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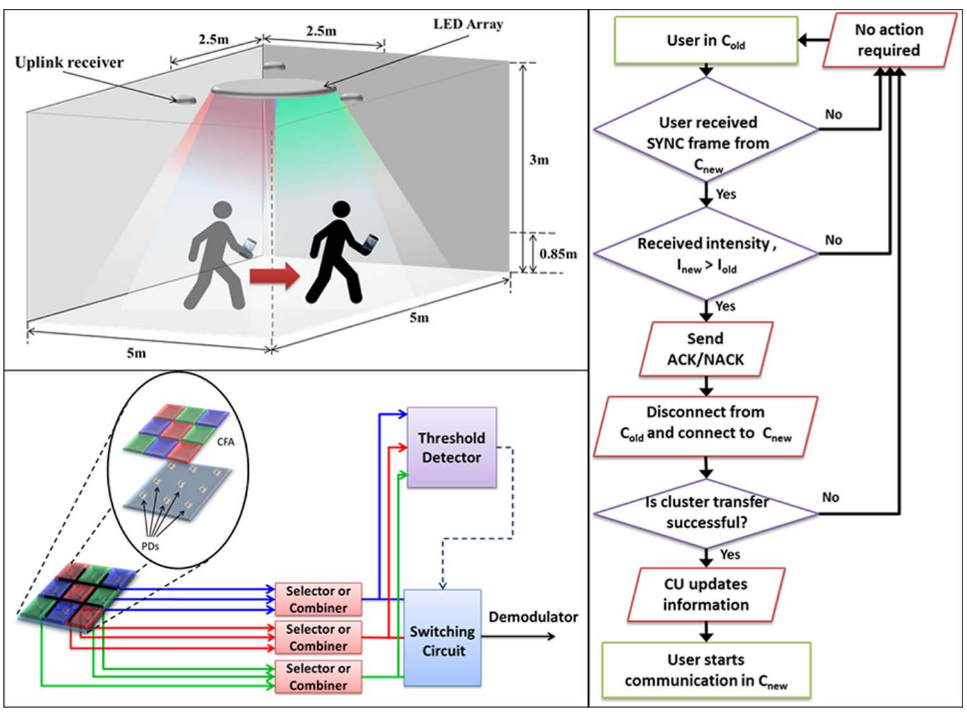

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Mobility Support for Full-Duplex Multiuser Bidirectional VLC Networks

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Abstract: In this paper, a novel and unique mobility support scheme for a color-clustered (CC) full-duplex multiuser (MU) bidirectional visible light communication (VLC) network is presented. Mobility is classified into two categories: intercluster and intracluster. In the proposed scheme, the mobility support is efficiently provided using a color filter array (CFA) at the downlink receiver. This CFA gives rise to receiver diversity in the form of selection combining yielding performance improvement. Simulations are conducted in terms of communication delay and frame loss rate relative to user speed and distance. In addition, the bit error rate (BER) performance and the data rate are analyzed in the CC MU VLC network. It is demonstrated that the proposed CFA and receiver diversity based mobility scheme in the CC MU VLC network offers superior performance in terms of BER and data rate in indoor environments.

Index Terms: Color filter array (CFA), mobility support, bidirectional visible light communication (VLC) network, color-clustered environment, multiuser.

1. Introduction

Visible light communication (VLC) has recently attracted renewed interest within the communication research community due to its inherent advantages. VLC is basically designed to offer communication and illumination simultaneously [1]–[3]. In addition to these two functionalities, one additional VLC functionality, which is referred to as motion detection, has recently been introduced [4].

VLC uses light emitting diodes (LEDs) to transmit a modulated beam of visible light [2]–[4]. As an attractive alternative to short range RF based wireless communications, VLC offers license-free spectrum with high bandwidth capacity in a cost-effective and easy-to-install manner. Recently, VLC has led to a light fidelity (Li-Fi) network as a wireless broadband communication technology [3]. This Li-Fi network presents a color cluster based user allocation scheme for a full duplex multiuser bidirectional transmission, but it lends itself to static users in a particular cluster only. In order for VLC to be viable as a future indoor wireless broadband communication, user mobility needs to be supported in indoor VLC environments. Although the users move at a relatively low speed in indoor environments, the effect of this low mobility on the system

TABLE 1

Uplink color allocation

Received color	Uplink color
Red	Green
Blue	Red
Green	Blue

performance can be significant with the dependence on channel variation [5]. Therefore, the user mobility needs to be comprehensively analyzed in various MU transmission scenarios.

In an effort of VLC standardization, the IEEE 802.15.7 standard focuses on point-to-point communication and dimming support, but it does not contemplate mobility support in VLC networks [6]. Recently, a cell ID-based approach has been proposed to address mobility issue in indoor VLC environments [7]. This approach is intended only for a single user and does not present any details for bidirectional communication links. Therefore, more comprehensive and analytical studies on the mobility support in VLC networks need to be reported in the literature.

In this paper, we propose a novel and unique mobility support scheme for a color clustered (CC) multiuser full-duplex bidirectional VLC network. In CC-VLC, a color filter array (CFA) is employed at the receiver for the mobility support. Also, this CFA gives rise to receiver diversity implemented via selection combining (SC) [8] at the downlink receiver. In the proposed scheme, mobility is classified into two categories: intracluster mobility within the identical cluster and intercluster mobility between two different clusters. To verify the effectiveness of the proposed scheme, computer simulations were carried out. It is found that the proposed CFA based scheme is efficient to support user mobility in a MU full-duplex bidirectional VLC network.

The rest of the paper is organized as follows. In Section 2, the system description is provided. Theoretical analysis is presented in Section 3. Section 4 discusses simulation results, and conclusions are drawn in Section 5.

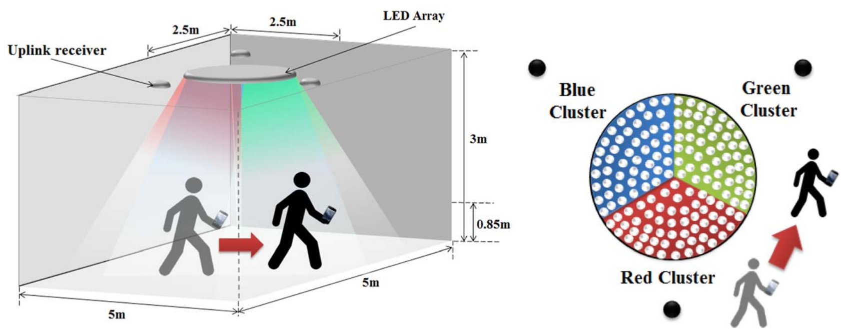
2. Proposed Mobility Support Scheme

The proposed mobility scheme is presented for multiuser bidirectional VLC networks. Since color clustered VLC network is considered a representative of MU bidirectional VLC networks, the proposed scheme is implemented in the color clustered VLC network [3]. In the color clustered VLC system, the users are allocated into separate color clusters and the user data is transmitted through the allocated color beam from the red, green, and blue (RGB) LEDs in the form of predefined frame structure [3], [8], [9]. That is, the data is first modulated and transmitted using a specific color, thus defining the cluster as red, blue or green cluster. The other two color beams are provided with the average DC bias to maintain white color for illumination purposes. At the receiving end, primary user separation is achieved by a color filter that is capable of distinguishing the colors. For uplink data transmission, the user data modulation is performed using a different color from the one used for downlink and transmitted via RGB LEDs. Table 1 shows uplink color allocation. In this way, a MU full-duplex bidirectional VLC link with minimal interference is established.

2.1 User Mobility in Color Clustered VLC Networks

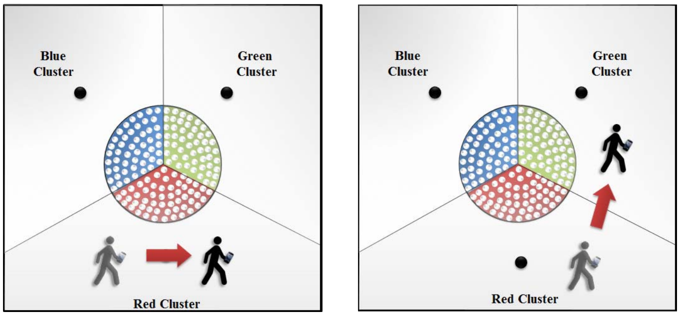
When the user moves in a color clustered VLC network, the user may not be able to communicate satisfactorily due to the user movement. Fig. 1(a) illustrates the user movement from one cluster to another, while Fig. 1(b) shows its top view.

It is apparent that the user (or user device) needs to maintain a communication link seamlessly, regardless of whether the user moves in and around the cluster at a certain speed v. Therefore, it is required to provide transparent mobility support with the best link quality in this MU bidirectional VLC network.



(a) (b)

Fig. 1. (a) User movement in a color clustered environment. (b) Top view of user movement.



(a) (b)

Fig. 2. User movement classification (a) Intracluster. (b) Intercluster.

2.2 Classification of User Movement

Basically, the user movement can be classified into the following two categories:

- *Intracluster movement*: This refers to the user movement within the same cluster in which the link is initially established. Fig. 2(a) shows the intracluster movement.
- *Intercluster movement*: This occurs when the user moves from one cluster to another in a color clustered VLC system. Due to the user crossing the cluster border, the communication link from the old cluster becomes weak as the user moves away. Eventually, that user is unable to communicate efficiently unless mobility scheme is supported as the new cluster utilizes a different color from the old cluster for both downlink and uplink [3]. Fig. 2(b) depicts the intercluster movement of the user.

Although these two categories of movement cause user performance degradation in the MU bidirectional VLC system, the intercluster movement is considered more detrimental to the link quality. To address this intercluster mobility issue more efficiently, CFA is proposed to employ in the downlink receiver as part of the mobility support scheme.

2.3 Color Filter Array

It is known that CFA is commonly used in photography [10]. That is, the color filters in a CFA extract the light by a wavelength range in such a way that the separately filtered intensities include the information about the color of light. As an example, the Bayer filter array is shown in Fig. 3(a) and gives the information about the intensity of light in red, green, and blue (RGB) wavelength regions.

A 3×3 Bayer filter array contains two blue, two red and five green color filters [13], which is regarded as a non uniform filter array. For the present mobility support scheme, a uniform array

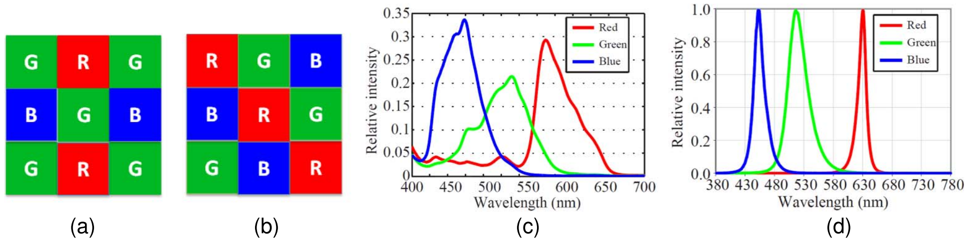


Fig. 3. (a) Bayer's CFA. (b) Proposed CFA. (c) Relative intensity profile for CFA [11]. (d) Relative intensity profile for RGB LED [12].

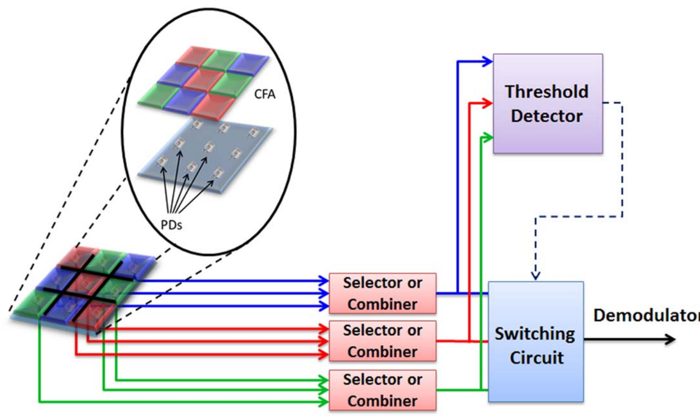


Fig. 4. CFA based receiver diversity.

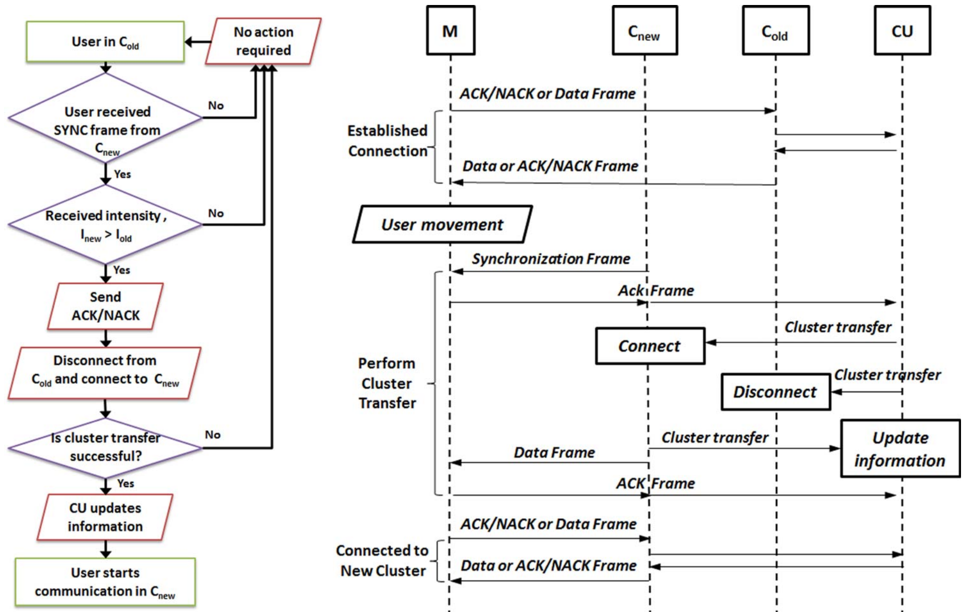
with the same number of color filters is proposed. This is due to the fact that SC is employed as a receiver diversity technique and thus the number of the received signals from each color must be identical. Fig. 3(b) shows the proposed CFA design for the present scheme. The proposed CFA constitutes 3 filters for each color. Observation of the relative intensity profiles for CFA and RGB LED in Fig. 3(c) and (d) respectively reveals that it may not be possible to fully filter out the effect of other colors in a color cluster by simply employing RGB LEDs and CFA, due to overlapping relative intensity profiles of CFA and RGB LED. Hence, it is important to note that the receiver diversity implemented via SC plays an important role in obtaining the most probable signal in the receiver. Fig. 4 shows the block diagram of CFA based receiver diversity.

2.4 Frame Structure and Mobility Support Algorithm

In [3], we have proposed three types of frames, i.e. synchronization frame (SYNC), acknowledgement/negative acknowledgement (ACK/NACK) frame and data frame. The user allocation process with the frame structure is detailed in [3].

The SYNC frame is initially generated and broadcast by the downlink transmitter (LED array). The synchronization frame is clearly distinguished by a 1010... sequence pattern in the field of data bits and the "Available/Occupied" bit always by "0," i.e. available, and the "Uplink/Downlink" bit set to "1," i.e. for downlink transmission. This SYNC frame is received by the transceiver unit and the acknowledgement is sent back to the uplink receiver using the ACK frame. The ACK frame is similar to SYNC frame and the differences are described in [3].

After the successful reception of the ACK frame, the downlink transmitter then transmits the actual data of the user using data frames as mentioned in [3]. ACK and NACK for data frames can be performed by using a special sequence of bits in the place of data bits in the frame.



(a) (b)

Fig. 5. (a) Mobility support algorithm for intercluster movement. (b) Sequence diagram for intercluster movement.

In the case of intracluster movement, the communication link is largely unaffected unless the user is on the move at a very high speed. For the intercluster movement, however, a transparent cluster transfer process needs to be ensured between the clusters. Fig. 5(a) shows the proposed algorithm for the intercluster movement. The intercluster process is performed from the old cluster, C_{old}, to new cluster, C_{new}. It can be observed from Fig. 5(a) that even after the reception of SYNC frame from C_{new}, the user device, M, looks for the higher intensity from C_{new} than the one from C_{old}, i.e. $I_{\text{new}} > I_{\text{old}}$. By obtaining the higher intensity from C_{new}, a successful cluster transfer process is achieved and the relevant information is updated in the control unit (CU).

In the proposed scheme, it is one important parameter to be defined, which is called *cluster transfer duration*. It is assumed that the cluster transfer process is completed within this cluster transfer duration. The bit duration in the present study is chosen in such a way that it should not be affected by multiple reflections in indoor VLC environments [1]. In view of this, the bit duration is chosen to be 5 ns. Therefore, a frame length of 256 bits corresponds to 1.28 μs. By taking into account the time for frame synchronization, which is equivalent to approximately 5 μs (1 SYNC frame, 2 ACK/NACK frame and 1 Data frame), and actual cluster transfer time of approximately 5 μs (between the clusters and CU, and approximate processing time), the cluster transfer duration, T, is assumed to be approximately 10 μs. The detailed sequence diagram for the intercluster movement is shown in Fig. 5(d).

It should be noted that the proposed scheme for mobility support can be implemented, not only in the color clustered environments but also in any other forms of MU environments such as cell based environments on the basis of location, frequency or wavelength with some necessary modifications.

3. Theoretical Analysis

In a mobility supported VLC network, communication delay would occur due to user speed v and communication radius d with respect to the central point of the receiving plane as shown in Fig. 6. In other words, the communication delay indicates the time difference caused by the movement of the user over a certain distance.

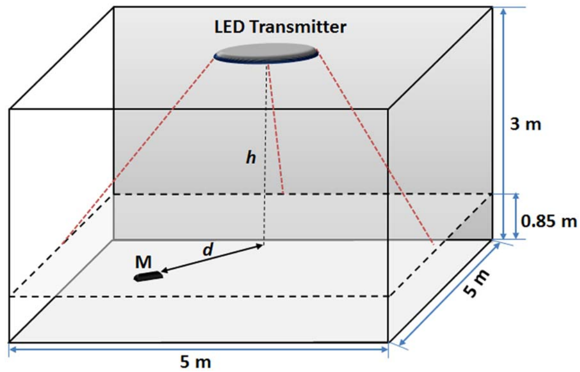


Fig. 6. Indoor VLC environment.

In the case of the intracluster movement, the communication delay d_{intra} is computed by

$$d_{\text{intra}} = \frac{(\sqrt{d^2 + h^2}) - h}{v} \tag{1}$$

where h represents the height of the LED array from the receiving plane.

On the other hand, the communication delay, d_{inter}, for the intercluster movement needs to be computed on the basis of T, which is assumed to be 10 μs as noted earlier. Therefore, d_{inter} is given by

$$d_{\text{inter}} = d_{\text{intra}} + T = \frac{(\sqrt{d^2 + h^2}) - h}{v} + T. \tag{2}$$

The frame loss rate, R_{loss}, can then be obtained as

$$R_{\text{loss}} = \frac{N_l}{N_t} = \frac{\frac{d_c}{D_f}}{N_t} \tag{3}$$

where N_l, N_t, and D_f denote the number of frames lost, the total number of transmitted frames, and the duration of a single frame, respectively. d_c represents the communication delay, which is either d_{intra} or d_{inter}.

4. Results and Discussion

To verify the effectiveness of the proposed scheme, extensive simulations were performed in an indoor environment. Fig. 6 illustrates schematically the underlying environment and the simulation parameters are described in Table 2.

Fig. 7(a) and (b) show the communication delay and frame loss rate relative to the communication radius, d, over intercluster and intracluster movements, respectively. The results are obtained with the user speed fixed to 5 km/h. It can be observed that the communication delay and frame loss rate increase linearly with increasing communication radius for both categories of the movement. This is due to the fact that the delay and frame loss rate become poorer as the user moves away from the transmitter.

A further analysis was performed to observe the effect of the user speed with the communication radius fixed to 2 m. Fig. 8(a) and (b) show the results. As expected, the delay for the intercluster movement is higher than the one for the intracluster movement. In addition, the frame loss rate increases sharply for the intercluster movement when the speed increases. It can be said that the effect of the user speed on the frame loss rate is very significant in the intercluster movement.

TABLE 2

Simulation parameters

Parameter	Value
Dimensions of the room	5m×5m×3m
Optical output power of each LED	60mW
Number of LEDs	2400 (3 clusters with 800 LEDs each)
PD physical area	1.0 cm^2
PD's field of view (FOV)	60°
Physical separation of PDs in PD array	1cm
Mac protocol	IEEE 802.15.7 [6]
Speed of the user	[4km/h 5km/h ... 12km/h]
Communication radius, d	[0.5m 1m ... 3.5m]
Operational wavelength of R, G, and B filters in CFA	650 nm, 510 nm and 475 nm
Handover duration	10μs
Simulation time	300s

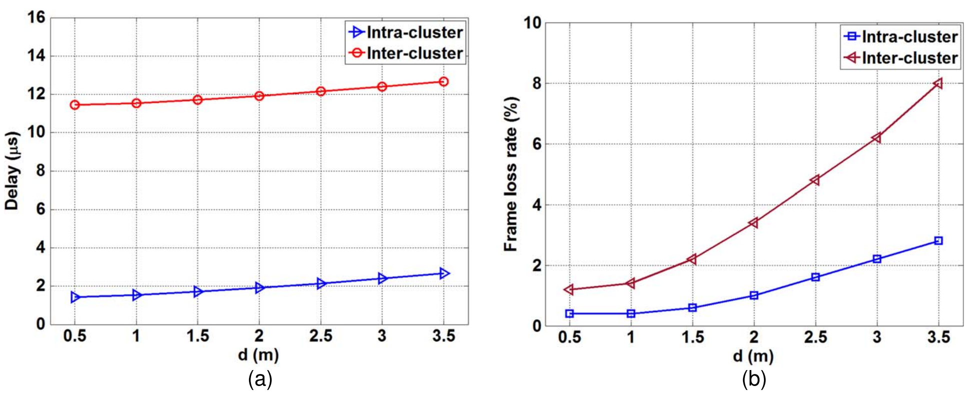


Fig. 7. On the effect of communication radius. (a) Communication delay variation. (b) Frame loss rate variation.

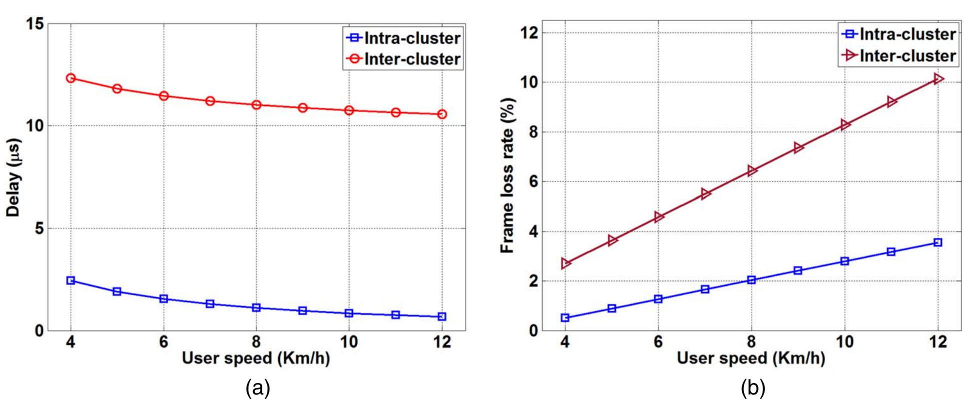
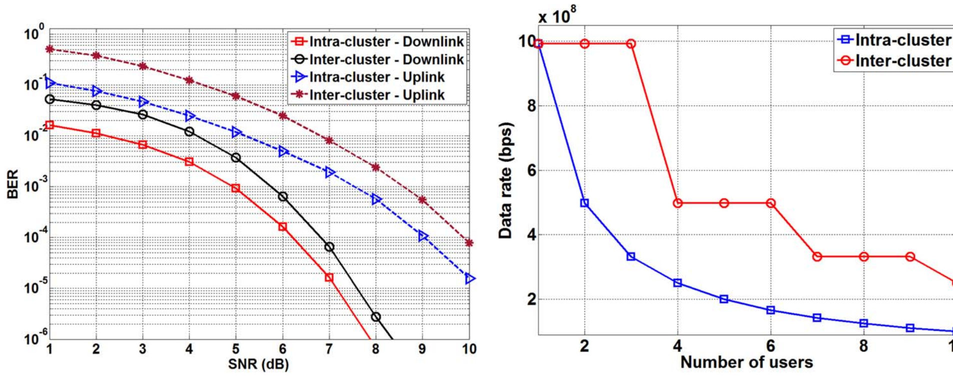


Fig. 8. On the effect of user speed. (a) Communication delay variation. (b) Frame loss rate variation.

It is also of interest to analyze bit error rate (BER) performance and data rate of the mobility supported MU VLC system. To this end, the user is assumed to be on the move at a constant yet realistic speed of 5 km/h for both intracluster and intercluster movement. Fig. 9(a) shows the



(a) (b)

Fig. 9. (a) BER performance relative to SNR values. (b) Data rate relative to the number of users.

BER performance. It is clear from Fig. 9(a) that the performance of downlink transmission is superior to the one for uplink. This is because the proposed scheme employs the receiver diversity based on CFA for downlink, thus yielding the improved performance. It is worth noting that a BER of 10^{-3} is attained at a SNR value of approximately merely 5.8 dB for the intercluster downlink transmission.

At the identical user speed, the data rate is evaluated in terms of the number of users. Fig. 9(b) shows the data rate analysis. For this data rate evaluation, 4-quadrature amplitude modulation-DC biased optical orthogonal frequency division multiple access (4-QAM-DCO-OFDMA) with 128 subcarriers [3] is employed. It can be seen that a minimum data rate of 110 Mbps is supported when the number of intracluster users in a single cluster is 10. Interestingly, it can also be viewed from Fig. 9(b) that when 10 users are uniformly distributed over all clusters, an achievable data rate sharply increases up to 250 Mbps at a minimum.

Therefore, it can be concluded from the observations that the proposed scheme offers a high-speed high-performance MU bidirectional VLC link with mobility support.

5. Conclusion

A novel and unique scheme for user mobility in a color clustered full-duplex multiuser bidirectional VLC network is presented. The unique frame structure and distinctive color allocation for downlink and uplink data transmission are employed for minimal interference. The color filter array is also proposed with a view to enhancing the multiuser performance in the form of the receiver diversity. With the mobility algorithm and sequence diagram provided, the proposed scheme is analyzed for both the intracluster and intercluster movement. Simulation results demonstrate that the proposed scheme presents very efficient user mobility supported MU bidirectional VLC networks.

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