more OFDMA uplink sub-channels
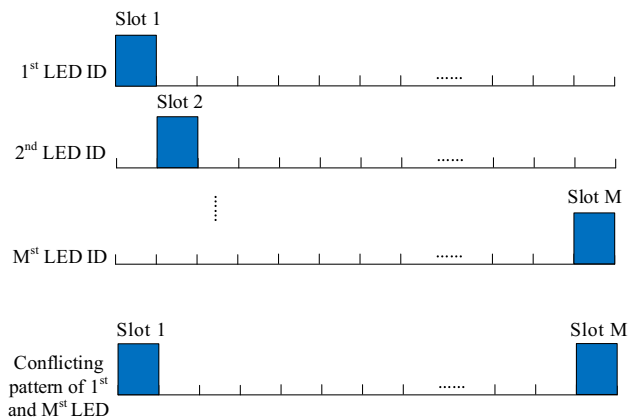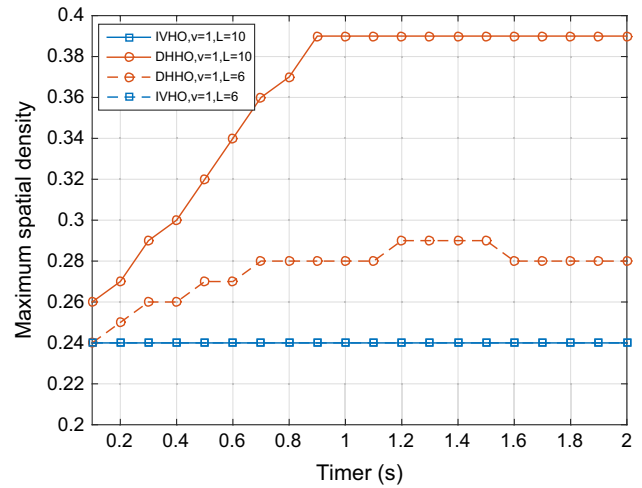

Fig. 6 LED ID in simulation
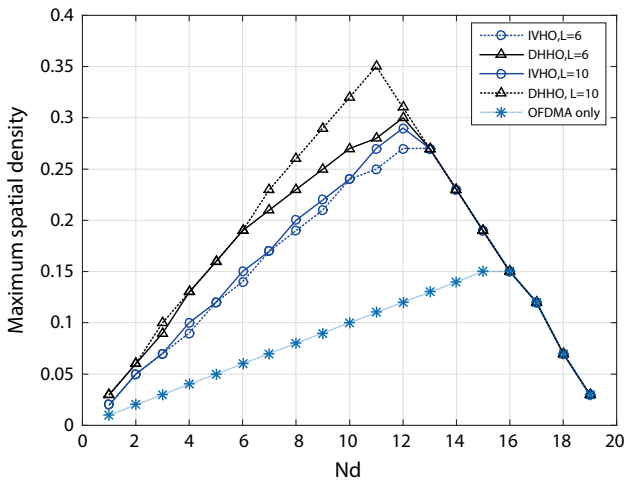
Fig. 7 Maximum spatial density against number of downlink subchannels of OFDMA network implementing IVHO and DHHO schemes, in which $v = 1$ m/s, Timer = 0.5 s, $N_u + N_d = 20$


Fig. 8 Maximum spatial density against the value of Timer implementing IVHO and DHHO schemes, in which $v = 1$ m/s, $N_d = N_u = 10$

are needed. For IVHO scheme, MTs have to handover to OFDMA network immediately once the optical channel is blocked. Hence, MTs have more opportunities to access to the OFDMA network and larger N_d is needed to obtain the same spatial density as DHHO scheme. In DHHO scheme, the setting of Timer makes MTs tend to dwell in the VLC network, which can support faster transmission and provide higher user spatial density.

In Fig. 8, the maximum spatial density of VLC-HetNet against the Timer are simulated. Obviously, the system performance of IVHO scheme is independent of Timer. While, for DHHO scheme, the MTs tend not to make a vertical handover immediately, but rather to delay a certain duration. When the value of Timer is larger than the period of crossing the overlapped area, no vertical handover is needed (e.g., Timer = 2 s). Under this scenario, the maximum spatial density depends on the number of time slots available in the VLC hotspots. As shown in Fig. 8, the setting of Timer could avoid unnecessary vertical handover from VLC to OFDMA network and hence, the system capacity of DHHO scheme is larger than IVHO scheme.

5.3 Average vertical handover number and downlink dwelling time ratio of VLC network

Figure 9 shows the average vertical handover number during one MT passes all the VLC hotspots versus the velocity of MT with $N_u = N_d = 10$, $\rho = 0.3$ s^{-1} m^{-2}, $L = 6$ and Timer = 0.5 s. The average vertical handover number of DHHO scheme is less than the one of IVHO scheme, which is due to the avoidance of the unnecessary frequent handovers. With v increases, the MTs may probably cross several VLC hotspots and the overlapped area in
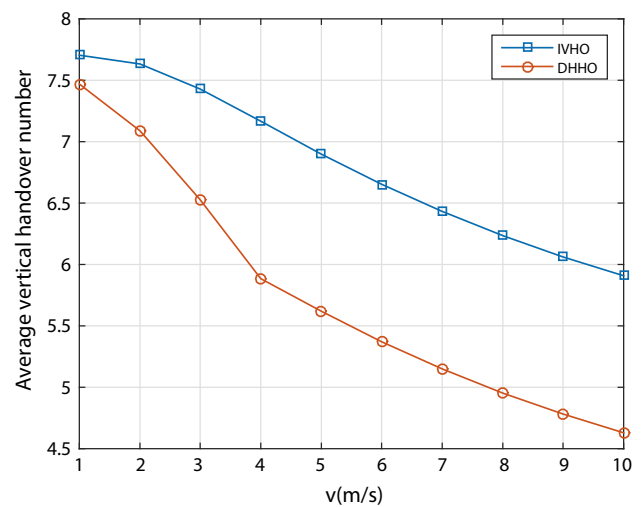
Fig. 9 Average vertical handover number against the velocity of MT implementing IVHO and DHHO schemes, in which $N_u = N_d = 10$, $\rho = 0.3$ s^{-1} m^{-2}, $L = 6$, Timer = 0.5 s

a short period. However, the successful access probability to the VLC or OFDMA network decreases because the vertical handover failed when the access time required is larger than the dwelling time of VLC or OFDMA network and hence, it results in reducing the successful vertical handover probability. Due to that, the VLC dwelling time ratio of IVHO scheme also reduces as shown in Fig. 10. Frequent vertical handover makes the VLC dwelling ratio of the IVHO scheme be less than the one of DHHO scheme. As the overlapped length l_o is 2 m, the duration time of MT in this overlapped area is described as $l_o/v = 2/v$ (s). When v increases, the value of $2/v$ decreases to approach the setting of Timer and VLC dwelling time ratio
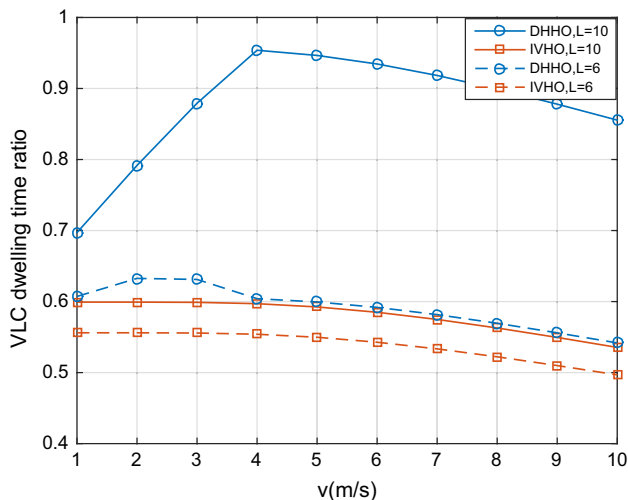
Fig. 10 VLC dwelling time ratio against the velocity of MT implementing IVHO and DHHO schemes, in which $N_u = N_d = 10$, $\rho = 0.3$ s^{-1} m^{-2}, Timer $= 0.5$ s

increases (e.g., DHHO scheme with 1 m/s < v < 4 m/s). While it means that the MT delays a duration of Timer (now it is still in VLC network) and trigger a vertical handover to OFDMA network because the MT has not entered another hotspot when Timer runs out. However, when 2/v is less than Timer, the horizontal handover from one hotspot to another always occurs. Large velocity drops the successful access probability of the MT to VLC network. The MT has to handover to the OFDMA network which makes the VLC dwelling ratio decrease. Seen from Fig. 10, the proposed DHHO scheme tends to make MTs stay in the VLC network as much as possible and it will offload the crowed RF network.

6 Conclusion

In order to solve the spectrum crisis in the RF wireless communications, we have developed a new integrated system: VLC-HetNet with its corresponding access and handover protocols which can ensure the continuity of service when MT moves. Furthermore, the simulation results show that large improvements are achieved in capacity performance of the VLC-HetNet, when compared to the pure RF system. Besides, the average vertical handover number and the VLC downlink dwelling time ratio has been analysed and simulated when the user motion model is considered.

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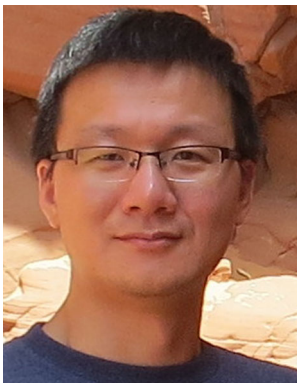
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