Optimizing the light source layout of the indoor visible light communication system

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ABSTRACT Aiming at the problem of uneven illuminance distribution in traditional indoor optical communication systems, this paper proposes a square + ellipse layout, using simulated annealing particle swarm algorithm to optimize the spacing of LED light sources, and optimize the uniformity of system illuminance and signal-to-noise ratio. The simulation results show that the optimized square + ellipse layout illumination ranges from 359.25 lx to 451.05 lx, and the mean square error reaches 12.66 lx. Signal noise ratio is between 18.54 dB and 20.75 dB, and the mean square error is 0.39 dB. Compared with the traditional square and elliptical layout, the illumination performance and communication performance are improved clearly, which provides a new reference scheme for indoor light source layout.

INDEX TERMS Visible Light Communication System, Illuminance, Signal-to-noise ratio, Light source layout

I. INTRODUCTION

SINGLE With the rapid development of information technology in recent years, the demand for wireless communication is gradually increasing. As a new communication method, visible light communication technology has gradually replaced the traditional wireless communication technology, visible light communication technology has gradually replaced traditional wireless communication technology [1], [2]. Compared with traditional radio frequency communication technology, visible light communication technology has the characteristics of high modulation bandwidth, strong confidentiality, and high signal-to-noise ratio. In order to realize the application of indoor visible light communication [3]–[5]. In order to realize the application of indoor visible light communication, it is necessary to arrange the light source. Reasonable light source layout can maximize the performance of the communication system [6].

Due to the huge development prospects of visible light communication technology, it has become one of the current research hotspots. Komine [7] et al obtained the illuminance distribution and signal-to-noise ratio distribution of the traditional square layout by simulating a $5 \times 5 \times 3$ room, and discussed the effects of inter-symbol interference and reflection. Zhao Li [8] et al. proposed a $4 + 1$ layout based on the traditional layout, and optimized the original layout while considering the uniformity of illumination and communication performance at the same time. Liu Hong [9] et al. optimized the square layout using multiple population genetic algorithms, and the experimental results showed that the optimized layout power distribution is more even. Zhao Li [10] et al. proposed an LED array with light strips, by searching for the optimal spacing between the light strips and the optimal spacing of the LED array, to achieve the optimization of the light source layout.

At present, most of the research focuses on finding the optimal distance between LEDs. Few people optimize the layout of light sources by controlling the number of LEDs. This paper proposes a square + ellipse layout method through adaptive simulated annealing particles. The group algorithm seeks the optimal distance between LEDs, and at the same time finds the optimal number of LEDs in the elliptical layout, so as to optimize indoor lighting performance and communication performance while reducing system power consumption.

II. INDOOR VISIBLE LIGHT COMMUNICATION SYSTEM MODEL

Constructing a $6 \times 5 \times 3$ rectangular room model as shown in Figure 1, the receiving plane is 2.15 m away from the roof. The coordinate system is established with the center...
of the bottom of the rectangle as the origin. The x-axis and y-axis are parallel to the two bottom edges of the room respectively, and the z-axis is perpendicular to the ground. The light source is placed at the top of the room.

Indoor optical communication links are divided into line-of-sight links (LOS) and non-line-of-sight links (NLOS). Studies show that in the receiving plane, direct received power accounts for 93.03% of the total received power, and reflected light for the first time accounts for 5.53% of the total received power. The proportion of two or more reflections in the total received power is very small, so this paper only studies the impulse response of direct and the first time reflection.

The light source is transmitted to the receiving plane through the channel, and the DC gain of the channel can be expressed as

$$H(0) = \begin{cases} A_{rx} R_0(\theta) \cos(\psi) T_s(\psi) g_s(\psi), & 0 < \psi < \psi_c \\ 0, & \psi > \psi_c \end{cases}$$

$$P_t = \sum_{i=0}^{n} P_{ti} H_i(0)$$

III. LIGHT SOURCE LAYOUT AND OPTIMIZATION

A. ALGORITHM OPTIMIZATION

The advantage of the PSO algorithm lies in its fast convergence speed and simple algorithm [11]. However, PSO algorithm also has the problem of weak search ability and easy to fall into local optimal solution. In order to solve this problem [12]–[14], this paper improves the algorithm from two aspects.
1) The improvement of inertia factor and learning factor

(1) Inertia factor

The inertia factor affects the global search ability and local search ability of the algorithm. As the iteration progresses, the particles need stronger local search ability, so the inertia factor should be gradually reduced. This article proposes an improved method for the inertia factor as

\[ w(k) = w_{\text{max}} - w_{\text{min}} \frac{k}{T_{\text{max}}} \]  

In the above formula, \( w(k) \) is the improved inertia factor, \( w_{\text{max}} \) is the maximum inertia factor, \( w_{\text{min}} \) is the minimum inertia factor, \( k \) is the current iteration number, \( T_{\text{max}} \) is the maximum iteration number. \( w_{\text{max}} \) and \( w_{\text{min}} \) take values 0.4 and 0.9 respectively, and \( T_{\text{max}} \) takes value 200.

(2) Learning factor

The learning factor, \( c_1 \) and \( c_2 \), represents the individual learning ability and the group learning ability of the particle, as the iteration progresses, the particles need to gradually enhance the group learning ability and reduce the individual learning ability. On this basis, this article improves the learning factor.

\[ c_1(k) = c_1 - c_1 \frac{k}{T_{\text{max}}} \]  
\[ c_2(k) = c_2 + c_2 \frac{k}{T_{\text{max}}} \]

In the above formula, \( c_1(k) \) and \( c_2(k) \) represent the improved individual learning factor and group learning factor respectively. \( c_1 \) and \( c_2 \) take values 0.4 and 0.9 respectively, are the value of the learning factor at the beginning of the algorithm iteration.

2) simulated annealing algorithm

This paper incorporates the annealing process in the simulated annealing algorithm into the particle swarm algorithm. When the initial temperature of the algorithm is high, simulated annealing particle swarm optimization makes population examples have larger probability to accept the optimal solution, so as to jump out of local optimal solution [15]. Specific algorithm process is shown in the Figure 3.

B. LIGHT SOURCE LAYOUT OPTIMIZATION

The traditional square layout and elliptical layout are shown in the follow figures and all light sources are distributed on the roof with a height of 3 meters. The square layout in Figure 4(a) consists of four \( 9 \times 9 \) LED arrays, where \( x_1 \) is the distance between the edge of the LED array and the x-axis, \( y_1 \) is the distance between the edge of the LED array and the y-axis, \( d \) is the distance between the LEDs in the array. The elliptical layout in Figure 4(b) consists of 324 LED arrays evenly distributed on the ellipse, where \( x_2 \) is the length of the long axis of the ellipse and \( y_2 \) is the length of the short axis of the ellipse.

Use the algorithm mentioned above to optimize the square \( x_1, x_2, d \) and the ellipse \( x_2, y_2 \), and change the indoor light source layout by changing the overall shape of the square and ellipse, thereby optimizing the indoor illumination distribution.
Figure 5 shows the illuminance for square and elliptical layouts picture. It can be seen from the figure that the mean square deviation of the illuminance of the square layout is 31.32 lx, and the uniformity is 77.70%. The mean square deviation of the illuminance of the elliptical layout is 35.46 lx, and the uniformity is 75.21%.

As can be seen from Figure 5 although the traditional square layout and elliptical layout can meet the basic requirements of indoor communication and identification, there are still problems such as uneven illumination. In order to solve these problems, this paper proposes a square + ellipse layout.

In the Figure 6, $x_1, x_2, y_1, y_2$ and $d$ are the targets to be optimized. In order to ensure the uniformity of the system's illuminance and the reliability of communication, this paper chooses the combination of the mean square error of illuminance and the mean value of the signal-to-noise ratio $f(x_1, x_2, y_1, y_2, d)$ as the optimal function. The function can be expressed as

$$f(x_1, x_2, y_1, y_2, d) = f_1 + \alpha \frac{1}{f_2}$$  (10)

Where $f_1$ is the mean square error of illuminance, and $f_2$ is the mean value of the signal-to-noise ratio of the receiving plane. The value of $\alpha$ in this article is 10.

In order to study the influence of the number of LEDs in the ellipse on the performance of the system, this paper studies the illuminance and signal-to-noise ratio of the system when $N$ is equal to 60-120.

| $N$  | Maximum /lx | Minimum /lx | Average /lx | Mean square error /lx |
|------|-------------|-------------|-------------|-----------------------|
| 60   | 411.85      | 315.24      | 379.36      | 14.19                 |
| 70   | 425.02      | 360.34      | 393.53      | 13.43                 |
| 80   | 438.03      | 344.20      | 407.85      | 12.88                 |
| 90   | 451.05      | 359.25      | 421.95      | 12.66                 |
| 100  | 465.42      | 374.26      | 436.10      | 12.78                 |
| 110  | 480.27      | 388.38      | 450.55      | 12.85                 |
| 120  | 494.92      | 402.63      | 464.90      | 12.99                 |

According to the data in Table 1 and Table 2, it can be indicated that as the number of LEDs in the ellipse increases, the
### TABLE 2. SNR parameters when N takes different values

| N      | Maximum /dB | Minimum /dB | Average /dB | Mean square error /dB |
|--------|-------------|-------------|-------------|----------------------|
| N = 60 | 19.97       | 17.32       | 18.92       | 0.47                 |
| N = 70 | 20.23       | 17.76       | 19.24       | 0.43                 |
| N = 80 | 20.49       | 18.14       | 19.55       | 0.40                 |
| N = 90 | 20.75       | 18.54       | 19.84       | 0.39                 |
| N = 100| 21.02       | 18.92       | 20.13       | 0.39                 |
| N = 110| 21.30       | 19.25       | 20.41       | 0.37                 |
| N = 120| 21.56       | 19.58       | 20.68       | 0.37                 |

maximum, minimum, average and mean square deviation of the system’s illuminance and signal-to-noise ratio gradually increase.

![Graph](image)

**FIGURE 7.** The relationship between the number of N and the objective function.

Figure 7 illustrates the relationship between the number of N and the objective function in the elliptical layout. It can be seen from the figure that as the number of LEDs in the elliptical layout increases, the value of the objective function first gradually decreases and then gradually grows until the objective function reaches its minimum value when N takes 90. So the value of N in this article is considered to be 90.

### IV. SIMULATION EXPERIMENT AND DATA ANALYSIS

The light source luminescence mode used in this article is Lambertian luminescence mode, and the specific simulation parameters are listed in Table 3.

### TABLE 3. Simulation experiment parameters

| Parameter                        | Value                       |
|----------------------------------|-----------------------------|
| Room size                        | 6 m × 5 m × 3 m             |
| Single led bulb power            | 2.0 w                       |
| Center luminous intensity        | 21.5 cd                     |
| Photodiode responsivity          | 0.53 A/W                    |
| Field of view at receiver        | 70°                         |
| Refractive index of concentrator n| 2                           |
| Half power angle                 | 70°                         |
| Gain of an optical filter        | 1.0                         |
| Background noise current         | 0.62 mA                     |
| Equivalent noise bandwidth       | 200 MHZ                     |
| Load resistance                  | 10KΩ                        |
| Reflectivity of walls            | 0.8                         |
| Detector physical area of a photodiode A | 1 cm²                     |

A. LIGHTING PERFORMANCE ANALYSIS

Figure 8 shows the overall illuminance image of the optimized square, elliptical, and square + ellipse layouts. It is apparent that the maximum illuminance of the square layout is 548.03 lx, the minimum is 375.86 lx, the mean square error is 31.32 lx, and the uniformity is 77.70 %. The maximum illuminance of the elliptical layout is 531.83 lx, the minimum
is 361.05 lx, the mean square error is 35.46 lx, and the uniformity is 75.21%. The maximum illuminance of the square + ellipse layout is 451.05 lx, the minimum is 359.25 lx, the mean square error is 12.66 lx, and the uniformity is 85.14%.

In order to verify the authenticity of the Matlab simulation results, this paper uses the Dialux software to analyze the above three light source layout methods to obtain the real distribution of room illumination.

Figure 9 shows the iso-illuminance diagram of the receiving plane 0.75 m away from the ground under the three light source layouts. It can be seen from the figure that the illuminance of the receiving plane is basically the same as the simulation result of Matlab.

The above-mentioned experimental data shows that the illuminance range of whether it is square, elliptical or square + ellipse layout ranges from 300 lx to 1500 lx [16], meeting the internationally regulated indoor lighting standards. But compared with the traditional square and elliptical layout, the layout model proposed in this paper reduces the dynamic range of illuminance and improves the uniformity of illuminance.

**B. COMMUNICATION PERFORMANCE ANALYSIS**

Figure 10(a) is a traditional square layout receiving plane signal-to-noise ratio distribution. The signal-to-noise ratio ranges from 18.64 dB to 22.59 dB, and the mean square error is 0.80 dB. Figure 10(b) is the traditional elliptical layout receiving plane SNR distribution. The SNR ranges from 18.04 dB to 22.23 dB, and the mean square error is 0.93 dB. Figure 10(c) is the square + ellipse layout to receive a planar signal-to-noise ratio distribution image. The signal-to-noise ratio ranges from 18.54 to 20.75 dB, and the mean square error is 0.39 dB.

It can be seen from the above that the new layout proposed...
in this article reduces the number of LEDs by 38, while reducing the fluctuation range of the signal-to-noise ratio, inter-symbol interference, system power consumption, and improving system reliability.

C. ALGORITHM COMPARISON ANALYSIS

Figure 11 is the iterative diagram of the particle swarm algorithm and the adaptive weight simulated annealing particle swarm algorithm proposed in this paper. It is worth noting from the figure that the particle swarm algorithm reduces the fitness value to about 21 after about 10 iterations, but in the subsequent iteration process, it falls into the local optimal solution and cannot get to the global optimal solution. In contrast, the algorithm proposed in this paper finally finds the global optimal solution after multiple iterations. So it is evident that the improved algorithm can meet the requirements and help to obtain the optimal light source layout.

V. CONCLUSIONS

Aiming at the problem of uneven illuminance distribution in visible light communication systems, this paper proposes a square + ellipse layout to build a $6m \times 5m \times 3m$ room model.

In terms of solving the optimal position, this paper uses the PSO algorithm to advance the process. Because the PSO algorithm has the problem of falling into the local optimal solution, the algorithm is improved from two aspects, and the combination of the mean square error of illuminance and the mean value of the signal-to-noise ratio is set as the fitness function. The optimal light source layout is found. The experimental results indicate that the optimized system illumination range is 359.25 - 451.05 lx, and the mean square error reaches 12.66 lx. The signal-to-noise ratio ranges from 18.54 to 20.75 dB, and the mean square error is 0.39 dB. Compared with the traditional square layout and elliptical layout, while reducing 38 LED light sources, the uniformity of illumination and signal-to-noise ratio is optimized, which provides a new reference solution for the layout of indoor light sources.

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