Mobility Analysis of Mobile VLC with Optical Zoom Antenna

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Abstract. This paper specifically analyse the mobility performance in optical zoom receiving mobile VLC. Optical zoom antenna adjust the optical gain by changing the FOV and then effect the signal to noise ratio (SNR) at the receiver. Firstly, with same transmit power, we analysis the communicable area between fixed focus VLC systems at different FOV. Besides, we contrast the mobility between fixed-focus and optical zoom VLC. Comparing with fixed focus VLC, the mobility can be increased by 90% with optical zoom receiving at 800Mbps. As data rate increasing, fixed focus system is completely disrupted, while the optical zoom antenna still ensure well mobility. According to these analysis, optical zoom antenna can guarantee a stable and high speed communication over a wide range in mobile VLC.

1. Introduction
Smart home need all intelligent devices indoor could access Internet [1]. For most indoor intelligent devices, they are dispersed. Thus, ensuring all devices can communicate well is an urgent issue. VLC is a technology combines the transmission task and illumination role with indoor infrastructure, offering advantageous such as low cost, long lifetime and a large number of available spectrum resources [2,3,4]. The spectrum energy distribution marches to Gaussian distribution, leading to a non-uniform communication performance within the room domain. Even worse, some region of the devices could not receive the signal [5].

Previously, researchers have been dedicated to high-speed VLC. Mobility is another research focus [6]. In 2018, an LED implementation approach based on hyperheuristic evolutionary algorithm (HypEA) show that mobility coverage optimized by 13.23% in compared with uniform deployment and 70.67% compared with centralized arrangement [7]. Later, the approached HypEA successfully investigated optimal LED deployment for fully mobile indoor VLC system at a height of 0.85m above the ground [8]. The uniformity of illumination was improved from 0.55 to 0.86 in a room with the size of 7.8 m×6 m×3m by a LED lamp arrangement algorithm, ensuring almost equal SNR effects for all locations indoor. There are 2 × 3 lamps distribute on the ceiling [9]. From the aspect of transmitter, in 2014, a linear programming (LP) method is proposed to optimize transmit power of LEDs, decreasing the fluctuation of received power [10]. In 2015, Zhang Jian optimized the distribution of SNR from the aspects of LED lamp layout and power optimization based on Genetic Algorithm [11]. These methods find the optimal solution to guarantee the mobility, while also limit the basic equipment in the house. When the size of the room changes, it need to find a new solution to ensure mobility. In 2016, optical zoom antenna was proposed to keep the stability and mobility signal in VLC [12]. However, the data analysis about optical zoom antenna is not detailed.
In our work, we sufficiently analyse the mobility in optical zoom receiving VLC. In section two, average mobility area ratio (M) is introduced to measure the comparable area of indoor VLC. Besides, we describe the SNR calculation formula with optical zoom antenna. Later, we set up a four LED lamp VLC system for the following simulation. Finally, we adequately analyse the mobility of fixed focus and optical zoom receiving mobile VLC with MATAELB. Mobility is a novel research direction in VLC. As the mobility improved, the communication reliability of smart home network can be guaranteed.

2. Average mobility area ratio (M) and SNR in mobile VLC

2.1. Average mobility area ratio (M) in VLC

The average mobility area ratio (M) is used to measure the mobility of indoor VLC, indicating the overall mobility achieved during the movement [7]. If the value of M is 0, it indicates the full communication interruption, whereas the value of R is 0, it indicates complete coverage the mobility of the receiver:

\[ M_{\text{average}} = \frac{\text{SNR} > 13.6}{\text{Total}} \]  

For on-off keying (OOK) modulation, The BER is:

\[ \text{BER} = Q(\sqrt{\text{SNR}}) \]  

Where \( Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-x}^{\infty} e^{-y^2/2} dy \). According to the relationship between BER and SNR, when the BER is less than 10\(^{-6}\), the SNR must be more than 13.6dB. In this way, based on Monte Carlo (MC) algorithm, \( M_{\text{average}} \) depend on every ray.

\[ M_{\text{average}} = \frac{\sum \text{APD}_{\text{SNR} > 13.6 \text{dB}}}{\text{APD}_{\text{Total}}} \]  

2.2. Signal to noise ratio (SNR) in VLC with optical zoom antenna

MC algorithm has a widespread application in VLC [13,14]. In this work, we use MC algorithm for describing the randomness of photos. It is assumed that four 10cm×10cm LED lamps are installed on the ceiling, and each LED lamp has a built-in four-color LED module. Any point on the illuminating surface is a point source \((x, y, z)\) with an intensity of \( I_0 \).

\[
\begin{align*}
\begin{cases}
    n_x = x_0 + a \cdot \sin \theta \\
    n_y = y_0 + b \cdot \sin \varphi \\
    n_z = 3
\end{cases}
\end{align*}
\]  

Where \( a \) and \( b \) is Side length of the LED lamp. \( \theta \) and \( \varphi \) are both random number:

\[
\begin{align*}
\varphi &= 2\pi r_3 \\
\theta &= 2\pi r_4
\end{align*}
\]  

Where \( r_3 \) and \( r_4 \) are both uniform random numbers between 0 and 1, generated by the rand function. LED acts as a Lambert radiation source, randomly sampling the exit direction of the light can uniquely determine a random light. Based on the MC algorithm, the luminous intensity of the random light is:

\[ I = I_0 \cdot \cos \gamma \]  

Where \( I_0 \) is the luminous intensity of LED source, \( \gamma \) is the angle between the emitted light and the surface normal. Simplify, we assume that the normal direction is perpendicular to the ceiling and is \((0, 0, -1)\).

Optical gain is defined as the ratio between the optical power received on the photosensitive surface of a detector when it’s equipped with and without an optical antenna [15]. For fixed-focus VLC system, the gain of the optical antenna can be expressed as:

\[ G(\psi) = \begin{cases} 
\frac{n^2}{\sin^2 \psi} & \psi < \Psi \\
0 & \psi > \Psi
\end{cases} \]
where \( n \) is internal refractive index, \( \Psi \) is FOV of optical antenna. As shown in figure 1, the acceptance angle of light A is smaller than FOV of APD and light A can be received. Inversely, light B can’t be received.

![Figure 1. Simple model of APD](image)

![Figure 2. Optical gain versus FOV and focal length](image)

![Figure 3. Channel model for NLOS VLC.](image)

The process of optical zoom antenna is to change the focal length of the antenna through the movement of optical lens. As shown in figure 2, we simulate the optical gain using the laboratory’s existing zoom antenna. The relationship between FOV and optical gain is inverse. For optical zoom receiving VLC system, the optical gain can be expressed as:

\[
G(\psi, f) = \begin{cases} 
\frac{n^2}{\sin^2(\Psi(f))} & \psi < \Psi \\
0 & \psi > \Psi 
\end{cases}
\]

(9)

Considering the channel model in figure 3, we consider the effects of wall reflection and the reflection coefficient of wall is 0.8. For the design of an NLOS optical link, the received power \( P_{r,i,j} \) at receiver \( i \) from ray \( j \) can be expressed as [2]:

\[
P_{r,i,j} = (H_{d,i,j} + H_{ref,i,j}) \times P_t
\]

(10)

Where \( H_{d,i,j} \) and \( H_{ref,i,j} \) are gain on direct path and reflect path respectively. \( P_t \) is the transmit power of single random ray.

\[
H_{d,i,j}(\psi, f) = \frac{(m+1)A_R}{2 \pi d^2} \cos^m(\gamma) T(\lambda, \psi) G(\psi, f) \cos(\psi) \quad 0 \leq \psi \leq \Psi
\]

\[
dH_{ref,i,j}(\psi, f) = \frac{(m+1)A_R}{2 \pi d^2 d_\psi^2} \rho dA \cos^m(\gamma) \times \cos(\alpha) \cos(\beta) T(\lambda, \psi) G(\psi, f) \cos(\psi) \quad 0 \leq \psi \leq \Psi
\]

(11)

(12)

where \( d \) is the distance between the transmitter and receiver, \( dA \) is the surface element of reflection wall, \( T(\lambda, \psi) \) is the transmission function of an optical filter, \( \gamma \) is the angle of the emergence, \( \psi \) is the angle of incidence, \( \Psi \) and \( f \) represent the FOV and the focal length of the optical zoom antenna.

According to the channel characteristics of indoor visible light communication, after free space propagation, the received power within \( \Psi \) can be expressed as equation (13)

\[
P_{r,total} = \sum_{i=1}^{\text{rays}} \{ H_{d,i,j} \times P_t + \int_{\text{wall}} \times P_t dH_{ref,i,j} \}
\]

(13)

For VLC system, AC power upload information and DC power correspond to average intensity. The SNR of APD at receiving surface is:

\[
\text{SNR}_t = \frac{(P_{AC,i} \cdot l_{0,i})^2}{\text{crosstalk}_{i,j} + \sigma_{\text{excess}}^2 + \sigma_{\text{dark}}^2 + \sigma_{\text{thermal}}^2}
\]

(14)

Where \( P_{AC,i} \) and \( P_{DC,i} \) are AC power and DC power of LED \( i \) respectively, \( P_{DC,j} \) is the DC power of LED, \( \sigma_{\text{excess}}^2, \sigma_{\text{dark}}^2, \sigma_{\text{thermal}}^2 \) are the excess noise, dark current noise, and thermal noise of the APD caused by photocurrent. \( \text{crosstalk}_{i,j} \) is spectral crosstalk for LED \( i \) form LED \( j \) [16]:

\[
\text{crosstalk}_{i,j} = \sum_{j=1}^{n} \left( P_{AC,j} \cdot l_{0,i,j} \right)^2
\]

(15)

in indoor VLC systems, user’s slow moving changes not only the propagation distance, but also the angle of incidence and irradiance. Both distance and angle are key factors for the capacity in VLC systems.
3. Indoor VLC geometric distribution model

![Figure 4. Multi-spectrum VLC block diagram](image1)

As shown in figure 4, signals are loaded on sub-communication channels using different colour LEDs. We assume each LED lamp adopts a unique random sequence to transmit information. Thus, spectral crosstalk is the most serious interference problem. APD need to select the maximum instantaneous SNR among the four LED lamps. So each LED lamp is responsible for a region, like in figure 5.

The indoor VLC system is set up in a room with a size of 5 m×5 m×3 m. There are four LED lamp are located at (1.2, 1.2, 3), (1.2, 3.6, 3), (3.6, 1.2, 3), (3.6, 3.6, 3) on the ceiling and every LED lamp is 10 watts. The semi-angle at half power $\Phi_{1/2}$ is 60°. Each white light LED lamp consist of four different colour LED. The central wavelength is 463nm (blue), 520nm (green), 595nm (orange), and 640nm (red), respectively. The semi-angle at half illuminance of the LEDs is 60° ($m=1$). According to the principle of mixed light, the coefficient ratio for mixing white light is about 1:1:1:1, so we design every colour of LED is 2.5 watts [17]. To ensure better forecast accuracy, we suppose each LED emits 50,000 random rays and there are 100 APDs in the receiving at the height of 0.85m above the ground level. The parameters of VLC system are given in table 1.

| Table 1. System parameters |
|-----------------------------|
| Order of the Lambert emission $m$ | $m = \ln 2 / \ln(\Phi_{1/2})$ |
| Active area of APD $A_R$ | 3 mm$^2$ |
| FOV of optical zoom antenna | Between 16° and 40° |
| Filter transmittance | 80% within the bandwidth, 0% out the bandwidth |
| Filter FWHM | 10 nm |

4. Mobility simulation results

4.1. Mobility in fixed focus VLC

![Figure 6. Scene diagram of indoor VLC. (a) Red monochrome VLC, (b) Green monochrome VLC, (c) RGBY four-spectrum VLC](image2)
Monochrome VLC system is that there is one spectrum signal channel in the VLC system, others are all hold the role of supplementing white light illumination, like Figure 6(a) and Figure 6(b). Multi-spectrum VLC use multi-colour LEDs and each colour of LED lamp is responsible for a corresponding region, like in Figure 6(c). Taking red LED lamp and green LED lamp as examples, we compare the communicable area between monochrome fixed focus VLC and multi-spectrum fixed focus VLC at the receiving plane. The transmit power of every LED lamp is the same.

![Figure 7](image1.png)

Figure 7. (a) and (b) are comparable area of red monochrome fixed focus VLC with 50° FOV; (c) and (d) are comparable area of green monochrome fixed focus VLC with 50° FOV.

As simulation results in figure 7 and figure 8, compared to monochrome VLC, the communicable area of RGBY four-spectrum VLC is in a higher proportion. For multi-spectrum VLC, the effect of the optical filter is more prominent, and the crosstalk is reduced, leading to a more stable communication. The problem is that with data rate increasing, the communication still suffer from mobility limitation.

![Figure 8](image2.png)

Figure 8. Comparable area of RGBY four-spectrum fixed focus VLC with 50° FOV

In the following analysis, we compared the mobility between different FOV VLC systems. According to the results in figure 8 and figure 9, the optical antenna with a small FOV is easy to achieve a high speed communication, but the mobility is limited. Contrary, for larger FOV VLC, the receiver could receive a wider field of light. A big communicable area could be achieved, but the communication capacity is limited due to the interference of crosstalk channel.

4.2. Mobility in optical zoom antenna VLC

Optical zoom antenna can change the optical gain by adjusting the FOV of receiver as shown in figure 3. The FOV of the optical zoom antenna we use can change between 16° and 40° and the maximal system gain is 20.66. The communicable area of optical zoom antenna VLC system show in figure 10. According to the calculation of M, at the speed of 800Mbps, with same transmit power, the mobility performance of RGBY optical zoom four-spectrum VLC can be improved by 90% compared with RGBY fixed focus four-spectrum VLC with 50° FOV. When the data rate is more than 1Gbps, the value M of fixed focus VLC is almost 0, meaning the communication outage. Value M of red, green and blue VLC with 50° FOV, RGBY fixed focus four-spectrum VLC with 50° FOV and RGBY optical zoom four-spectrum VLC is shown in figure 11.
5. Conclusion

Mobility is an urgent problem to VLC system. In our work, we add focal length into the SNR formula and analyse the mobility of VLC with optical zoom antenna. We contrast the average mobility area ratio (M) between fixed focus and optical zoom antenna VLC. According to the calculation results, the optical zoom antenna effectively provide optical compensation in mobile VLC. The optical zoom antenna receiving VLC can support a more stable mobile communication, especially at high speed transmission.

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