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Pervasive Visible Light Positioning System using White LED Lighting

堀川 修平† 小峯 敏彦† 春山真一郎† 中川 正雄†

† 慶應義塾大学 理工学部 情報工学科 〒223-8522 横浜市港北区日吉 3-14-1
E-mail: †{horikawa,komine,haruyama,nakagawa}@nkgw.ics.keio.ac.jp

あらまし 屋内における高精度な測位を可能とするために，室内 LED 照明の各 LED からの光を利用した測位システムを提案する．光の持つ直進性やレンズを用いて分離することが出来る性質を利用することで，各 LED からの 3 次元空間座標信号を分離することが可能となる．受信側は Photo Diode Array を有した 2 次元センサを考える．この 2 次元センサ上で少なくとも 3 つの LED からの信号を受信しさえすれば所望の位置を算出することが可能となる．誤差として考えられるのは LED の中心と受信したピクセルの中心とが異なることにより発生するものである．しかし，これは十分に 2 次元センサのピクセル分解能を細かく，また 3 ピクセルの選択方法を変えることで室内において高精度な測位が可能となることを確認した．

キーワード 光無線通信, 可視光通信, 白色 LED 照明, 測位

Pervasive Visible Light Positioning System using White LED Lighting

Shuhei HORIKAWA†, Toshihiko KOMINE†, Shinichiro HARUYAMA†, and Masao NAKAGAWA†

† Dept. of Information and Computer Science, Keio University
3-14-1, Hiyoshi, Kohoku, Yokohama, 223-8522 Japan
E-mail: †{horikawa,komine,haruyama,nakagawa}@nkgw.ics.keio.ac.jp

Abstract We propose a new system that carries out positioning in the indoor environment. It can determine the receiver's position where each white LEDs in a lighting send differential three dimensional space coordinate and a two-dimensional sensor, receives the signal. It is possible to separate the signal from each LED using a lens. If it receives at least three lights separated spatially by using a lens, and demodulates each three dimension space coordinate data, it is possible to compute three-dimensional.

Key words wireless optical communications, visible-light communications, white LED light, positioning

1. Introduction

Recently LEDs are being useful for illumination porposes. LED is more advantageous than the existing incandescent in terms of long life expectancy, high tolerance to humidity, low power consumption, and minimal heat generation lighting. LED is used in full color displays, traffic signals, and many other means of illumination. InGaN based highly efficient blue and green LED have become commercially available. By mixing three primary colors (red, green and blue), white color can be produced.

This white LED is considered as a strong candidate for the future lighting technology [1]〜[7]. Compared with conventional lighting methods, white LED has lower power consumption and lower voltage, longer lifetime, smaller size, and cooler operation. The Ministry of International Trade and Industry of Japan estimates that, if LED replaces half of all incandescent and fluorescent lamps currently in use, Japan could save six mid-size power plants, and reduce the production of greenhouse gases. A national program underway in Japan has already suggested that white LED is considered as a general lighting technology of the 21st.

1.1 Optical Communications utilizing White LED Lights

A group including the author has proposed an optical wireless communication system that employs white LEDs for indoors wireless networks [8]〜[10]. In this system, LED is not only used as a lighting device, but also used as a communication device (Fig. 1).

It is a kind of optical wireless communication that uses the "visible" white ray for communication purposes. This dual function of LED, for lighting and communication, cre-

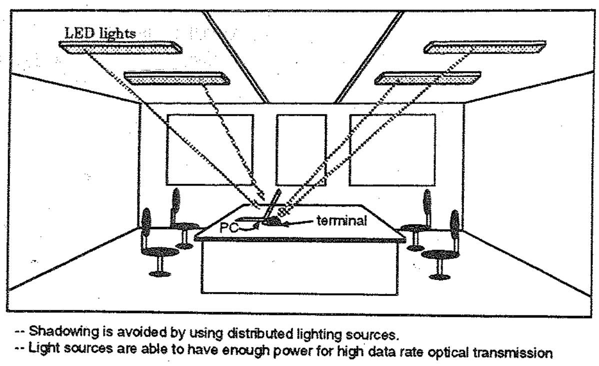

図 1 Wireless optical data transmission system also working as indoor lighting.

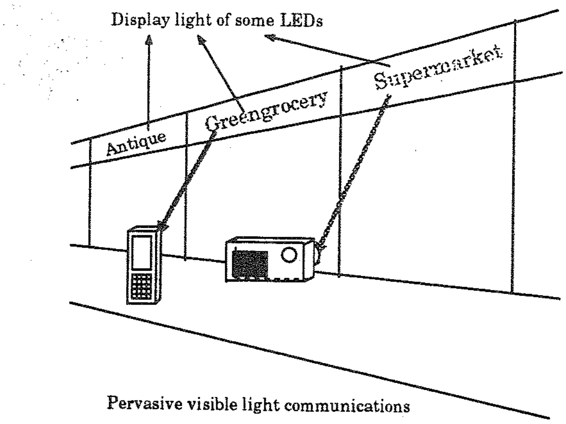

図 2 Pervasive visible light communications.

ates many new and interesting applications. The function is based on the fast switching of LEDs and the modulation of the visible-light waves for free-space communications. The proposed system has following advantages:

- Compared with infrared wireless communication, visible LED light has higher power.
- The shadowing can be minimized, because LED lights are distributed within a room.
- The installation is easy, and LED is aesthetically pleasing.
- They do not cause or suffer from radio or electromagnetic interference.

1.2 Pervasive Visible Light Communications

Pervasive computing is defined that computers or networks support a human life by recognizing our circumstances as follows.

- One's position and recognition information.
- The position and attribute information on substances.
- Space circumstances (light, temperature, humidity and so on)

Besides, "pervasive" means that equipments exist generally like PC, televition, PDC, the display of an electric device and so on. Recently, these visible light elements are using LED. Pervasive visible light communications becomes possible by connecting these devices seamlessly.

There is GPS (Global Positioning System) as a system to measure the position all over the world. This system carries out positioning using at least three satellites which stay over 20,000km. However, positioning errors become large under the influence of multi-path in the indoor environment. On the other hand, the positioning system using laser light is proposed. This system is that one's position is detected by getting two angle information from laser light. However, receiver must have its direction information using Gyroscope or Geomagnetism sensor in advance.

In this paper, we focus on recognizing the position information and propose Visible Light Positioning System. It can simply determine the receiver's position where each white LED in a lighting send different three dimensional space coordinate and a receiver, such as two dimension sensor, receives the signal. And we evaluate the validity.

This paper is organized as follows. In Chapter 2., the author shows basic knowledge for lighting engeering. In Chapter 3., the author proposes a positioning system using white LED lighting. In Chapter 4., the author discusses a positioning error. Conclusions are given in Chapter 5..

2. Lighting Design Based on Lighting Engineering

2.1 Basic Properties of LED Lights

We will explain the basic properties of LED lights. LED lights have two basic properties, a luminous intensity and a transmitted optical power. The relationship between photometric and radiometric quantities is explained in [11]~[14]. Luminous intensity is the unit that indicates the energy flux per a solid angle, and it is related to illuminance at an illuminated surface. At this time, the energy flux is normalized with visibility. The luminous intensity is used for expressing the brightness of an LED. On the other hand, the transmitted optical power indicates the total energy radiated from an LED, which is a parameter from the point of view of optical communication.

The luminous intensity is given as:

$$I = \frac{d\Phi}{d\Omega}, \tag{1}$$

where Φ is the luminous flux, which can be given from the energy flux Φ_e as:

$$\Phi = K_m \int_{380}^{780} V(\lambda)\Phi_e(\lambda)d\lambda, \tag{2}$$

where $V(\lambda)$ is the standard luminosity curve, K_m is the maximum visibility, and the maximum visibility is about 683 lm/W at $\lambda = 555$ nm.

The integral of the energy flux Φ_e in all directions is the transmitted optical power P_t, given as:

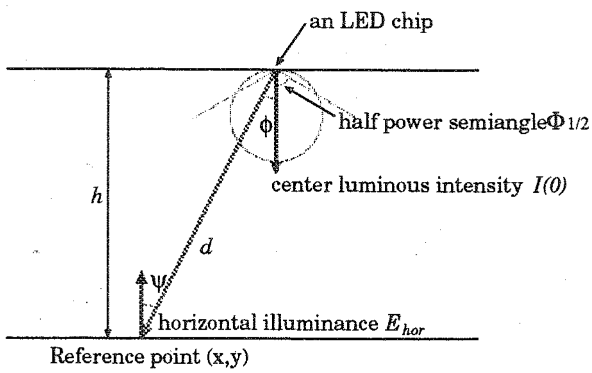

図 3 Calculation for horizontal illuminance.

$$P_t = \int_{\Lambda_{min}}^{\Lambda_{max}} \int_0^{2\pi} \Phi_e d\theta d\lambda, \qquad (3)$$

where Λ_{min} and Λ_{max} are determined by the sensitivity curve of the photodiode.

2.2 Illuminance of LED Lighting

In this subsection, the distribution of illuminance at a desk surface will be discussed. The illuminance expresses the brightness of an illuminated surface. As shown in Fig. 3, the luminous intensity in angle ϕ is given by

$$I(\phi) = I(0)\cos^m(\phi). \qquad (4)$$

A horizontal illuminance E_{hor} at a point (x, y) is given by

$$E_{hor} = I(0)\cos^m(\phi)/d^2 \cdot \cos(\psi), \qquad (5)$$

where $I(0)$ is the center luminous intensity of an LED, ϕ is the angle of irradiance, ψ is the angle of incidence, and d is the distance between an LED and a detector's surface. In this paper, it is assumed that an LED chip has a Lambertian radiation pattern [15]~[17]. Thus, the radiant intensity depends on the angle of irradiance ϕ. m is the order of Lambertian emission, and is given by the semi-angle at half illuminance of an LED $\Phi_{1/2}$ as $m = -\ln 2/\ln(\cos\Phi_{1/2})$. For example, $\Phi_{1/2} = 60.0$ deg. corresponds to $m = 1$.

The consideration for illuminance of LED lighting is required. Generally, illuminance of lights is standardized by International Organization for Standardization (ISO). By this set of standards, illuminance of 200 to 1500 lx in required for office work.

2.3 Design of White LED Lights

We will discuss the design of LED lighting in terms of the illuminance. A typical office room is used as a model room (Fig.4). And, we have a LOS (Line-Of-Sight) link between the receiver and the LED lighting as transmitter. The optical signal is intensity modulated. As a modulation scheme, we employ SC-BPSK and 2-PPM. We use 1071 (21 × 51) LEDs in lighting equipment LEDs are placed 1 cm apart from each other, thus the size of 21 × 51 LEDs is 0.41 m × 1.00 m.

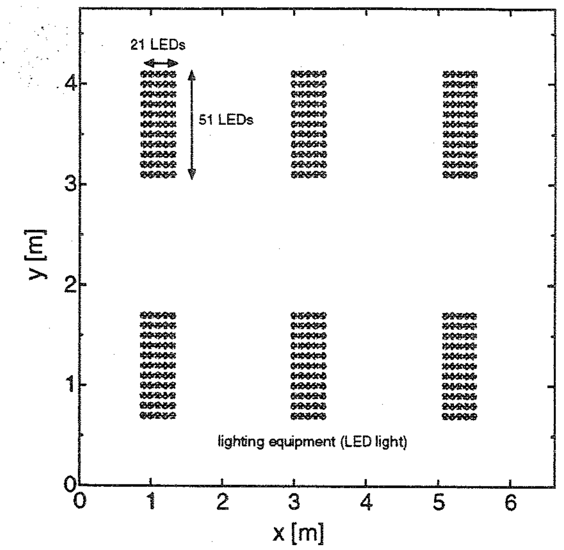

図 4 The room size is 6.64 × 4.75 × 3.0 m^3. LED lights, capable of optical transmission, are installed at a height of 3.0 m from the floor.

表 1 Parameters.

Transmitted power of LED	20 × 10^{-3} [mW]
Semi-angle at half power	70.0 [deg.]
Center luminous intensity	0.73 [cd]
The number of LEDs in a lighting	21 × 51
Installation interval of LEDs	0.01 [m]
The size of lighting equipment	0.40 × 1.00 [m^2]

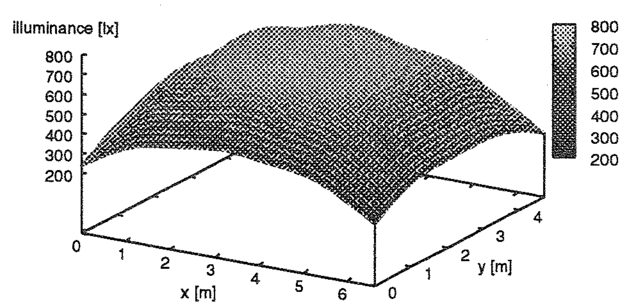

図 5 The distribution of illuminance.

The transmitted power of each LED is 20.0 mW (O/E conversion efficiency 0.53 A/W) and semi-angle at half power is 70 degrees. The simulation parameter is shown in Table 1. The distribution of horizontal illuminance (at height is 1.0 m) is shown in Fig. 5.

Figure 5 shows that the sufficient illumination (200–1500 lx) is obtained in all the places of the room. Therefore, this result shows that this LED lighting can be used as lighting.

3. System Model

3.1 Proposed Model

We assume the lighting or the display which has many light sources as a transmitter. For example, the light source can be high-speed response LED. In Fig.1, at least three LEDs have a different three dimensional space coordinates (x1, y1,

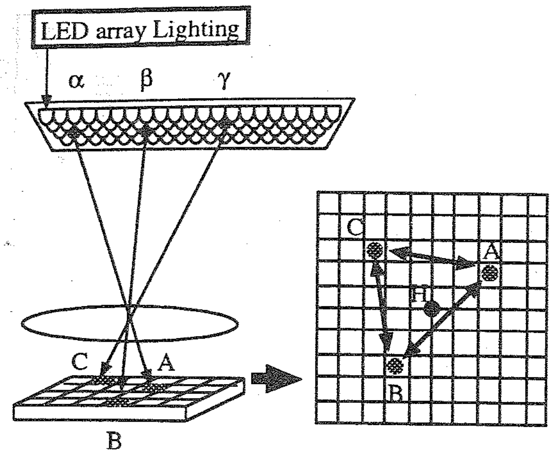

図 6 Proposed positioning system

z1), (x2, y2, z2), (x3, y3, z3), respectively. And it is referred to as α, β, γ, respectively. Each LED sends different three dimensional space coordinate data.

As a receiver, we use the two dimensional sensor. It receives light separated spatially by using a lens, and demodulates each three dimension space coordinate data. In Fig.6, we set pixels separeted spatially by using a lens to A, B, C, respectively. And distance to the center O (x, y, z) of the lens is h, the center above two dimension sensor is H.

The distance between the received pixels on a two dimensional sensor is D_{AB}, D_{BC}, D_{CA}. where the coordinates of A, B, and C are (X1, Y1), (X2, Y2), and (X3, Y3), respectively.

$$D_{AB} = \sqrt{(X1 - X2)^2 + (Y1 - Y2)^2} \tag{6}$$

$$D_{BC} = \sqrt{(X2 - X3)^2 + (Y2 - Y3)^2} \tag{7}$$

$$D_{CA} = \sqrt{(X3 - X1)^2 + (Y3 - Y1)^2} \tag{8}$$

Besides, the distance between the center of lens and the received pixels is D_{OA}, D_{OB}, D_{OC}. respectively.

$$D_{OA} = \sqrt{(X1^2 - Y1^2) + h^2} \tag{9}$$

$$D_{OB} = \sqrt{(X2^2 - Y2^2) + h^2} \tag{10}$$

$$D_{OC} = \sqrt{(X3^2 - Y3^2) + h^2} \tag{11}$$

We can determine $\angle AOB$, $\angle BOC$, and $\angle COA$ as follows from fig.?? and (6) - (11).

$$\cos\angle AOB = \frac{D_{BC}^2 + D_{CA}^2 - D_{AB}^2}{2D_{BC}D_{CA}} \tag{12}$$

$$\cos\angle BOC = \frac{D_{AB}^2 + D_{CA}^2 - D_{BC}^2}{2D_{AB}D_{CA}} \tag{13}$$

$$\cos\angle COA = \frac{D_{AB}^2 + D_{BC}^2 - D_{CA}^2}{2D_{AB}D_{BC}} \tag{14}$$

In the same way, the distance between the transmitted LEDs is $d_{\alpha\beta}$, $d_{\beta\gamma}$, $d_{\gamma\alpha}$. respectively.

$$d_{\alpha\beta} = \sqrt{(x1 - x2)^2 + (y1 - y2)^2 + (z1 - z2)^2} \tag{15}$$

$$d_{\beta\gamma} = \sqrt{(x2 - x3)^2 + (y2 - y3)^2 + (z2 - z3)^2} \tag{16}$$

$$d_{\gamma\alpha} = \sqrt{(x3 - x1)^2 + (y3 - y1)^2 + (z3 - z1)^2} \tag{17}$$

As shown in Fig.6, the following values can be known.

$$\cos\angle\alpha O\beta = \cos\angle AOB \tag{18}$$

$$\cos\angle\beta O\gamma = \cos\angle BOC \tag{19}$$

$$\cos\angle\gamma O\alpha = \cos\angle COA \tag{20}$$

In equations (18), (19), and (20), the distance between the center of lens and the transmitted LEDs is $d_{O\alpha}$, $d_{O\beta}$, $d_{O\gamma}$. respectively.

$$d_{O\alpha}^2 = d_{\alpha\beta}^2 - d_{O\beta}^2 + 2d_{O\alpha}\cdot d_{O\beta}\cos\angle\alpha O\beta \tag{21}$$

$$d_{O\beta}^2 = d_{\beta\gamma}^2 - d_{O\gamma}^2 + 2d_{O\beta}\cdot d_{O\gamma}\cos\angle\beta O\gamma \tag{22}$$

$$d_{O\gamma}^2 = d_{\gamma\alpha}^2 - d_{O\alpha}^2 + 2d_{O\gamma}\cdot d_{O\alpha}\cos\angle\gamma O\alpha \tag{23}$$

From the above, we can determine the desire position O (x, y, z) by calculating the following formulas.

$$(x - x1)^2 + (y - y1)^2 + (z - z1)^2 = d_{O\alpha}^2 \tag{24}$$

$$(x - x2)^2 + (y - y2)^2 + (z - z2)^2 = d_{O\beta}^2 \tag{25}$$

$$(x - x3)^2 + (y - y3)^2 + (z - z3)^2 = d_{O\gamma}^2 \tag{26}$$

3.2 Optical Wireless Channel

In an optical link, the channel direct current (DC) gain is given as: [15], [16]

$$H(0) = \begin{cases} \dfrac{(m+1)A}{2\pi d^2}\cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi), & \\ \qquad 0 \leqq \psi \leqq \Psi_c, & \\ 0, \qquad 0 > \Psi_c, & \end{cases} \tag{27}$$

where A is the physical area of the detector in a photo diode (PD), d is the distance between a transmitter and a receiver, ψ is the angle of incidence, ϕ is the angle of irradiance, $T_s(\psi)$ is the gain of an optical filter, and $g(\psi)$ is the gain of an optical concentrator. Ψ_c denotes the width of the field of vision at a receiver. The optical concentrator $g(\psi)$ can be given as [18]:

$$g(\psi) = \begin{cases} \dfrac{n^2}{\sin^2\Psi_c}, & 0 \leqq \psi \leqq \Psi_c, \\ 0, & \psi > \Psi_c, \end{cases} \tag{28}$$

where n denotes the refractive index.

3.3 Noise Model

Next, we assume that the noise is AWGN. In optical channels, the quality of transmission is typically dominated by shot noise [15], [16]. The desired signals contain a time-varying shot-noise process which has an average rate of 10^4 to 10^5 photons/bit. In our channel model, however, intense ambient light striking the detector leads to a steady shot noise having a rate of order of 10^7 to 10^8 photons/bit, even if a receiver employs a narrow-band optical filter. Therefore, we can neglect the shot noise caused by signals and model the ambient-induced shot noise as a Gaussian process [19]. When little or no ambient light is present, the dominant noise source is receiver pre-amplifier noise, which is also signal-independent and Gaussian (though often non-white). Accordingly, the optical wireless channel model is expressed as follows:

$$y(t) = Rx(t) \otimes h(t) + n(t), \tag{29}$$

where $y(t)$ represents the received signal current, $x(t)$ represents the transmitted optical pulse, $n(t)$ represents the AWGN noise, and the symbol $\otimes$ denotes convolution. R represents an optical / electric (O/E) conversion efficiency at a user terminal's PD.

In this paper, a non-directed line-of-sight (LOS) path is assumed. Thus, transmitted pulses are not obstructed and the relation $h(t) = H(0)$ stands. The received optical power P_r is derived by the transmitted optical power P_t, as follows:

$$P_r = H(0) \cdot P_t. \tag{30}$$

In our channel model, the information carrier is a light-wave whose frequency is about 10^{14} Hz. Hence, the Doppler frequency of fading is higher than the data rate. Moreover, detector dimensions are in the order of thousands of wavelengths, leading to efficient spatial diversity, which prevents multipath fading. For the above reasons, multipath fading can be neglected.

Therefore, the received electrical signal-to-noise ratio (SNR) is given by [15], [16]:

$$\mathrm{SNR} = \frac{R^2 P_r^2}{\sigma_{total}^2}, \tag{31}$$

$$\sigma_{total}^2 = \sigma_{shot}^2 + \sigma_{cir}^2, \tag{32}$$

assuming that σ_{total}^2 is dominated by shot noise caused by signals and the ambient environment σ_{shot}^2 and circuit noise σ_{cir}^2 over the desired bandwidth B. The shot noise of σ_{shot}^2 is given by the optical power of background light P_{bg} as :

$$\sigma_{shot}^2 = 2qR(P_r + P_{bg})BF_t, \tag{33}$$

where q represents an elementary change (1.602×10^{-19} C), R represents an O/E conversion efficiency and F_t represents a noise factor.

The circuit noise of σ_{cir}^2 is given by the thermal noise and result from amplifier causes as :

$$\sigma_{cir}^2 = \frac{4kT}{R_F}BF_t + \frac{4kT}{3R_F}BF_t, \tag{34}$$

where k represents a Boltzmann constant (1.381×10^{-23} J/K), T represents an absolute temperature and R_F represents a load resistance.

表 2 Parameters

Physical area of a PD	2.0 [cm^2]
Gain of optical filter	1.0
Refractive index	1.5
Absolute temprature	298 [K]
O/E conversion efficiency	0.53[A/W]
Load resistance	10.0 [kΩ]
Noise factor	2.0
Back ground current values	0.0 [dBm]
Data rate	100 [kbps]
FOV of a terminal	45.0 [deg.]
X range of receiver	$0.0 \leqq$ x [m] $\leqq 6.64$
Y range of receiver	$0.0 \leqq$ y [m] $\leqq 4.75$
Focal length	0.02 [m]
The number of pixels	100 x 100
	200 x 200
	400 x 400
	800 x 800

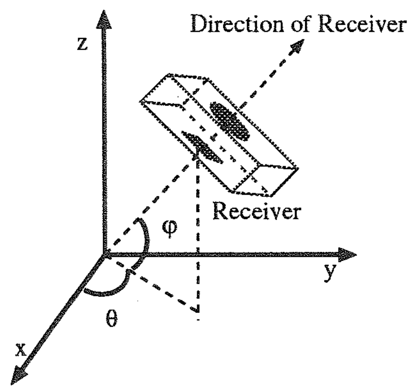

図 7 Direction of receiver.

4. Numerical Results and Discussion

4.1 Influence of interferences

In this section, we define the parameter about numerical analysis, and show in Table 2. We assume that receiver's direction shows in Figure 7. where ϕ is elevation angle from 0 deg. to 90 deg. and θ is horizontal angle from 0 deg. to 350 deg..

Here, when we use two dimensional sensor as a receiver, the adjacent LEDs may be projected into the same pixel. In this case, since 2-PPM modulation doesn't use some subcarriers, some LEDs' signal are added. As a result, it causes an

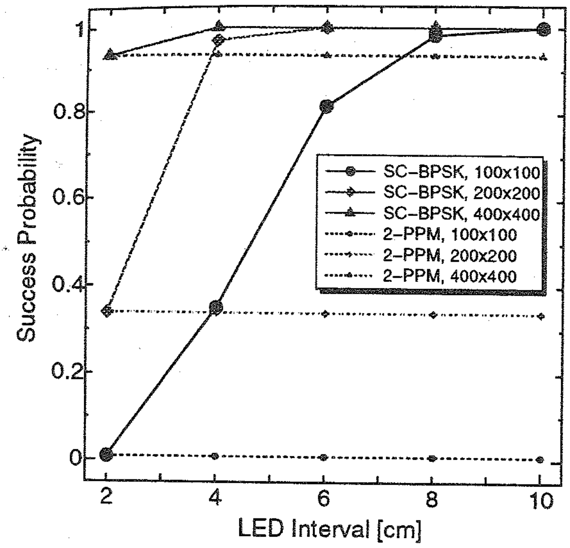

図 8 Influence of interference produced because the adjacent LEDs are subjected to light into the same pixel.

error. But, when we modulate SC-BPSK modulation, even if the adjacent LEDs are projected into the same pixel, if subcarrier between the adjacent LEDs is different, there will be no interference. We analyzed the influence of interference by comparing 2-PPM modulation to SC-BPSK modulation. And, when we raise pixel resolution, the interference will be reduced. In Figure 8, when the pixel resolution is low, even if it extends the interval between the same information LEDs, the success probability of 2-PPM modulation doesn't improve. Since 2-PPM modulation doesn't use the some subcarriers, the interference of the adjacent LEDs doesn't change. However, if the pixel resolution is raised, the influence of interference improves. If we raise pixel resolution and extend the interval between the same information LEDs, removal of the influence of interference is possible.

4.2 Influence of Pixel Selections

In this section, we discuss the influence by some selection methods of pixels. when the ray from an LED is projected to a sensor, it is not always projected to the center of a pixel. When we calculate the desired position assuming that the ray is projected to the center of a pixel, it causes the positioning error. The scale of positioning error depends on which pixels to use for calculating positions..

Then, we show the four selection methods of pixels as follows.

1. The farthest three pixels from the center of a receiving field.
2. The nearest three pixels from the center of a receiving field.
3. The distance between three pixels is the furthest pixels.
4. The distance between three pixels is the nearest pixels.

表 3 Simulation results

	1	2	3	4
SC-BPSK	2.18 [mm]	1.26 [mm]	2.99 [mm]	1.23 [mm]
2-PPM	2.85 [mm]	2.26 [mm]	3.48 [mm]	1.34 [mm]

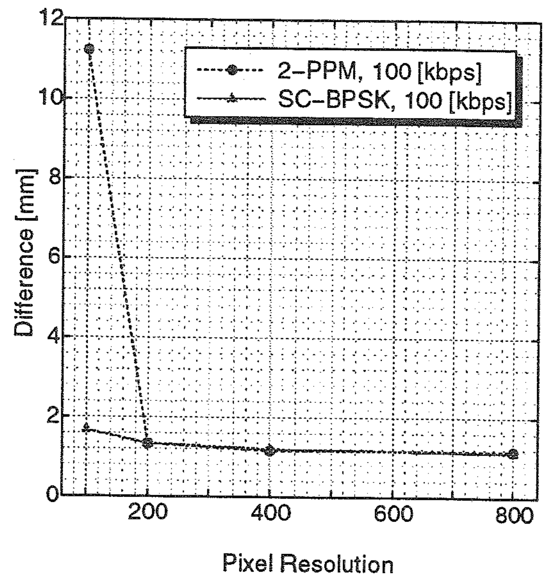

図 9 Positioning difference

Table 3 shows the results of the simulations on 2-PPM and SC-BPSK modulation. In 2-PPM and SC-BPSK modulation, the selection process 4 is the best characteristic. This is related to Equation (21), (22), (23). In the selection process 4, the value of $\angle\alpha O\beta$, $\angle\beta O\gamma$, and $\angle\gamma O\alpha$ is small. On the other hand, the value of $\angle\alpha O\beta$, $\angle\beta O\gamma$, and $\angle\gamma O\alpha$ is large, in the selection process 3. So, when the angle is large, the value of cos changes sharply within 90 deg.. The differences of an angle influences a positioning error greatly. However, when the angle is small, the value of cos changes roughly within 90 deg.. The differences of an angle influences a positioning error small. Therefore the selection process 4 is the best.

4.3 Influence of Pixel Resolution

In this section, we discuss the influence of raising pixel resolution on positioning accuracy. At present, the two dimensional receiver with high pixel resolution is difficult, and 200 x 200 is at most. But, higher pixel resolution will become possible in the future. We simulated the influence by raising pixel resolution as follows. Here, we have located the positioning information LEDs at 0.10 m interval.

Figure 9 shows the results of the simulations on 2-PPM and SC-BPSK modulation on optimum selection method.

In 2-PPM modulation, when the pixel resolution is the highest, the differences are kept within 1.6 mm. But, when the pixel resolution becomes low, the differences become large. We found it is greatly dependent on the pixel resolution. In Figure 8 when the pixel resolution is low, not many pixels are available. That is why, even if we used the optimum selection method, the best three pixels can't be chosen in many cases.

In SC- BPSK modulation, we found the differences are dependent on the pixel resolution. But, even if the pixel resolution becomes low, the differences don't almost change. In Figure 8, even if the pixel resolution is low, few pixels are available for calculating positions. That is why, the best three pixels can be chosen in many cases.

Accordingly, when we use the low pixel resolution as a receiver, we had better select SC-BPSK as a modulation scheme. However when we use the high pixel resolution as a receiver, both 2-PPM and SC-BPSK can be used as a modulation.

5. Conclusion

White LEDs will play an important role in future electric lighting technology. The white LEDs have a high power output, a long lifetime, and a high power efficiency. Consequently, they are drawing considerable attention. A group including the author has proposed an indoor visible-light communication utilizing white LED lights. White LEDs are utilized not only as a lighting source but also as an optical transmitter in the proposed system. In this paper, we focus on a positioning system and proposed pervasive visible light positioning system using white LED lighting.

It is very difficult to measure a position in indoor such as office and household. The authors proposed positioning system using white LED lighting. Based on numerical analyses and computer simulations, the proposed system is promising for indoor positioning system. Our systems is expected as indoor positioning scheme of next generation.

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