Fundamental Analysis for Visible-Light Communication System using LED Lights

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Abstract — *White LED offers advantageous properties such as high brightness, reliability, lower power consumption and long lifetime. White LEDs are expected to serve in the next generation of lamps. An indoor visible-light communication system utilizing white LED lights has been proposed from our laboratory. In the proposed system, these devices are used not only for illuminating rooms but also for an optical wireless communication system. Generally, plural lights are installed in our room. So, their optical path difference must be considered. In this paper, we discuss about the influence of interference and reflection. Based on numerical analyses, we show that the system will expect as indoor communication of next generation*[1].

Index Terms — visible-light communication, white LED light, intersymbol interference, optical wireless communication, illuminance.

I. INTRODUCTION

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. Now, InGaN based highly efficient blue and green LED has become commercially available. By mixing three primary colors (red, green and blue), we can produce white. 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, if LED replaces half of all incandescent and fluorescent lamps currently in use, Japan could save equivalent output of six mid-size power plants, and reduce the production of greenhouse gases. A national program underway in Japan has already suggested that white LED deserves to be considered as a general lighting technology of the 21st century owing to electric power energy consumption.

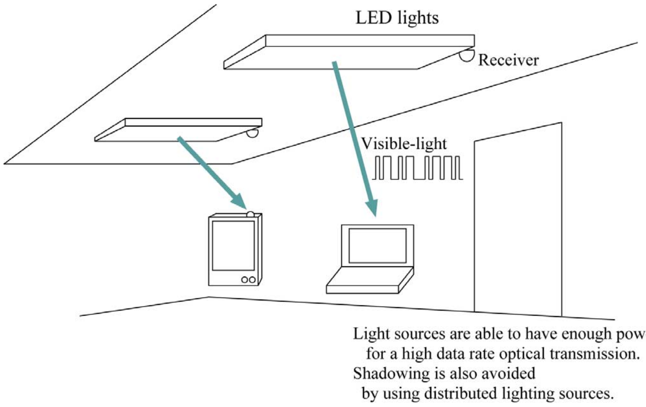

Fig. 1. Visible-light communication system utilizing white LED lights.

Our group has proposed an optical wireless communication system that employing white LEDs for indoors wireless networks [8]-[11]. In this system, LED is not only used as a lighting device, but also to be used as a communication device. It is a kind of optical wireless communication that uses the “visible” white ray as the medium (Fig. 1). This dual function of LED, for lighting and communication, emerges 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:

- Optical data transmission with few shadowing throughout a whole room is enabled by high power and distributed lighting equipment.
- Lighting equipment with white LEDs is easy to install and aesthetically pleasing.

In order to realize this system, study of optical properties as lighting equipment and an optical transmitter is required. Thus, some numerical analyses for the proposed system were performed, and are reported herein. And we discuss about difference between visible-light communication and other optical wireless communication. Through numerical analyses, we found that the proposed system is viable candidate for indoor wireless data transmission systems.

This paper is organized as follows. In section II, the design of white LED lighting based on illumination engineering is shown. In section III, the feature of the proposed system as communication devices is shown. In section IV, the influence of interference is discussed and the difference of optical wireless communication is described. In section V, the influence of FOV (field of view) is discussed. Finally, our conclusions are given in section VI.

II. LED LIGHT DESIGN

A. 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

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transmitted optical power. The relationship between photometric and radiometric quantities is explained in [12]-[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, and as 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 Ω is the spatial angle, and 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:

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

where Λ_{min} and Λ_{max} are determined by the sensitivity curve of the PD (photo diode).

B. 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. The luminous intensity in angle ϕ is given by

$$I(\phi) = I(0)\cos^m(\phi). \tag{4}$$

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

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

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_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][16]. 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 300 to 1500 lx in required for offices work.

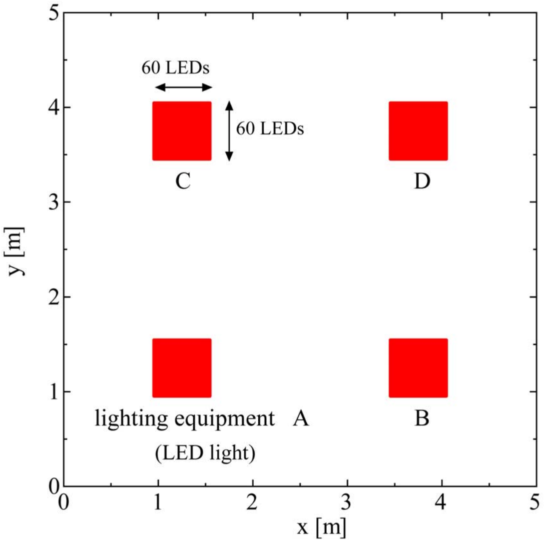

Fig. 2. The model room. The room size is 5 m × 5 m × 3 m. The desk of height is 0.85 m from the floor. The LED light of height is 2.5 m from the floor.

TABLE I
PARAMETERS.

transmitted optical power	20 [mW]
semi-angle at half power	70 [deg.]
center luminous intensity	0.73 [cd]
number of LEDs	3600 (60 × 60)
LED interval	0.01 [m]
size of LED light	0.59 × 0.59

C. Design of White LED Lights

Now, we will discuss the possible application of the proposed system in terms of some numerical analyses. A room was assumed for the purpose of these analyses. The room size is 5.0 m × 5.0 m × 3.0 m. Fixtures in the room were arranged as shown in Fig. 2.

LED Lights, capable of optical transmission, were installed at a height of 2.5 m from the floor. The height of the desk is 0.85 m, and a user terminal was put on the desk. The number of LED lighting equipments was 4, and each LED light was filled with 3600 (60 × 60) LEDs. The space between LEDs is 1 cm. The semi-angle at half-power of an LED chip is 70 deg., the center luminous intensity of an LED chip is 0.73 cd, respectively. The transmitted optical power of an LED chip is 20.0 mW. Those conditions summarized in Table I.

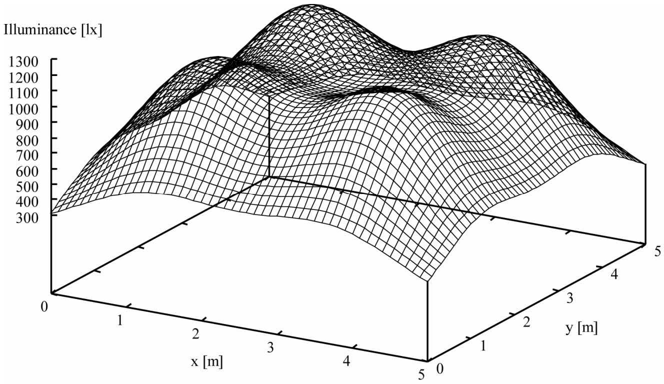

Fig. 3. The distribution of illuminance. Min. 313.5 lx, Max. 1211.5 lx, Ave. 865.7 lx.

Figure 3 shows the distribution of horizontal illuminance at a user terminal equipped with the LED lights listed in Table I. From this figure, the sufficient illuminance, is 300 to 1500 lx by ISO, is obtained in all the places of the room. Therefore, this result shows that this LED lighting has function as lighting.

III. RECEIVED POWER FROM LED LIGHTS

A. *Received Power of Directed Light*

In the paper, we assume an optical wireless channel, and this condition is applied to later analyses.

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

$$H(0)=\begin{cases}\dfrac{(m+1)A}{2\pi D_d^{\,2}}\cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi), \\ \qquad 0\le\psi\le\Psi_c, \\ 0, \\ \qquad \psi>\Psi_c,\end{cases} \tag{6}$$

where A is the physical area of the detector in a PD, D_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 [15]:

$$g(\psi)=\begin{cases}\dfrac{n^2}{\sin^2\Psi_c}, & 0\le\psi\le\Psi_c, \\ 0, & 0\ge\Psi_c,\end{cases} \tag{7}$$

where n denotes the refractive index.

The received optical power P_r is derived by the transmitted optical power P_t, as follows:

TABLE II
PARAMETERS.

FOV at a receiver	60 [deg.]
detector physical area of a PD	1.0 [cm^2]
gain of an optical filter	1.0
refractive index of a lens at a PD	1.5
O/E conversion efficiency	0.53 [A/W]

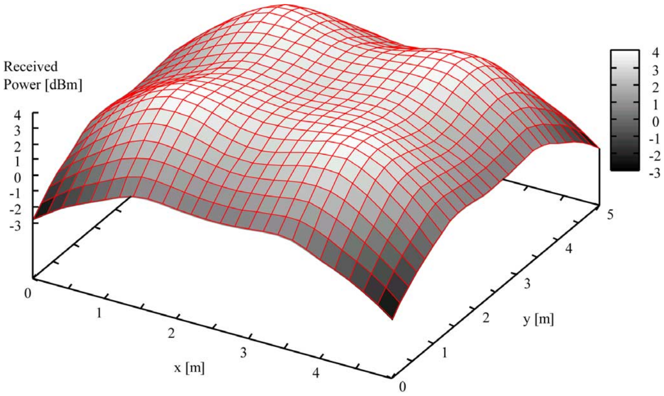

Fig. 4. The distribution of received power. Min. -2.8 dBm, Max. 4.0 dBm, Ave. 2.0 dBm.

$$P_r=H(0)\cdot P_t. \tag{8}$$

In these analyses, the parameters listed in Table 2 were used. The FOV is 60.0 deg., and the physical detection area of a PD is 1.0 cm^2. The gain at an optical filter is 1.0, and the refractive index of an optical concentrator is 1.5. The O/E conversion efficiency of a PD is 0.53 A/W, and a silicon PD whose peak sensitivity is in visible wavelength is assumed. The spectral response at a PD has wavelength selectivity, whereas we can design the optical bandpass filter with multiple thin dielectric layers. Besides, white LEDs emit light at a wide wavelength. Consequently, we can use a desired wavelength at which the response at a PD is good.

Figure 4 shows the distribution of received power of directed light from LED lights listed in Table II. From this figure, the received power is -2.8 to 4.0 dBm in all the places of the room. The received power, which is very big energy compared with infrared communication, will make broadband communication possible.

B. *Received Power of Reflected Light*

Next, let us consider the effect of reflective light by walls. The received power is given by the channel DC gain on directed path $H_d(0)$ and reflected path $H_{ref}(0)$.

$$P_r=\sum^{LEDs}\left\{P_tH_d(0)+\int_{walls}P_t dH_{ref}(0)\right\}. \tag{9}$$

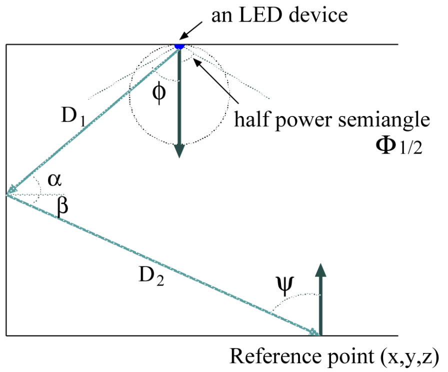

Fig. 5. Propagation model of diffused link.

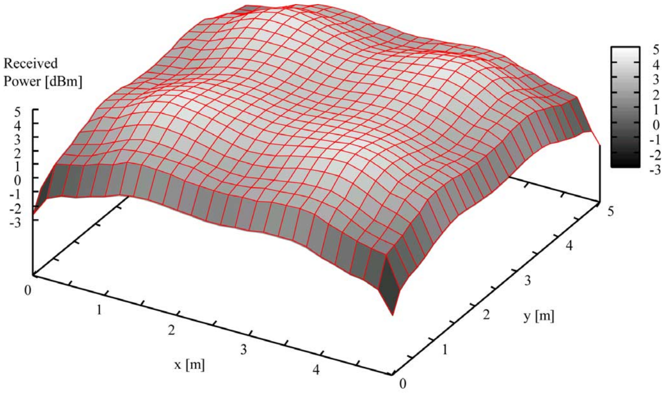

Fig. 6. The distribution of received power with reflection. Min. -2.8 dBm, Max. 4.2 dBm, Ave. 2.5 dBm.

The channel DC gain on the first reflection is [16]

$$dH_{ref}(0)=\begin{cases}\dfrac{(m+1)A}{2\pi^2 D_1^2 D_2^2}\rho dA_{wall}\cos^m(\phi)\cos(\alpha) \\ \qquad \cos(\beta)T_s(\psi)g(\psi)\cos(\psi), \\ \qquad 0\le\psi\le\Psi_c, \\ \qquad 0, \\ \qquad \psi>\Psi_c,\end{cases} \tag{10}$$

where D_1 is the distance between an LED chip and a reflective point, D_2 is the distance between a reflective point and a receiver, ρ is the reflectance factor, dA_{wall} is a reflective area of small region, ϕ is the angle of irradiance to a reflective point, α is the angle of irradiance to a reflective point, β is the angle of irradiance to the receiver, ψ is the angle of incidence (Fig. 5).

Figure 6 shows the distribution of received power including influence of reflection. From this figure, the received power is -2.8 to 4.2 dBm in all the places of the room. The received average power including reflection is about 0.5 dB larger than the directed received average power.

IV. INTERSYMBOL INTERFERENCE

Generally, lights are distributed within a room and the irradiance of light is wide for function of lighting equipment. In visible-light communication using LED lights, the large received power, which consists of the optical paths differing by delay propagation, causes intersymbol interference. Therefore, we define that each LED lights transmit same signal simultaneously, and we will discuss about their optical path difference.

A. Optical Wireless Channel

We assume that the noise in an AWGN (additive white Gaussian noise). In optical channels, the quality of transmission is typically dominated by shot noise [15]. The desired signals contain a time-varying shot-noise process which has an average rate of 10^4 of 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 [17]. 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 on-white). Accordingly, the optical wireless channel model is expressed as follows:

$$Y(t)=\gamma X(t)\otimes h(t)+N(t). \tag{11}$$

where $Y(t)$ represents the received signal current, γ is the detector responsivity, $X(t)$ represents the transmitted optical pulse, $h(t)$ is the impulse response, $N(t)$ represents the AWGN, and the symbol $\otimes$ denotes convolution.

The average transmitted optical power P_t is given by

$$P_t=\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T}X(t)dt. \tag{12}$$

In visible-light communication, LED lights, which have function of communication, are distributed within a room and the irradiance of light is wide for function of lighting equipment. Thus a non-directed LOS (line of sight) path is assumed. The channel is given by [15]

$$H(0)=\int_{-\infty}^{\infty}h(t)dt. \tag{13}$$

We consider OOK (on off keying) modulation scheme. In OOK, light is transmitted to encode a one bit, and no light is transmitted encode a zero bit. We will assume a rectangular pulse shape whose duration equals the bit period. The BER (bit error rate) is given by

$$OOK: BER=Q(\sqrt{SNR}), \tag{14}$$

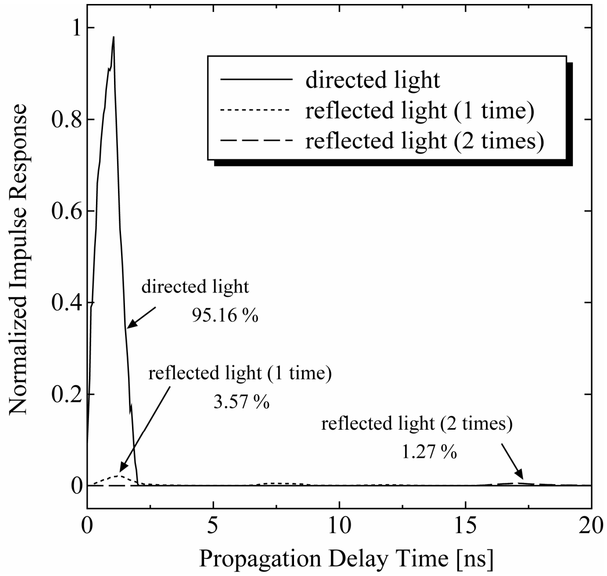

Fig. 7. Impulse response (0.01, 0.01, 0.85).

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-y^2/2} dy. \tag{15}$$

For example, to achieve BER = 10^{-6} it requires SNR = 13.6 dB in the OOK modulation. A received optical power of SNR = 13.6 dB is required for a stable communication link.

B. *Impulse Response*

In visible-light communication system, the lighting equipments are installed in a ceiling and it has large superficial area. Therefore visible-light communication system has particular impulse response differing from infrared communication. In this subsection, we will discuss about impulse response.

Figure 7 shows the impulse response at corner of the room (0.01, 0.01, 0.85) from (6), (8) and (10). We show the rate of each light (directed light, the first reflected light and the second reflected light) to the received light in the figure. From this figure, the rate of the reflected light is small enough compared with directed light. So, in visible-light communication, the influence of the directed light is large and it depends on performance of the system greatly. In this paper, we consider until the first reflection for convenience of computer analysis.

C. *SNR Performance with Intersymbol Interference*

Next we will discuss SNR distribution. An SNR can express the quality of communication. The signal component S is given by

TABLE III
PARAMETERS.

open-loop voltage gain	10
fixed capacitance	112 [pF/cm^2]
FET channel noise factor	1.5
FET transconductance	30 [mS]
absolute temperature	298 [K]
background light current	5100 [μA]
data rate	100.0 [Mb/s]

$$S = \gamma^2 P_{rSignal}^2, \tag{16}$$

where desired signal power $P_{rSignal}$ is

$$P_{rSignal} = \int_0^T \left(\sum_{i=1}^{LEDs} h_i(t) \otimes X(t) \right) dt. \tag{17}$$

Further, multipath fading can be neglected in optical wireless channel. In our channel model, the information carrier is a light wave whose frequency is about 10^{14} Hz. 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.

We assume OOK with rectangular transmitted pulses of duration equal to the bit period, and a receiver filter that equalized the received pulse to have a raised-cosine spectrum with 100% excess bandwidth. The equalizer output contains a Gaussian noise having a total variance N that is the sum of contributions from shot noise, thermal noise and intersymbol interference by an optical path difference

$$N = \sigma_{shot}^2 + \sigma_{thermal}^2 + \gamma^2 P_{rISI}^2, \tag{18}$$

The received power by intersymbol interference P_{rISI} is

$$P_{rISI} = \int_T^{\infty} \left(\sum_{i=1}^{LEDs} h_i(t) \otimes X(t) \right) dt. \tag{19}$$

A shot noise variance is given by

$$\sigma_{shot}^2 = 2q\gamma(P_{rSignal} + P_{rISI})B + 2qI_{bg}I_2B, \tag{20}$$

where q is the electronic charge, B is equivalent noise bandwidth, I_{bg} is background current. And we have defined the noise bandwidth factors I_2 = 0.562. In this paper, we assume the use of a p-i-n/FET transimpedance receiver [18][19]. We neglect the noise contributions from gate leakage current and 1/f noise. The thermal noise variance is given by

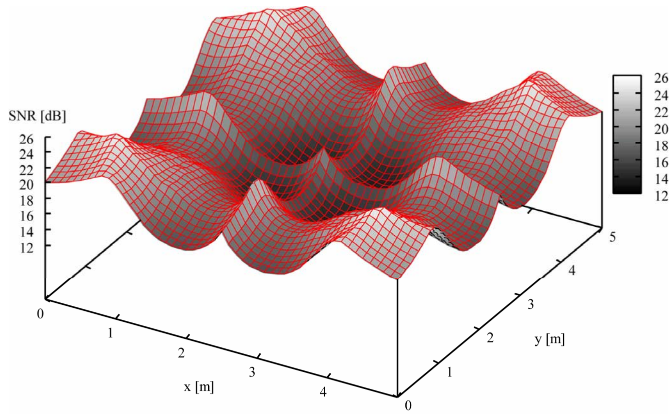

Fig. 8. The distribution of SNR with intersymbol interference (directed light). Min. 12.7 dB, Max. 24.8 dB, Ave. 18.9 dB.

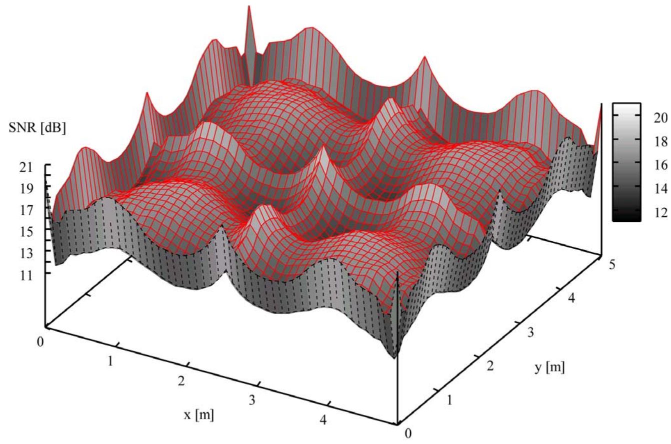

Fig. 9. The distribution of SNR with intersymbol interference (reflected light). Min. 11.6 dB, Max. 20.1 dB, Ave. 15.4 dB.

$$\sigma^2_{thermal} = \frac{8\pi k T_K}{G}\eta A I_2 B^2 + \frac{16\pi^2 k T_K \Gamma}{g_m}\eta^2 A^2 I_3 B^3, \quad (21)$$

where the two terms represent feedback-resistor noise, and FET channel noise, respectively. Here, k is Boltzmann's constant, T_K is absolute temperature, G is the open-loop voltage gain, η is the fixed capacitance of photo detector per unit area, Γ is the FET channel noise factor, g_m is the FET transconductance, and $I_3 = 0.0868$. In our numerical examples, we choose the following parameter values [20]: $T = 295$ K, $\gamma = 0.54$ A/W, $G = 10$, $g_m = 30$ mS, $\Gamma = 1.5$, $\eta = 112$ pF/cm^2, and $B = 100$ Mb/s (Table III). And we assume the background current from direct sum light [21].

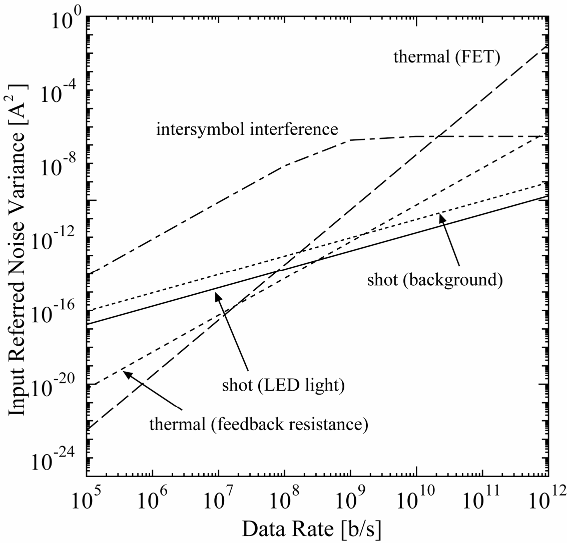

Fig. 10. The influence of noise on data rate.

The distribution of SNR is shown in Fig. 8 and 9. Figure 8 is shown the performance of directed light, and Fig. 9 is shown the performance including reflected light. From those figures, the required SNR is obtained in almost all the places of the room. So, the proposed system makes it possible to transmit at 100 Mb/s. Since the high power as lighting can be used for communication, visible-light communication can obtain high quality easily.

From the Fig.4 and 6, the received average power including reflection is about 0.5 dB larger than the directed received average power. However, from the Fig. 8 and 9, the average SNR including intersymbol interference is about 2 dB smaller than the directed received average power. It means that the intersymbol interference has large influence on performance at 100 Mb/s, compared with the reflection. The influence of noise variance on data rate is shown in Fig. 10. Since the high power as lighting, we know that the influence of intersymbol interference is larger than others until 20 Gb/s.

Therefore, many LEDs installed on the ceiling generate an optical path difference, which causes an intersymbol interference on the received wavelength. And, this system utilizes many LED chips and the received optical power is high. Thus, by intersymbol interference, the communication performance is degraded severely.

V. DATA RATE AND FIELD OF VIEW

In optical wireless communication (including infrared wireless communication), an intersymbol interference depends on a data rate and a FOV of transmitter and receiver. However, in visible-light communication, it depends on a data rate and a FOV of receiver since a transmitter should have wide angle of irradiance for function of lighting. In this section, we will discuss about the relation between received SNR and FOV or data rate.

Figure 11 is shown the relation between FOV and received SNR with intersymbol interference. At the model room (Fig. 2), we plot the maximum SNR, average SNR and minimum SNR on the graph. In this model, we do not assume a tracking. So, when FOV is smaller than 40 deg., the blind area exists. In this figure, we know that the received SNR is required throughout

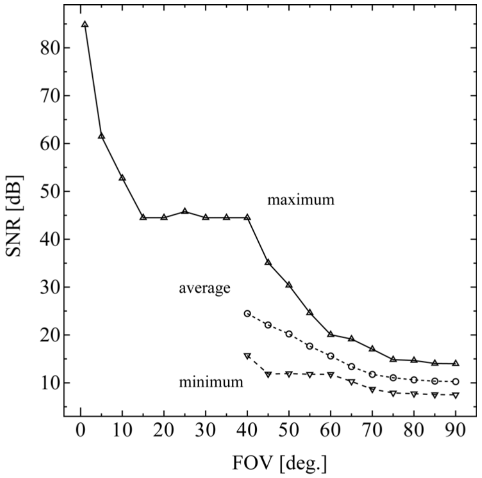

Fig. 11. FOV vs. SNR with intersymbol interference (no tracking).

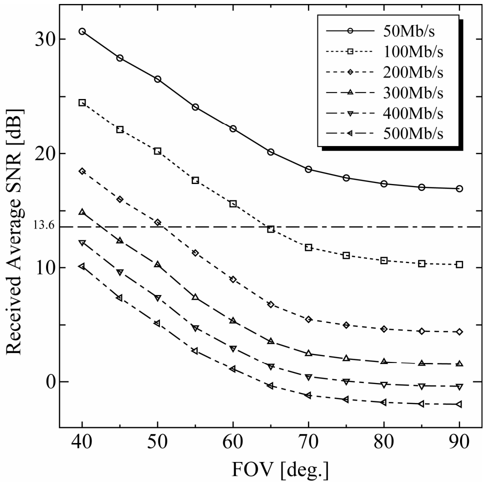

Fig. 12. FOV vs. received average SNR with intersymbol interference (no tracking).

a whole room when the FOV is 40 to 60 deg.. Small angle of irradiance gets better performance since the intersymbol interference is decreased. Figure 12 is shown the received average SNR with intersymbol interference for each data rate. We know that the received average SNR decreases at high data rate. When we expect the data rate of 200 Mb/s, we must design that the FOV is 40 to 50 deg..

Figure 13 is shown the relation between FOV and received average SNR with tracking. When we expect the data rate of 300Mb/s, we must design that the FOV is smaller than 30 deg.. Figure 13 is shown the relation between data rate and received SNR with tracking. When the FOV is 5 deg., the data rate is about 10 Gb/s. A tracking makes high speed communication possible.

Therefore, when visible-light communication system has not tracking, it makes about 200 Mb/s data transmission possible. When visible-light communication system has tracking, it makes about 10 Gb/s data transmission possible.

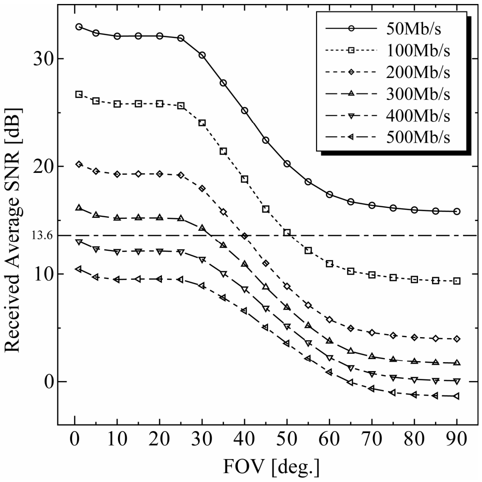

Fig. 13. FOV vs. received average SNR with intersymbol interference (tracking).

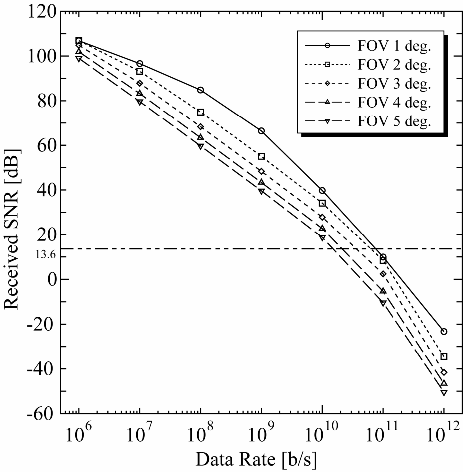

Fig. 14. Data rate vs. SNR with intersymbol interference (tracking).

VI. CONCLUSION

In this paper, we discussed about the fundamental analysis for visible-light communication system using LED lights. In visible-light communication system, it is important to meet the requirements for optical lighting and optical transmission. We discussed about those requirements and showed the example of design. And we knew that the system made communication and lighting possible. Next, we discussed about the influence of reflection and intersymbol interference. And we showed that the communication performance is degraded severely by intersymbol interference. In visible-light communication system, the LED lights are distributed within a room and the irradiance of light is wide for function of lighting equipment. Therefore, the intersymbol interference depended on the data rate and the FOV of receiver. We explained the relation between the data rate and the FOV and suggested the potential of high speed data transmission like 10 Gb/s.

Many light sources can substitute LED. And visible-light communication system makes high data rate possible easily. Consequently, the visible-light communication system will expect as indoor communication system of next generation. Further research on these would make LED lighting communication feasible.

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