Novel handover scheme for indoor VLC systems

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Abstract
Managing mobility in visible light communication systems is one of the main encounters that requires to be tackled. In this paper, we propose subcarrier multiplexing tones as control signals for handover in visible light communication systems. These control tone signals are unmodulated signals, and each light unit is given a unique unmodulated control signal. One light unit is used to send the data to the user, which is the best light unit. At a receiver side, band pass filters are used to separate subcarrier multiplexing tones. This enables receiver to connect with all light units via subcarrier multiplexing tones. The carrier to noise ratio of each control tone signal is estimated at the receiver, which leads to make the receiver connects with the light unit that offers the best connection during its mobility.

INTRODUCTION

In visible light communication (VLC) systems, light units are used for both illumination and data communication. The coverage area of each light unit is small and one LED light unit (access point, AP) is not enough for lighting and for data communication in indoor environments such as homes and offices. Therefore, to get full coverage, multiple VLC-APs are needed to maintain lighting and wireless connections in the whole area of the indoor environments. In addition, distance between VLC-APs and the optical receiver has a great impact on the performance of VLC systems. Therefore, managing the mobility of the user (changing from the serving VLC-AP to a candidate VLC-AP) in VLC systems is one of the main challenges that needs to be handled. Consequently, proper indoor handover mechanism is needed between VLC-APs.

To manage the mobility in VLC systems, many methods have been used. Based on the intensity of the received signal, a handover was investigated in two indoor VLC cases: overlapping and non-overlapping cases [1]. To decrease the delay of the handover, predictive and pre-scanning received signal strength was proposed in [2, 3]. The coverage area of VLC-APs was dynamically altered to obtain the handover during the mobility of the user [4]. Two algorithms were proposed to manage the soft handover in the orthogonal frequency division multiple access (OFDMA) VLC system [5]. In these two algorithms, a user that was in the overlapping area of two VLC-APs, was served by two VLC-APs and these two VLC-APs used different frequencies. A handover in a VLC system was proposed based on the joint transmission [6] in which the mobile user served by two VLC-APs when moved toward the edge of the cell. Based on the location of users, users were divided to two classifications named primary users (when users near to VLC-AP) and secondary users (when users far from the VLC-AP). Comparing with the hard handover, the joint transmission algorithm leads to enhance the data rate of the VLC system while the UE was located at the edge of the VLC-AP [6]. However, the effect of the ISI was not considered in [6]. Due to the difference time of arrival of the signals from the allocated VLC-APs to the UE, this leads to introduce a sever ISI and consequently reduce the 3-dB channel BW, which is used to measure the ability of the indoor channel to support high data rates. OFDMA was used where each VLC-AP was given a range of frequencies to manage the handover during user’s mobility [7]. Reference signal received power (RSRP) was proposed for handover skipping in a VLC system in which the mobility of the user was monitored without needing to a feedback signal from a user to the VLC-AP [8].

There are two types of handover horizontal and vertical. In this paper, a horizontal handover is used where the user is transferred from one VLC-AP to another. While vertical handover occurs when the user is transferred from one VLC-AP to another that uses different access technology for example from VLC to Wi-Fi, this type of handover is out of scope of this work. It should be noted that the goal of this work is not to
improve the data rate of the UE. The main goal of this work is to propose control signals that are used to ease the process of the handover in indoor VLC systems. The main benefits of our proposed handover scheme are: (1) To reduce the time wasted, (2) the VLC-AP does not need knowledge about the location of UE and (3) the VLC-AP does not require knowledge about the direction moving of the UE. In this paper, we proposed a novel handover scheme for indoor VLC systems using subcarrier multiplexing (SCM) tones as control signals. Control tone signals have been used in VLC systems to manage the communication between transmitters and receivers [9–11]. Each VLC-AP is given a unique SCM tone, which added to the data signal. Thus, the control signal and the data signal are sent simultaneously. At the optical receiver, band pass filters (BPFs) are utilized to separate SCM tones. In addition, a subcarrier monitoring system is used to calculate the power of each SCM tone. The user equipment (UE) is served by only one VLC-AP, which is the VLC-AP that offers the best performance. However, other VLC-APs (VLC-APs that do not send a data) send only SCM tones. Hence, the UE connects with all VLC-AP through SCM tones. Consequently, during the mobility of the UE, the best VLC-AP is always allocated to the UE by observing the power of the control tones. In the proposed handover scheme, we used the carrier to noise ratio (CNR) of the control tones signal to decide if the UE requires a handover or not. It should be noted that many advantages are obtained by our proposed handover scheme. These benefits are (i) the UE is always connected with the best VLC-AP as the power level of each SCM control tone is known at the controller, (ii) in our proposed scheme, VLC-AP does not require knowledge about the UE's location, which leads to ease the design of the VLC systems, (iii) our proposed handover scheme does not depend on knowledge about UE's moving direction as the received power of each subcarrier multiplexing tone is known at the controller, and this enables the controller to know the target VLC-AP and iv) once the UE requires a handover, the controller gives an order to switch the UE from the host VLC-AP to the target VLC-AP without any processing time delay, which eliminates the blockage probability.

The paper is organised as follows. Section 2 shows the setup of the simulation. In section 3, the design of the transmitters is given while Section 4 gives the design of the receiver. The proposed handover scheme is given in Section 5. Finally, Section 6 gives conclusions.

2  |  SYSTEM MODEL

To evaluate and study the performance of the handover of the indoor VLC system, a simulation tool was developed in an unfurnished room with no windows and doors. The room has a dimension of 10 m × 10 m × 3 m (length, width and height) as shown in Figure 1(a). Only line of side (LOS) is considered in this work [12].

In this paper, we employed RYGB laser diodes (RYGB-LDs) as sources of illumination and data communication. To get an appropriate illumination level in the room, which is not less than 300 lx [12], 16 VLC-APs (4 × 4) have been used and each VLC-AP has 9 RYGB-LDs (3 × 3). The centre luminous intensity of each RYGB-LD is 192 cd [13] with a semi angle of 50°. Moreover, each RYGB-LD emits power of 1.9 W [13] and sends a data in a form of Lambertian pattern due to using a diffuser. These VLC-APs were located at (0.5 m, 0.5 m, 3 m), (3.5 m, 0.5 m, 3 m), (6.5 m, 0.5 m, 3 m), (9.5 m, 0.5 m, 3 m),
(0.5 m, 3.5 m, 3 m), (3.5 m, 3.5 m, 3 m), (6.5 m, 0.5 m, 3 m),
(9.5 m, 0.5 m, 3 m), (0.5 m, 3.5 m, 3 m), (3.5 m, 3.5 m, 3 m),
(6.5 m, 3.5 m, 3 m), (9.5 m, 3.5 m, 3 m), (0.5 m, 6.5 m, 3 m),
(3.5 m, 6.5 m, 3 m), (6.5 m, 6.5 m, 3 m), (9.5 m, 6.5 m, 3 m),
(0.5 m, 9.5 m, 3 m), (3.5 m, 9.5 m, 3 m), (6.5 m, 9.5 m, 3 m),
and (9.5 m, 9.5 m, 3 m). The location of each VLC-AP with its
coverage area is depicted in Figure 1(b).

In this work, we considered only LOS illumination and the
calculation of the illumination due to LOS components can be
found in [14]. We obtained the cumulative distribution function
(CDF) of the illumination on the communication floor of the
room due to only LOS components as shown in Figure 1(c).
As can be seen, about 5% of the total area of the room was
illuminated with lighting level less than 300 lx. These locations
at corners of the room, which can be ignored without loss of
generality.

3 TRANSMITTER DESIGN FOR THE
PROPOSED HANDOVER SCHEME

It is worth knowing that VLC-APs are utilized for lighting
and then for data transmission in VLC systems. Therefore, an
acceptable lighting level should be obtained in indoor environ-
ments. Thus, many VLC-APs are installed to obtain the required
illumination level, which means that the overlap between multi-
ple VLC-APs is very high. Besides that, due to the use of intensity
modulation and direct detection, photodetector responds to
all transmitted signals from overlapping VLC-APs, which means
that multiple VLC-APs are treated as one transmitter. Hence,
SCM tones are used as control signals to (1) classify each VLC-
AP by giving each VLC-AP a unique frequency, (2) find the best
VLC-AP for the UE and (3) enable the controller to switch the
UE from the host VLC-AP to the target VLC-AP without any
processing time delay, which eliminates the blockage probability.

In our VLC system, a controller (see Figure 1(a)) is utilized to
manage and setup the connection between transmitters (VLC-
APs) and the UE. At each VLC-AP, a unique control tone signal
\(C_k(2\pi f_k t)\) is combined with a data signal \(D_k(t)\) as shown in
Figure 2. The control signal is used to identify the VLC-AP, to
find the best VLC-AP for the UE and to manage the handover
process when the UE moves from one VLC-AP to another. As
can be seen in Figure 2, the VLC-AP adds the baseband data signal
with the control signal that has a unique frequency to identify the
VLC-AP.

In order to prevent the overlap between the data signal and
the control signal, a low pass filter (LPF) is used to reshape the
data signal within an occupied bandwidth of the data \(BW_{data}\).
In addition, we considered the sinusoidal control signal is an
unmodulated tone that has a very narrow bandwidth of \(BW_{tone}\).
In addition, the total power of the VLC-AP is divided between
the data signal and the control signal. Thus, the data signal is
multiplied by a power coefficient factor of \(a\) and the control
signal is multiplied by a power coefficient factor of \(b\), where \(a + b = 1\), as can be seen in Figure 2. Later we will calculate the
amount power that is allocated for the data signal and for the
control signal of the VLC-AP.

It should be noted that the control tone signal is monitored
by the UE. Consequently, the measurement of the power level
of the control tone signal is reported to the controller. Thus, the
controller has the information of all VLC-APs. Hence, informa-
tion from control signals is utilized to decide if the UE requires
a handover or not.

3.1 Receiver design for the proposed
handover scheme

At the receiver, the light signal is converted to an electrical sig-
nal by the photodetector (PD). In addition, a transimpedance
amplifier (TIA) is used to amplify the electrical signal as shown
in Figure 3. Due to sending the data signal and the control signal
simultaneously, band pass filters (BPFs) are used to catch up the
control signals. Each BPF has a central frequency equal to the
given frequency of each control tone signal. In addition, the number of the BPFs in the optical receiver is equal to the
number of the VLC-APs of the VLC system. A control tone monitor (CTM) is utilized to monitor and calculate the level of the power of each control tone signal as shown in Figure 3. In addition, the CTM sends a periodically feedback signal, which is an IR signal, to the controller every monitoring time slot (MTS). Since control tone signals are unmodulated signals, the required bandwidth of each BPF ($B_{W_{BPF}}$) can be small. We can determine the required bandwidth of each BPF by using the MTS as: $B_{W_{BPF}} \geq \frac{2}{MTS}$ [9]. It should be noted that based on the feedback signal, the controller decides the action required for the UE (i.e. does the UE requires a handover or not).

It should be noted that SCM tones are utilized as control signals without increasing the complexity of the system. This is because of using a simple local oscillator at VLC-APs to generate the unique frequency for each VLC-AP. In addition, BPFs which are easy and cheap to implement are used at the optical receiver to separate SCM tones.

4 | HANDOVER PARAMETERS SET UP

4.1 | User motion indicator

The motion indicator of the UE is shown in Figure 4. It worth knows that this motion indicator appropriate for any random movement of the UE. This is due to at each MTS, the UE sends a feedback signal to the controller to inform the controller the amount of the received power of each control tone signal. Hence, the controller knows the direction of the UE as can be seen in Figure 4. Therefore, the handover is made whenever the target VLC-AP offers a good connection to the UE. For example, when the UE approaches the overlapping area between VLC-AP1, VLC-AP2 and VLC-AP3, the UE will still connect with VLC-AP1 if the VLC-AP1 offers the best connection to the UE. Otherwise, the handover will be made (the UE will be connected to VLC-AP2 or VLC-AP3). It should be noted that the time spent of the UE in each VLC-AP can also be estimated as shown in Figure 4. The time spent of the UE is given as $N \times MTS$ where, $N$ is the number of MTS that is calculated while the UE still connecting with the best VLC-AP. The time spent can be used to indicate that if the UE is a mobile UE, a nomadic UE or a stationary UE.

4.2 | Carrier to noise ratio of the handover

Due to the unique frequency ($f_k$) of each control tone signal, there is no interference between these control signals. In other words, the UE’s receiver monitors the power level of the control tone signals from multiple VLC-APs with zero level interference.
between them except the cross-interference of the BPF (with few kHz bandwidth), which we neglected. Thus, the carrier to noise ratio of the \(k\)th control tone signal \((\text{CNR}_{\text{tone}}^k)\) at the optical receiver is given as:

\[
\text{CNR}_{\text{tone}}^k = \frac{(bP_{\text{th}}, b_{\text{th}} R)}{N_r B_{\text{tone}}} \tag{1}
\]

where, \(b\) is the power coefficient factor of the control tone signal, \(P_{\text{th}}\) is the total transmitted power of each VLC-AP and \(b_{\text{th}}\) is the channel gain of the \(k\)th VLC-AP. Calculation of \(b_{\text{th}}\) due to LOS components can be found in [15]. \(R\) is the PD responsivity and \(N_r\) is the noise power spectral density at the optical receiver.

The signal to noise ratio of the \(k\)th control tone signal \((\text{SNR}_{\text{tone}}^k)\) at the optical receiver is given as:

\[
\text{SNR}_{\text{tone}}^k = \frac{(aP_{\text{th}}, b_{\text{th}} R)}{N_r B_{\text{data}}} \tag{2}
\]

where, \(a\) is the power coefficient factor of the data signal and \(a = 1 - b\).

Dividing Equation (1) over (2), we can relate the \(\text{CNR}_{\text{tone}}^k\) to the \(\text{SNR}_{\text{tone}}^k\) of each VLC-AP as:

\[
\text{CNR}_{\text{tone}}^k = \left(\frac{b}{1-b}\right)^2 \left(\frac{B_{\text{data}}}{B_{\text{tone}}}\right)^2 \text{SNR}_{\text{tone}}^k \tag{3}
\]

It should be noted that control tones are used to manage the connection between VLC-APs and the optical receiver. In other words, these control signals are not used to convey a data. Thus, there are a bandwidth penalty and power penalty of using control tone signals.

### 4.3 Bandwidth of the control tone signals

The VLC system is limited by the transmitter, receiver or channel bandwidth as illustrated in Figure 5. However, we considered LOS components only, this leads to a flat channel of the indoor VLC system. Thus, the total bandwidth of the VLC system is limited by the transmitters or the receiver (PD) of the indoor VLC system. However, we used RYGB LDs as transmitters and we deal with low data rate (a few Mb/s). Thus, the data rate is limited by the bandwidth of the optical receiver only, as we considered only LOS components and we used LDs as sources of illumination and data communication. The area of the PD is 0.25 cm², which enable it to work at a bandwidth of 122 MHz. Calculation of the bandwidth of the PD can be found in [10]. In addition, we used TIA that proposed in [16], which has a bandwidth of 300 MHz and thermal input noise current of 2.5 pA/√Hz.

The total bandwidth overhead \((B_{\text{OH}})\) occupied by the control tone signals can be written as:

\[
B_{\text{OH}} = \frac{G_{\text{d,tones}} + \Delta f_N + G_{\text{tones-rc}}}{B_t} \tag{4}
\]

where \(G_{\text{d,tones}}\) is the guard band between the data bandwidth and the first centre frequency \((f_1)\) of the control tone signal, \(N\) is the number of VLC-APs, \(\Delta f\) is the guard band between control tone signals, \(G_{\text{tones-rc}}\) is the guard band between the last centre frequency \((f_N)\) of the control tone signals and the receiver bandwidth and \(B_t\) is the total available bandwidth that is limited by the PD bandwidth. In this paper, the \(B_{\text{data}}\) is selected to be 100 MHz, \(B_{\text{tone}}\) is chosen to be 2 MHz, which is equal to the bandwidth of the BPF, \(\Delta f\) is 2 MHz and \(G_{\text{d,tones}}\) and \(G_{\text{tones-rc}}\) are selected to be 1 MHz. The centre frequency of the first control tone signal \((f_1)\) is 102 MHz while the center frequency of the last control tone signal \((f_N)\), here, \(N = 10\) is 120 MHz. Therefore, the \(B_{\text{OH}}\) is 20 MHz, which represents 16.67% of the total bandwidth of our proposed system.

### 4.4 Power of the control tone signals

To calculate the power penalty attributed to the use of control signal tones. The data rate has been calculated of the optical user when it is located at the edge of the \(k\)th VLC-AP, which represents the worst case as the distance between the UE and the VLC-AP became maximum at this location. The data rate that can be offered by the \(k\)th VLC-AP \((R_{\text{kth}})\) to the UE with intersymbol interference free transmission (i.e. the total bandwidth, \(B_t\), is less than the channel bandwidth) can be written as:

\[
R_{\text{kth}} = \frac{B_{\text{data}} \log_2 (1 + \frac{(1-b) P_{\text{kth}} R}{\sigma_{\text{data}}^2})}{\sigma_{\text{data}}^2} \tag{5}
\]

where, \(b_{\text{kth}}\) is the channel gain of \(k\)th VLC-AP, \(\sigma_{\text{data}}^2\) is the total variance noise due to optical receiver thermal noise, background shot noise and data signal shot noise. An increase in the power coefficient factor of the control tone signal \((b)\) leads to a decrease in the data rate and this is defined as power penalty because of using control tone signals as can be seen in Equation (5).

Figure 6 shows the data rate penalty due to increasing the power coefficient factor of the control tone signal \((b)\) when the
FIGURE 6  Data rate penalty versus power coefficient power of the control signal \(b\)

UE is located at the edge of a VLC-AP. It should be noted that the results were obtained when the VLC system operates with a bit error rate (BER) not more than \(10^{-6}\), \(\text{SNR} = 13.6\) dB for on-off-keying (OOK) modulation [17]). When \(b\) is increased, this leads to a decrease in the allocated power of the data and consequently reduces the SNR. Thus, the data rate should be reduced (data rate penalty) to keep the VLC system works with BER not more than \(10^{-6}\) as depicted in Figure 6.

4.5  Coverage probability

In this work, the control tone signals are used to manage the connection between the UE and VLC-APs as well as to manage the handover process. In addition, a part of the total power of each VLC-AP is given to the control tone signal. However, these control tone signals are not used to convey the data. Thus, the amount of the power that will be given to each control tone signal should be optimized. It should be noted that allocating low power to each control tone signal, leads to make the received power of the control tone signal lower than the total noise of the optical receiver, which makes wrong decision in the optical receiver to select the best VLC-AP for the UE. In contrast, allocating high power for each control tone signal, leads to reduce the amount of the data rate that can be transmitted to the UE. Thus, the amount of the allocated power of each control tone signal should be optimized.

The coverage probability of the control tone signals is calculated to find the amount of the power that should be assigned to each control tone signal. The coverage probability of any control tone signal can be defined as the probability of the received \(\text{CNR}_{k\text{th}}\) is larger than a certain threshold \((\text{Th})\). The coverage probability of the \(k\)th VLC-AP \((P_{k\text{th}}^{\text{Cov}})\) is given as:

\[
P_{k\text{th}}^{\text{Cov}} = P\{\text{CNR}_{k\text{th}} > \text{Th}\}
\]  

(6)

Figure 7 illustrates the coverage probability of each control tone signal for different threshold values and when the power coefficient factor \((b)\) was 10%, 20%, 30% and 40% of the total VLC-AP transmitted power. It should be noted that the value of the \(\text{Th}\) can be used to estimate the probability of error in the optical receiver decision to make the UE connects with the best VLC-AP [10]. From Equation (3), we can find the optimum value of the \(\text{Th} (\text{CNR})\) based on the \(\text{SNR}\). To get a good connection link for the data channel, we considered 13.6 dB for the \(\text{SNR}\) which, gives BER of \(10^{-6}\) as we used OOK modulation [17]. In addition, \(b\) was selected to be 30% of the total VLC-AP transmitted power. Thus, the \(\text{Th}\) value is 22.3 dB, which gives coverage probability of 85% and BER of \(10^{-6}\). In addition, the data rate penalty is about 5% when \(b\) was selected to be 0.3 as can be seen in Figure 6.

4.6  Handover cost

The handover cost is a unitless amount that is utilized to measure the time wasted due to handover processing [18]. The handover cost is a multiplication of handover rate with the delay of the handover processing [18]. To evaluate the handover cost for our proposed scheme and the received signal strength scheme, we assumed the UE trajectory that shown in Figure 8(a). In addition, for the received signal strength strategy, we assumed that the UE re-evaluate its connections at each 1 s intervals. To re-evaluate the performance of the UE’s link, the controller activates one VLC-AP to send a pilot signal and the power of this pilot signal is calculated at the optical receiver. The VLC-AP that has the best received optical power will be allocated to the UE. Thus, at each 1 s intervals, the controller checks the links performance of all VLC-APs in the received signal strength scheme. If the time required to find the power of each SCM tone is 1 ms, the received signal strength scheme requires 10 ms \((10 \text{ VLC-APs} \times 1\text{ ms})\) to find the target VLC-AP at each 1 s intervals. However, in our proposed scheme, the UE connects with all VLC-APs simultaneously via SCM tone, which leads to reduce the required time to find the target VLC-AP.
FIGURE 8 (a) Black line represents the trajectory of the UE on the communication floor of our proposed room and (b) the handover cost of the received signal strength and our proposed schemes

Figure 8(b) shows the handover cost of our proposed scheme and the received signal strength scheme when the UE moves with different speeds along the trajectory illustrated in Figure 8(a). It should be noted that we used the same analysis that was used in [18] to get the handover cost. Compared with received signal strength scheme, our proposed scheme has lower handover cost as can be seen in Figure 8(a).

5 CONCLUSIONS

A novel handover scheme for indoor VLC systems was proposed in this paper. We used control tone signals to manage the handover of the indoor VLC systems. In this work, the UE connected with the best VLC-AP for data transmission. However, the UE connected with all VLC-APs through control tone signals. Thus, the optical receiver has information about all VLC-APs during the mobility of the UE. The required bandwidth (16.6% of the total bandwidth of our proposed VLC system) and the required power (0.3 of the total power of the VLC-AP) of each control tone signal were calculated. In addition, the optimum threshold value (CNR) was calculated to decide if the UE required a handover or not. This optimum threshold was 22.3 dB, which gives coverage probability of 85% and BER of $10^{-6}$ of the transmitted data.

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