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Performance Analysis of Single Light Source Bidirectional Visible Light Communication Reverse Reflection Link

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Abstract: The LED light source is an important light source for indoor visible light communication. It has the characteristics of a large divergence angle and a high transmission rate. Therefore, using LED as the light source for visible light full-duplex communication can not only satisfy the lighting requirements but also transmit information at high speed. To analyze the factors that affect the optical power of the indoor single-light source visible light communication uplink receiving end, an indoor visible light communication model was established, and mathematical calculation formulas were derived based on the model establishment, and the maximum movable range formula of the retroreflective end under specific conditions was derived; The reliability of the formula was verified with the help of Zemax simulation software. Theoretical analysis and experimental results show that increasing the movement range of the retroreflective end can be achieved by increasing the lens diameter, reducing the focal length, and increasing the link distance.

Keywords: visible light communications; uplink; moving retroreflective end; effective incidence angle

1. Introduction

Visible light communication uses light as the transmission medium [1]. It has the two major advantages of high speed of optical communication and security of wireless communication and realizes the integration of lighting and communication at the same time. It has been listed as a new-generation communication technology [2].

Since visible light communication was proposed in 1999 [3], its transmission rate has been getting higher and higher, and it has continuously achieved breakthrough results. It has now reached 10 Gbps [4], but the uplink has always been a bottleneck inhibiting its development. Many studies focus on the form of uplink and propose solutions that integrate radio frequency WIFI [5], infrared [6], etc. with visible light. Heterogeneous links not only increase the complexity of the system but also limit the application of visible light communication in certain scenarios. Vucic J et al. configured light sources at the terminal and built a time-division duplex visible light bidirectional link. By configuring the user time slot length, they improved the dynamic flexibility of asymmetric homogeneous link services [7]. However, the terminal's illumination [8,9] is not only detrimental to the mobility of the terminal but will also have a certain impact on indoor lighting. Using the principle of optical reflection to establish a reflection link based on cat's eye inverse modulation is an important technical means to achieve single-light source bidirectional visible light communication [10-12]. It has the advantages of low power consumption, high security, low system structure complexity, and no electromagnetic interference [13]. Sun Y et al. analyzed the impact of the cat's eye inverse modulator structural parameters and link distance on the system's reflected light characteristics [14]. At present, research on reverse modulation visible light communication mainly solves problems such as the modulation format of the retroreflection signal and the suppression method of interference between links. To meet the high-speed, low-interruption, and other requirements for user hotspot high-

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capacity scenarios and small indoor scenarios [15], and to adapt to future 6G application development, the design of visible light communication systems needs to support mobility management and combine homogeneous uplinks. Road analysis of the impact of terminal mobility on the uplink is an important challenge in visible-light communication networking.

This paper establishes a bidirectional link model of a single light source indoor visible light communication system, combines the geometric optics method, studies the reasons that affect the spot offset of the detector surface at the receiving end of the retroreflection link, and analyzes the factors that affect the terminal mobility, including the link Distance, lens focal length, lens diameter, etc. Adjusting these parameters will help improve the impact of terminal movement on the received signal. The results obtained from the study have important reference significance for the structural design of indoor two-way visible light communication systems.

2. System model

An equivalent model of the visible light retroreflection link consisting of LED, convex lens, reflective surface, and detector is established, as shown in Figure 1. The light beam radiated by the LED converges to the reflective surface after passing through the modulation lens. The light beam reflected by the reflective surface passes through the modulation end lens, and the receiving end lens, and finally reaches the detector surface. The distance between the two lenses is L, the focal lengths of the receiving end and modulating end lenses are both f, and the vertical distance between the LED and the receiving end lens optical axis is H. If a certain light l_1 in the LED radiation beam reaches the modulating end lens Input point A, the distance between this point and the optical axis of the lens is h, the angle between the light l_1 and the horizontal direction is α, the angle between the light l_1 and the horizontal direction after exiting the modulation end lens is σ. Then the outgoing light after reflection by the reflecting surface is the angle between the horizontal direction is β, and the longitudinal offset of the light spot formed by the reflected light l_2 after passing through the receiving end lens and reaching the detector is d.

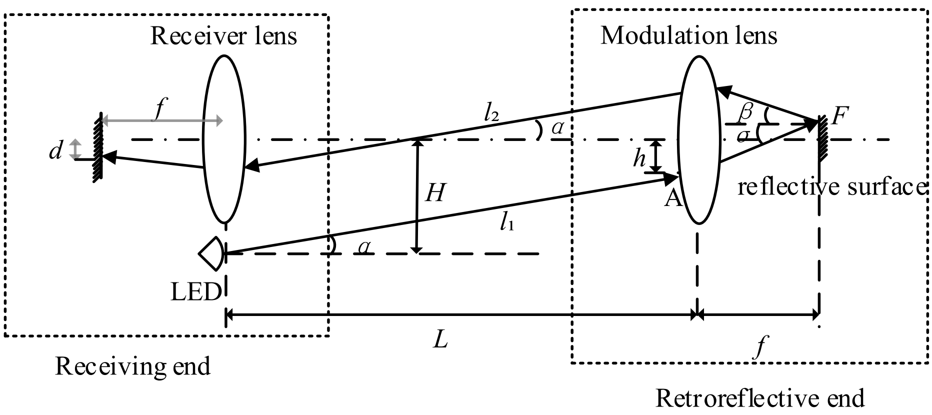

Figure 1. Uplink system model.

3. Retroreflective end mobility analysis

In a single-light source reverse visible light communication system, the optical power at the receiving end of the reflection link changes as the position of the retroreflective end changes, which will affect the optical power intensity at the receiving end, thereby affecting the efficiency of signal reception.

3.1. Lenses at both ends are coaxial

In the ideal optical system of the retroreflective link shown in Figure 1, the receiving end lens and the modulating end lens are coaxial, and the reflecting surface is at the focal plane of the convex lens. According to the thin lens theory, after parallel light passes through the optical system, it must intersect at a certain point on the focal plane of the image side. l_1 and l_2 are regarded as a group of rays entering the modulation lens and intersecting at point F on the focal plane. When, according to the law of reflection and the principle of the reversible optical path, the angle between l_1 and the optical axis is α, and the longitudinal offset is

$$d = f \times \tan\alpha \tag{1}$$

The offset of the light spot that reaches the detection surface after passing through the reverse modulation end will increase with the increase of α and f. According to the geometric relationship in the figure, we can know

$$\tan\alpha = \frac{H \pm h}{L} \tag{2}$$

Among them, ± depends on the location of the light incident point. When the light incident point is above the optical axis of the reverse end lens, + is taken, otherwise - is taken.

Substituting formula (2) into formula (1), we can get

$$d = \frac{H \pm h}{L} \times f \tag{3}$$

When other conditions remain unchanged, the spot offset distance d decreases with the increase of the link distance L and the distance h between the light incident point and the optical axis of the receiving end lens. As the distance H between the LED and the optical axis of the receiving end lens increases, the focal length increases.

By analyzing the characteristics of light transmission when coaxial, the angle of the reflected light cannot exceed the upper edge of the modulating lens. The light passing through the modulating lens must be able to reach the receiving lens, so the following two conditions need to be met

$$\begin{cases} 2f\tan\alpha < H - \dfrac{D}{2} \\ (\tan\alpha + \tan\beta) f \le \dfrac{D}{2} \end{cases} \tag{4}$$

In

$$\tan\beta = \tan\alpha + \frac{h}{f} \tag{5}$$

Through formula (4), we can get

$$\arctan\left(\frac{2H - D}{2(L-2f)}\right) \le \alpha \le \arctan\left(\frac{2H + D}{4(L-f)}\right) \tag{6}$$

According to the calculation formula of the luminous flux of the Lambertian light source, the effective luminous flux Φ reaching the retroreflective end lens can be obtained as

$$\Phi = \int_0^{2\pi} d\varphi \int_{\alpha_{\min}}^{\alpha_{\max}} I_0 \sin\alpha\cos\alpha d\alpha \tag{7}$$

Considering that the Lambertian light source has isotropic uniformity and its luminous intensity is I_0, we can get

$$\Phi = \pi I_0 (\sin^2\alpha_{\max} - \sin^2\alpha_{\min}) \tag{8}$$

Assuming that the reflection coefficient of the reflecting surface is m, and the transmittances of the retroreflective end lens and the receiving end lens are both τ, then the luminous flux Φ' that can reach the receiving end lens is

$$\Phi' = m\tau\Phi \tag{9}$$

3.2. The lenses at both ends are non-coaxial

3.2.1. When the optical axis of the modulation end lens moves upward

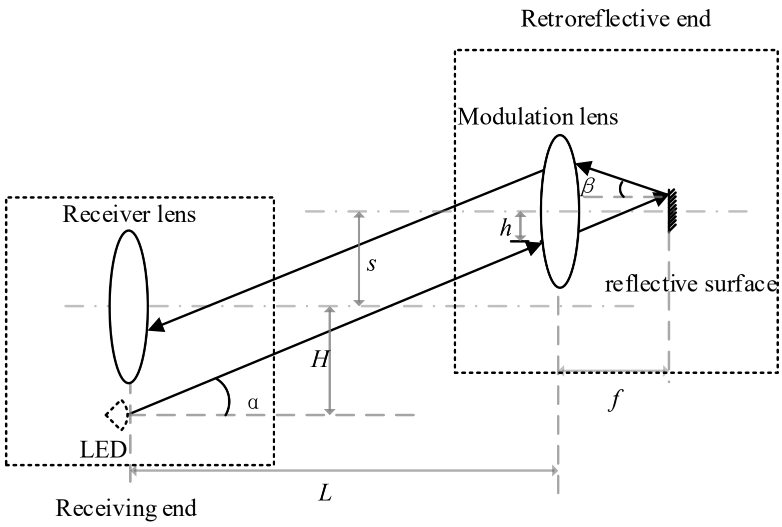

Figure 2. Schematic diagram of the upward movement of the retroreflective end.

It can be obtained from Figure 2

$$\tan\alpha = \frac{H+s-h}{L} \tag{10}$$

According to the principle of optical path transmission, the value range of α is

$$\frac{2H+4s\text{-}D}{4(L-f)} \le \tan\alpha \le \frac{2H+4s+D}{4(L-f)} \tag{11}$$

And

$$\tan\alpha \ge \frac{2H+2s-D}{2(L-2f)} \tag{12}$$

By combining formulas (11) and (12), we can get

$$\frac{2H+2s-D}{2(L-2f)} \le \tan\alpha \le \frac{2H+4s+D}{4(L-f)} \tag{13}$$

By substituting the value range of α obtained from formula (13) into formula (8), the optical power intensity value of the receiving end when the retroreflective end moves upward by a distance s can be obtained. When the equal sign in the above equation is established, that is

$$\frac{2H+2s-D}{2(L-2f)} = \frac{2H+4s+D}{4(L-f)} \tag{14}$$

From this, it can be obtained that the maximum range in the retroreflective end can move upward is

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$$s = \frac{3DL}{4f} - \frac{HL}{2f} - D \tag{15}$$

It can be seen from formula (15) that the upward movable distance of the retroreflection end is related to the lens diameter *D*, the distance *H* between the light source and the receiving end lens optical axis, the lens focal length *f*, and the link distance *L*.

3.2.2. Modulation end lens moves down

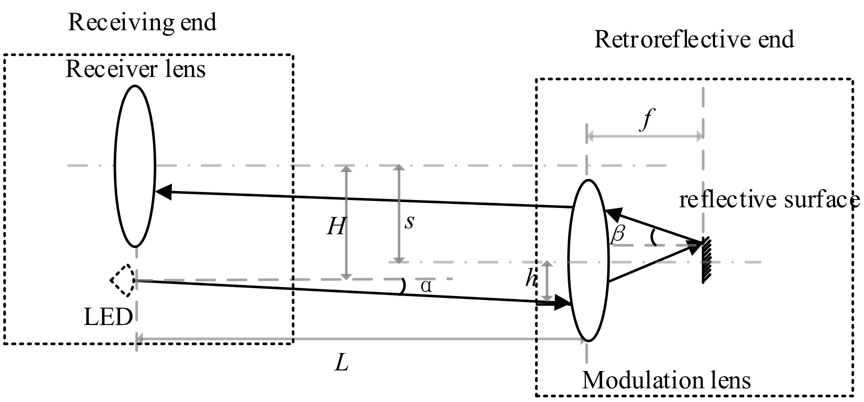

Figure 3. Schematic diagram of the retroreflective end moving downwards.

Figure 3 shows the situation when the retroreflective end moves downward along the vertical direction of the optical axis. It can be seen that

$$\tan\alpha = \frac{H - s - h}{L} \tag{16}$$

When $\tan\alpha \geq 0$

$$\tan\alpha \geq \frac{2H - D - 2s}{2(L - 2f)} \tag{17}$$

$$\frac{2H - D - 4s}{4(L - f)} \leq \tan\alpha \leq \frac{2H + D - 4s}{4(L - f)} \tag{18}$$

By combining formulas (17) and (18), we can get

$$\frac{2H - D - 2s}{2(L - 2f)} \leq \tan\alpha \leq \frac{2H + D - 4s}{4(L - f)} \tag{19}$$

because $L - f > 0$, when $2H + D - 4s \geq 0$, so $H - \frac{D}{2} \leq s \leq \frac{H}{2} + \frac{D}{4}$, Formula (19) becomes

$$\frac{2H - 2s - D}{2L} \leq \tan\alpha \leq \frac{2H + D - 4s}{4(L - f)} \tag{20}$$

If $\tan\alpha \leq 0$, then $s > \frac{H}{2} + \frac{D}{4}$

$$\tan\alpha \geq \frac{2H - 2s - D}{2L} \tag{21}$$

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And

$$\frac{2H-D-4s}{4(L-f)} \le \tan\alpha \le \frac{2H+D-4s}{4(L-f)} \tag{22}$$

By combining formulas (21) and (22), we can get

$$\frac{2H-2s-D}{2L} \le \tan\alpha \le \frac{2H+D-4s}{4(L-f)} \tag{23}$$

Substituting the result obtained from formula (23) into formula (8), the optical power intensity value of the receiving end when the retroreflection end moves downward by a distance s will be obtained. When the equal sign is established, that is

$$\frac{2H-2s-D}{2L} = \frac{2H+D-4s}{4(L-f)} \tag{24}$$

(1)

The maximum distance that the reverse end moves downward can be obtained

$$s = \frac{3LD}{4f} - \frac{LH}{2f} + H - \frac{D}{2} \tag{25}$$

(2)

Combining formula (15) and formula (25), the maximum movable distance of the retroreflective end can be determined from the link distance *L*, lens focal length *f*, lens diameter *D*, and the distance *H* between the light source and the optical axis of the receiving end lens.

4. Numerical analysis

To analyze the mobile performance of the reverse modulation end of the single-light source bidirectional visible light communication system and analyze the factors affecting the mobile performance of the retroreflective end, assume that the distance *H* between the LED light source and the receiving end lens is 100mm, and the light source luminous power P is 1W.

4.1. Retroreflective end movable range

Figure 4 shows the variation curve of the maximum moving distance of the retroreflective end with the link distance when the lens focal length is $f = 150mm$. It can be seen from the figure that under the same lens aperture parameters, there is a linear relationship between the maximum moving distance of the retroreflective end and the link distance. That is, the greater the link distance, the maximum movable distance of the retroreflective end also increases. The lens diameter also affects the maximum moving distance of the retroreflection end. The larger the lens diameter, the greater the slope of the change curve, indicating that the lens diameter has a greater impact on it.

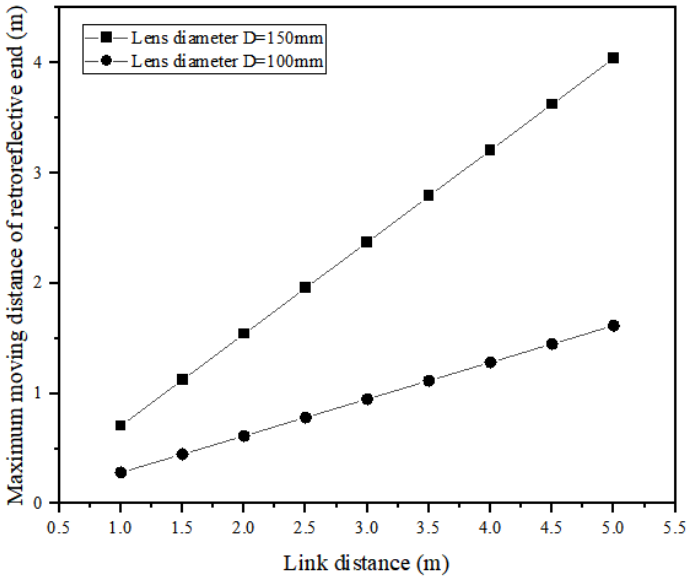

Figure 4. Variation curve of the maximum moving distance of the retroreflective end with the link distance *L*.

When the lens diameter is, the maximum moving distance of the retroreflection end changes with the link distance L, as shown in Figure 5. Under the same lens focal length, there is a linear relationship between the maximum moving distance of the retroreflective end and the link distance. That is, the greater the link distance, the greater the maximum distance the retroreflective end can move. The focal length of the lens also affects the maximum moving distance of the retroreflective end. The smaller the focal length of the lens, the greater the slope of the change curve, which means that the focal length of the lens has a greater impact on it.

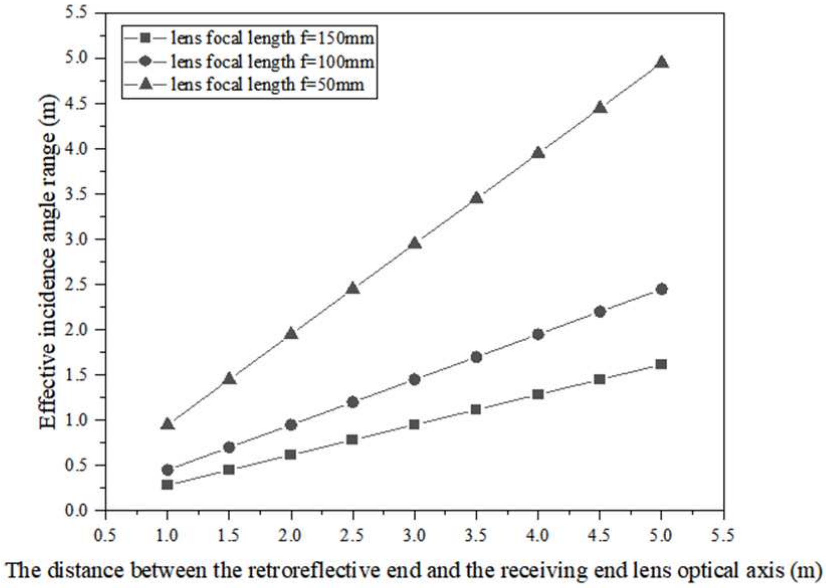

Figure 5. The variation curve of the maximum moving distance of the retroreflective end with the link distance *L* under different lens focal lengths *f*.

4.2. Effective angle of incidence

Under the conditions of lens focal length and lens diameter, the minimum incident angle and maximum incident angle of the light that can be received change as the retroreflective end moves, as shown in Figure 6. As the retroreflective end and the receiving end lens center light the greater the distance between the axes, the greater the launch angle that can reach the receiving end, and the

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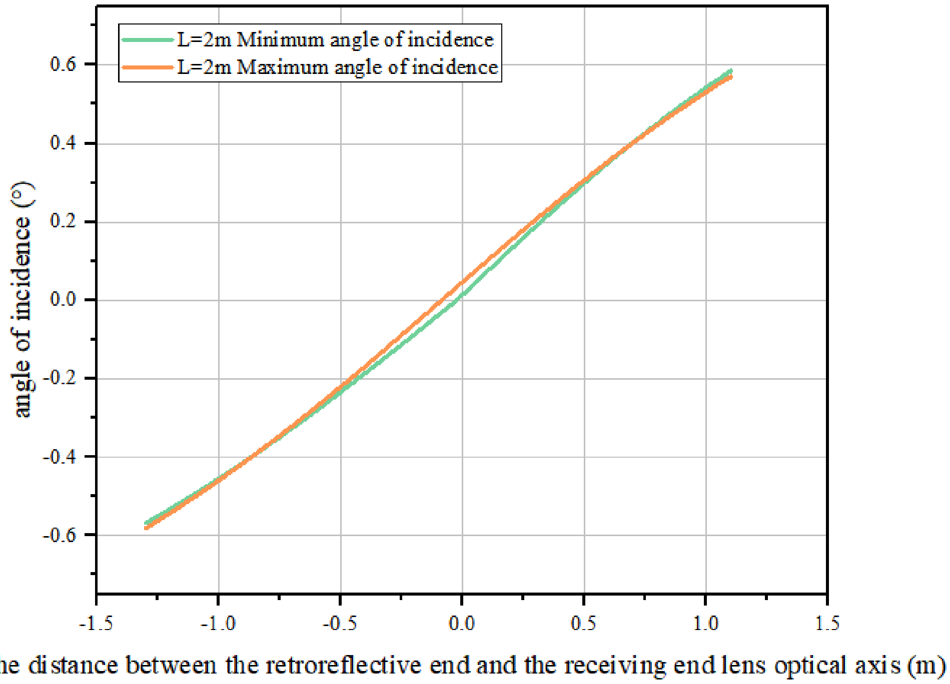
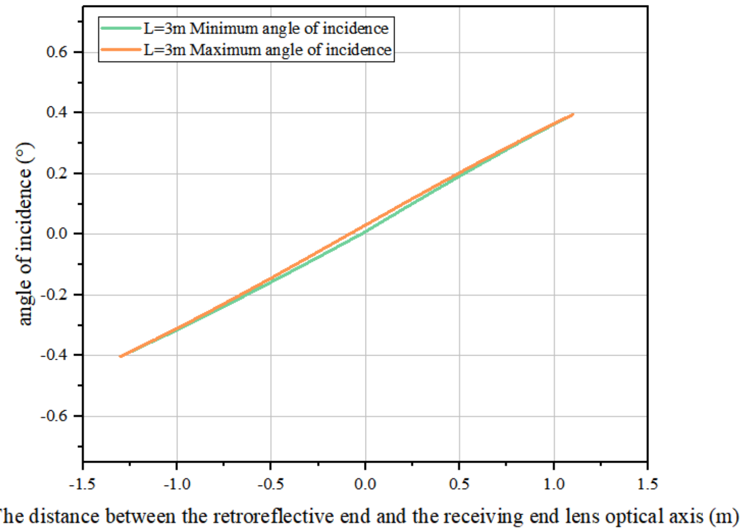
smaller the difference between the maximum incident angle and the minimum incident angle. As the link distance increases, the impact of the incident angle as the retroreflective end moves becomes smaller, the difference between the maximum incident angle and the minimum incident angle becomes smaller, and the movement range of the retroreflective end increases. Increasing the incident angle will lead to an increase in the offset of the light spot reaching the detector, so the larger the link distance, the smaller the requirement for the detector area. Therefore, appropriately increasing the link distance will help increase the movement range of the retroreflective end.



(**a**) $L = 2m$



(**b**) $L = 3m$

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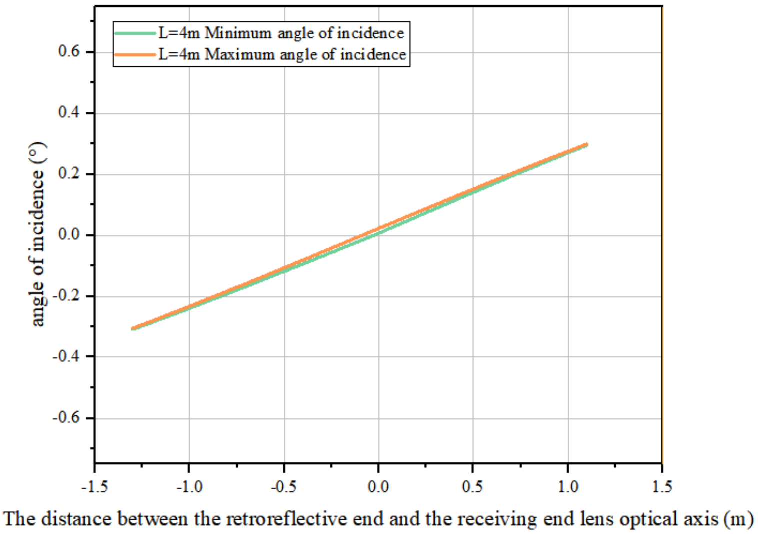

(c) $L = 4m$

Figure 6. Under different link distances L, the change curve of the effective incident angle as the retroreflection end moves.

Figure 7 is a graph showing the change of the effective incident angle range with the position of the retroreflection end under the conditions of link distance and lens focal length with different lens apertures. It can be seen from the figure that when the lens diameter is the same, the effective incident angle range will become smaller as the retroreflective end moves away from the central optical axis of the receiving lens. When the retroreflective end lens and the receiving end lens are coaxial, the effective incident angle range is the largest. For different lens diameters, the effective incident angle range changes with a similar trend as the retroreflection end changes. However, the larger the lens diameter, the greater the maximum value of the effective incident angle range.

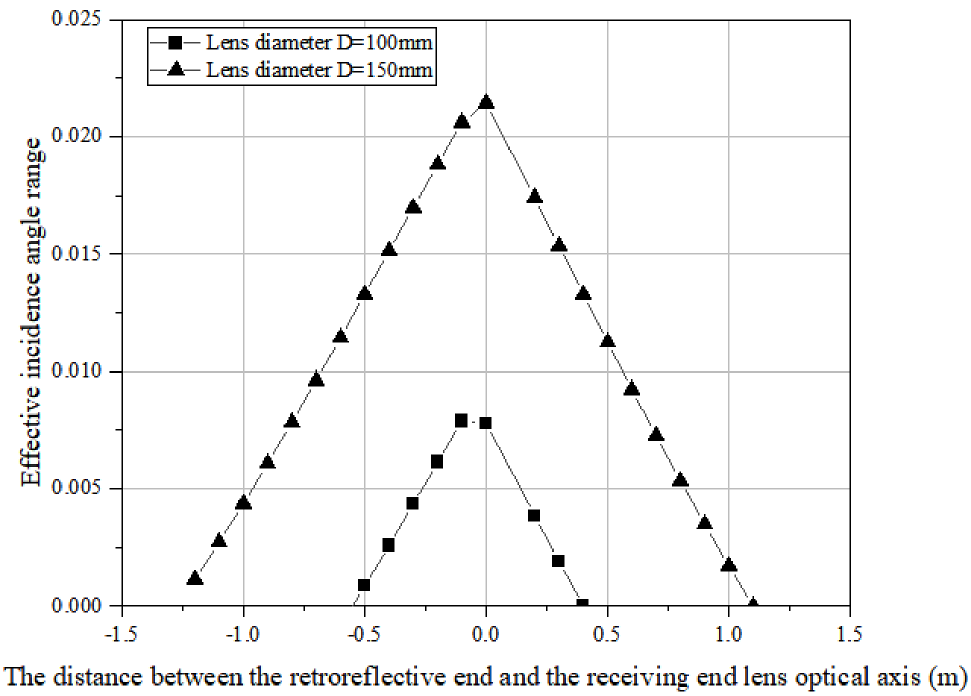

Figure 7. Variation curve of the effective incident angle range with the movement of the retroreflection end for different lens diameters.

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Figure 8 is a graph showing the change of the effective incident angle range with the position of the retroreflection end under the conditions of link distance and lens focal length $D = 150mm$, at different lens focal lengths. It can be seen that when the focal length of the lenses is the same when the retroreflective end lens is closer to the central axis of the receiving end lens, the effective incident angle range is the largest. For different lens focal lengths, the larger the lens focal length, the more obvious the change in the position of the retroreflection end in the effective reflection angle range. In practice, if the change in the effective reflection angle range can be reduced as much as possible within a large moving range, it will be beneficial to the receiving end in identifying the received signal. Therefore, a lens with a large aperture and a small focal length should be selected as a focus for visible light communication as much as possible.

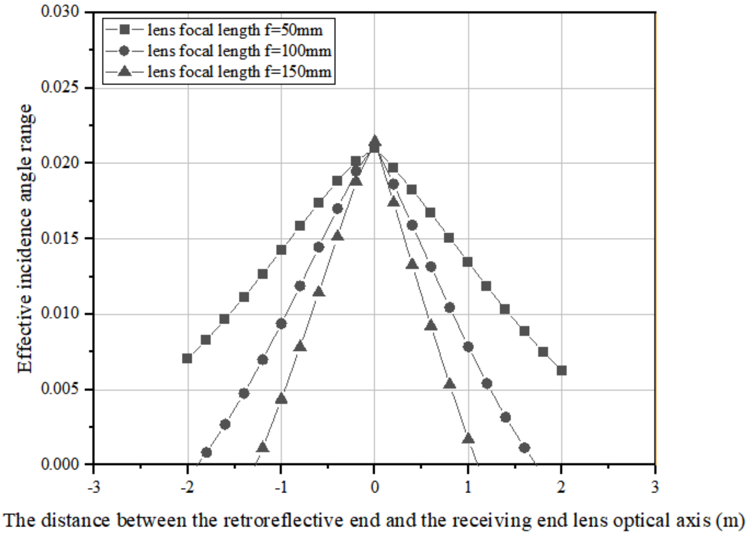

Figure 8. The effective incident angle range changes with the position of the retroreflection end when the lens focal length *f* is different.

5. Zemax simulation analysis

To further explore the factors affecting the visible light communication uplink, Zemax simulation software was used to verify the above results. The initial conditions set are shown in Table 1

Table 1. Simulation initial conditions.

parameter	numerical value
LED luminous power	1W
LED divergence angle	60°
link distance	3m
Distance between LED and receiver lens	180mm
lens material	BK7
Lens diameter	150mm
lens focal length	150mm

The data fitting curve of the maximum moving range of the retroreflection end as a function of the link distance L is shown in Figure 9. Under the same conditions as the simulation, the obtained results are consistent with the curve trend obtained by numerical calculation, that is, as the link distance increases, the maximum moving distance of the retroreflective end also increases. Since the simulation environment is close to the actual optical path of the lens, the maximum moving distance of the retroreflective end obtained through simulation shows a certain degree of nonlinearity.

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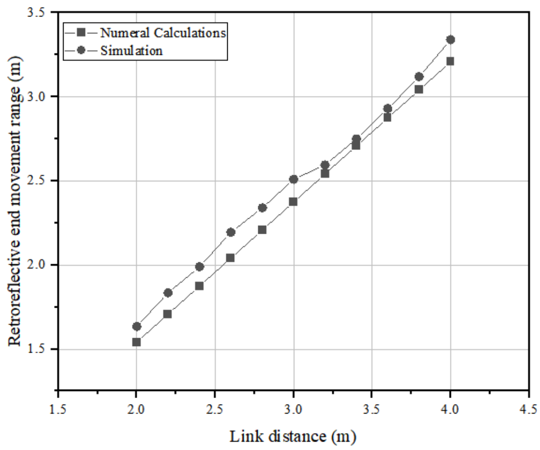

Figure 9. The curve of the movement range of the retroreflector as a function of link distance.

Figure 10 shows the fitting curve of the maximum movable range of the retroreflective end as a function of the link distance at different lens apertures when other initial simulation conditions remain unchanged. Comparing Figure 4, we can see that there is a peak in the maximum moving range of the retroreflective end of the curve obtained by simulation, but the numerically calculated curve does not have this feature. This is because after the number of light rays set in the simulation reaches a certain distance, the light is too sparse, resulting in the reflection back. Less light is undetectable, so the maximum range of movement of the retroreflective end becomes smaller as the link distance increases. Before the peak, the simulated fitting curve has the same trend as the curve obtained by numerical calculation, which further verifies the accuracy of the numerical calculation method.

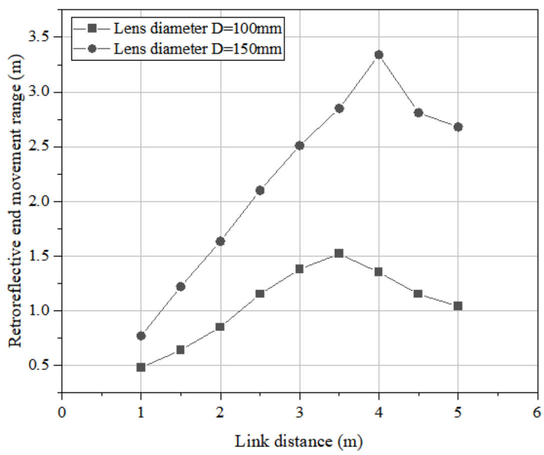

Figure 10. Simulation fitting curve of the maximum movable range of the retroreflective end changing with the link distance L for different lens diameters.

6. Conclusion

This paper establishes a "cat's eye" equivalent model and uses geometric optics methods to derive the calculation method of the minimum incident angle and the maximum incident angle of the light that can reach the receiving end when the two lenses at the transmitting and receiving ends are coaxial and non-coaxial respectively; in the chain When the path distance, lens diameter, lens focal length and light source position are determined, the maximum movable range of the retroreflective end is theoretically analyzed and simulated and verified. Through research and analysis, it can be seen that increasing the lens diameter, reducing the lens focal length, and increasing the link distance will help the retroreflective end increase the movement range, and will help maintain the stability of the incident light angle range, thereby stabilizing the power reception of the receiving end. The results have reference significance for the design and layout of visible light communication systems in different environments.

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Informed Consent Statement: The study did not require ethical approval.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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