TDOA-Based Optical Wireless Indoor Localization Using LED Ceiling Lamps

Soo-Yong Jung, Swook Hann, and Chang-Soo Park, *Member*, IEEE

**Abstract — ** *We propose an optical wireless indoor localization using light emitting diodes (LEDs) and demonstrate it via simulation. Unique frequency addresses are assigned to each LED lamp, and transmitted through the light radiated by the LED. Using the phase difference, time difference of arrival (TDOA) localization algorithm is employed. Because the proposed localization method used pre-installed LED ceiling lamps, no additional infrastructure for localization is required to install and therefore, inexpensive system can be realized. The performance of the proposed localization method is evaluated by computer simulation, and the indoor location accuracy is less than 1 cm in the space of 5m x 5 m x 3 m.*[1]

Index Terms — Indoor localization, time difference of arrival, light emitting diode, visible light communications.

I. INTRODUCTION

Indoor localization has numerous potential applications in the robotic industry, indoor navigation service, and public safety. Though, outdoor location sensing has already been well-developed using global positioning system (GPS), using GPS for indoor location sensing is still difficult because of the poor satellite coverage in indoor environments. To date, a number of techniques have been proposed and studied for indoor location sensing, most using a positioning technique based on triangulation, fingerprinting, scene analysis, and proximity [1]-[3]. To use the triangulation technique, it is required to measure the angle or distance between a reference point and a mobile terminal, and there are several methods to measure for this purpose such as, angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), and received signal strength intensity (RSSI) [11], [12]. Depending on the positioning system, different probing signal—infrared radiation (IR) [4], ultrasonic [5], [6], or radio frequency (RF) [7]-[10]—can be attempted. However, the positioning systems based on IR or ultrasonic require an additional cost and time to deploy a network infrastructure of location sensors, and system based on RF have difficulties in acquiring accurate location coordinates caused by multipath fading and non-line of sight (non-LOS) conditions in indoor environment [13]. Moreover, the RF based positioning systems are limited in hospitals, kindergartens, airplanes, and areas with RF sensitive equipment.

To overcome these problems, we propose an indoor positioning system using light emitting diodes (LEDs). Recently, the use of LEDs for landscape architecture or illumination has attracted attention, and the LED industry is rapidly growing as LEDs have several advantages such as long life expectancy, high tolerance to humidity, low power consumption, and environmental friendliness [14]. Therefore, we can expect that the existing fluorescent lamps will be replaced with LED lights in near future. Moreover, LEDs can modulate electrical signals into lightwave signals at high speed. Using these two properties, e.g., lighting and transmission, indoor wireless optical communication systems based on LEDs have been proposed [15]-[19].

In this paper, an indoor positioning system under LED ceiling lamps environment is proposed and then a positioning technique based on a TDOA method is demonstrated. Because ceiling lights can be seen from any place in an indoor environment, this system can work under LOS conditions, and typical detector areas are thousands of wavelengths, leading to spatial diversity that prevents multipath fading [20]. Moreover, this system uses existing infrastructure of LED ceiling lamps for affording cost effective indoor localization and also can cover RF limited area.

II. CHANNEL MODEL FOR LED CEILING LIGHT

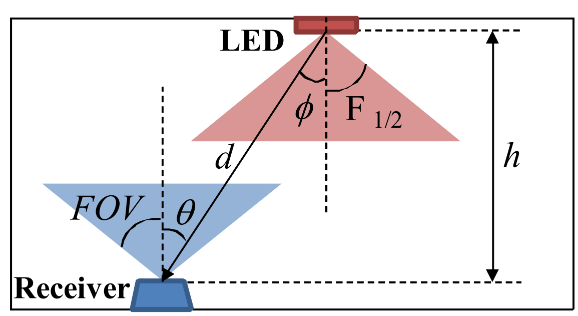

Fig. 1. System parameters of LED optical wireless channel

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The radiation of a LED chip follows Lambertian radiation pattern. A generalized Lambertian radiant intensity is given by [21]

$$R(\phi)=\frac{n+1}{2\pi}P_T\cos^n(\phi), \tag{1}$$

where n is the mode number of the radiation lobe, P_T is the source power, and ϕ is the angle of irradiance with respect to the transmitter perpendicular axis, as depicted in Fig. 1. The mode number n is given by $n=-\ln 2/\ln(\cos\Phi_{1/2})$, where $\Phi_{1/2}$ denotes the LED view angle at half power.

In optical wireless channel, if the distance d, is much larger than detector size A_R, then the received irradiance is approximately constant over the surface of the detector and all of the signal energy arrives at the receiver at approximately the same time. Thus, the impulse response for this optical wireless channel is approximately a scaled and delayed Dirac delta function [22]:

$$h(t)=\frac{n+1}{2\pi}\cos^n(\phi)d\Omega rect\left(\frac{\theta}{FOV}\right)\delta\left(t-\frac{d}{c}\right), \tag{2}$$

where $d\Omega$ is the solid angle expressed as $d\Omega=\cos(\phi)A_R/d^2$, FOV is field of view of the receiver, and c is the speed of light. The rectangular function is defined by:

$$rect(x)=\begin{cases}1, & for\ |x|\le 1\\ 0, & for\ |x|>1\end{cases}. \tag{3}$$

The channel gain, H(ω), is Fourier transform of the channel impulse response h(t), and can be expressed as

$$H(\omega)=\frac{n+1}{2\pi d^2}A_R\cos^n(\phi)\cos(\theta)rect\left(\frac{\theta}{FOV}\right)\cdot\exp\left(-j\omega d/c\right) \tag{4}$$

We use the transmitting signal of the LEDs with a frequency of less than 5 MHz over the channel. The channel is assumed to be distortion-less, and it means a gain $H(\omega)$, is equal to channel DC gain $H(0)$, for all frequencies of interest in our model. Thus, the average received optical power is given by $P_R = H(0)P_T$. The performance of visible light communication systems depends greatly on the LOS link [2]. Thus, for simplicity in analysis, only directed light is considered.

III. Location Estimation

In this section, we propose the localization method under the channel of LED ceiling light. To estimate the locations of an object in the room, three LED lamps are used and each LED lamp has a unique frequency address (F-ID). Based on the property that LED can modulate signals while being used as a lighting device, each LED lamp transmits its assigned F-ID. Detecting phase difference between the transmitted signals, time difference of arrival is estimated. Fig. 2 shows a configuration of the system.

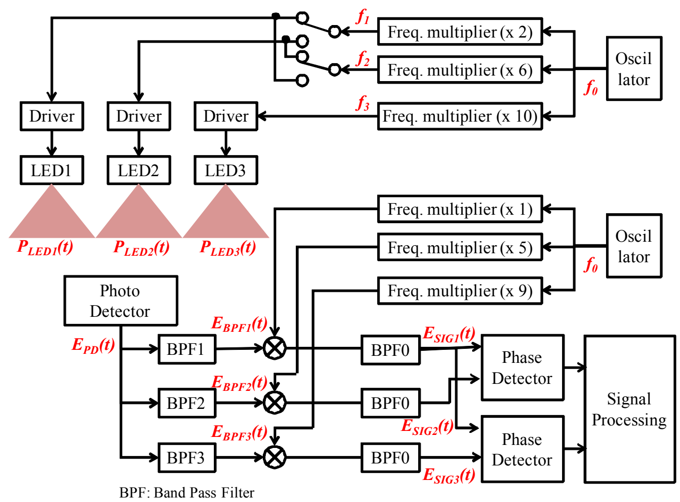


Fig. 2. Proposed system configuration

In the first step, F-ID1 (f_1), F-ID2 (f_2), F-ID3 (f_3) are assigned to LED1, LED2, and LED3, respectively, and each F-ID is synchronized. Then, the radiated optical power from each LED ramp can be expressed as

$$\begin{cases}P_{LED1}(t)=P_{CONT}+P_{MOD}\cos(2\pi f_1 t+\varphi_0)\\ P_{LED2}(t)=P_{CONT}+P_{MOD}\cos(2\pi f_2 t+\varphi_0),\\ P_{LED3}(t)=P_{CONT}+P_{MOD}\cos(2\pi f_3 t+\varphi_0)\end{cases} \tag{5}$$

where P_{CONT} and P_{MOD} are continuous and modulated optical signal, respectively, and φ_0 is initial phase of the radiated optical signal. In the optical transmission system, a photo detector is commonly used as the first stage device of a receiver, because it is a photoelectric conversion device. The output signal of the photo detector is an absolute square of the received optical signal, expressed as,

$$\begin{aligned}E_{PD}(t)&=K\cdot|R\cdot P_{REC}(t)|^2\\ &=K\cdot|R\cdot\{P_{LED1}(t)\otimes h_1(t)\\ &+P_{LED2}(t)\otimes h_2(t)+P_{LED3}(t)\otimes h_3(t)\}|^2\end{aligned}, \tag{6}$$

where $P_{REC}(t)$ is the received optical signal, R is responsivity of the photo detector, K is constant of proportionality, and $h(t)$ is the channel impulse response, and $\otimes$ is a convolution operator. Then, there are lots of frequency components after the photo detector such as, DC, f_1, f_2, f_3, $2f_1$, $2f_2$, $2f_3$, f_1+f_2, f_2+f_3, f_1+f_3, f_2-f_1, f_3-f_2, and f_3-f_1. To extract F-IDs only without any signal interference, f_2 = 3x f_1 and f_3 = 5x f_1 should be used. The output signal of the photo detector is inserted to band pass filters (BPFs) whose pass band is adjusted to the each F-ID. After the BPF, the signal can be expressed as

$$\begin{cases} E_{BPF1}(t) = L_1 \cdot \cos\{2\pi f_1 (t - d_1/c) + \varphi_0\} \\ E_{BPF2}(t) = L_2 \cdot \cos\{2\pi f_2 (t - d_2/c) + \varphi_0\}, \\ E_{BPF3}(t) = L_3 \cdot \cos\{2\pi f_3 (t - d_3/c) + \varphi_0\} \end{cases} \tag{7}$$

where, $L_i = 2 \cdot K \cdot R \cdot H(0)_i \cdot P_{CONT} \cdot P_{MOD}$ (i is 1, 2, or 3), d_i is distance between LED_i and the receiver. To detect the phase difference between each signal, we need unified frequency signals. Frequency down converter composed with a mixer and a BPF is used for that purpose. After down conversion, the signals are expressed as

$$\begin{cases} E_{SIG1}(t) = K_1 \cos\{\pi f_1 t - 2\pi f_1 d_1/c + \varphi_{TOT}\} \\ E_{SIG2}(t) = K_2 \cos\{\pi f_1 t - 6\pi f_1 d_2/c + \varphi_{TOT}\} \\ E_{SIG3}(t) = K_3 \cos\{\pi f_1 t - 10\pi f_1 d_3/c + \varphi_{TOT}\} \end{cases}, \tag{8}$$

where φ_{TOT} is total phase shift by electrical path. Now, we can extract phase difference using the phase detector based on Hilbert transform. The phase difference between $E_{SIG1}(t)$ and $E_{SIG2}(t)$, and between $E_{SIG1}(t)$ and $E_{SIG3}(t)$ are

$$\Delta\phi_{12} = 2\pi f_1 \frac{d_1 - 3d_2}{c} = \tan^{-1}(I_{12}/Q_{12}), \tag{9}$$

$$\Delta\phi_{13} = 2\pi f_1 \frac{d_1 - 5d_3}{c} = \tan^{-1}(I_{13}/Q_{13}). \tag{10}$$

In the above equations, I and Q are obtained from following relations,

$$\begin{cases} I_{12} = E_1(t) \cdot Hilb[E_2(t)] - Hilb[E_1(t)] \cdot E_2(t) \\ Q_{12} = E_1(t) \cdot E_2(t) + Hilb[E_1(t)] \cdot Hilb[E_2(t)] \end{cases}, \tag{11}$$

where, $Hilb[\bullet\ ]$ is Hilbert transform.

In the second step, F-IDs for LED1 and LED2 are switched. That is, F-ID1 is modulated to LED2 and F-ID2 is modulated to LED1. After the same process as the previous step, we get following additional information

$$\Delta\phi_{21} = 2\pi f \frac{d_2 - 3d_1}{c} = \tan^{-1}(I_{21}/Q_{21}). \tag{12}$$

Using (9), (10), and (13), we obtain the distance value,

$$\begin{cases} d_1 = -\frac{1}{8}\frac{c}{2\pi f_1}\left[\tan^{-1}\left(\frac{I_{12}}{Q_{12}}\right) + 3\tan^{-1}\left(\frac{I_{21}}{Q_{21}}\right)\right] \\ d_2 = \frac{1}{3}\left[d_1 - \tan^{-1}\left(\frac{I_{12}}{Q_{12}}\right)\frac{c}{2\pi f_1}\right] \\ d_3 = \frac{1}{5}\left[d_1 - \tan^{-1}\left(\frac{I_{13}}{Q_{13}}\right)\frac{c}{2\pi f_1}\right] \end{cases} \tag{13}$$

Based on these distance values and trilateration, we can estimate the location.

IV. Performance Evaluation

We evaluated the proposed method using computer simulation. Fig. 3 depicts the simulation model.

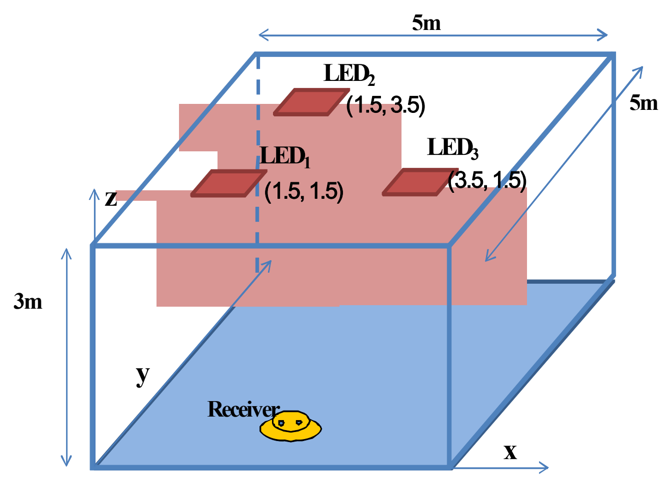


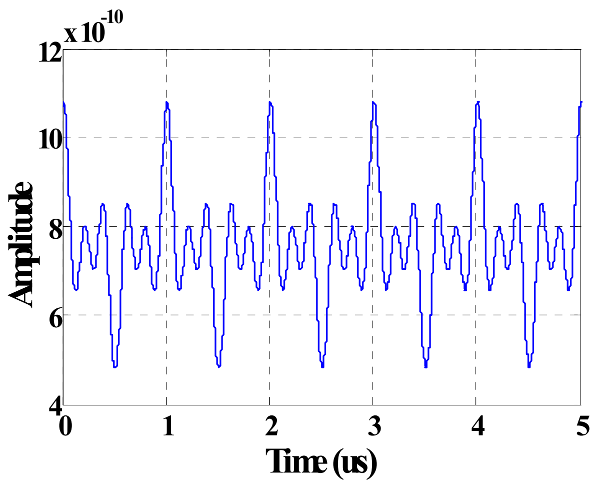
Fig. 3. System model for indoor localization

As you can see in Figure 3, the dimension of the system model is 5.0 m x 5.0 m x 3.0 m. We used three LED ceiling lamps located in (1.5, 1.5, 3), (1.5, 3.5, 3), and (3.5, 1.5, 3). The simulation parameters are summarized in the Table I.

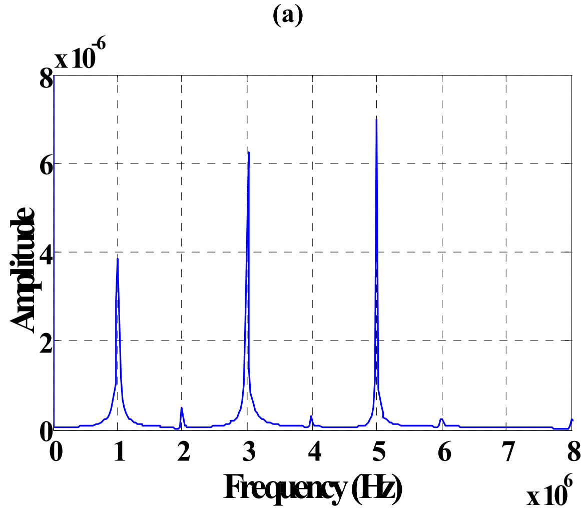
TABLE I
SIMULATION PARAMETERS

Parameters	Value
LED radiation power	1 W
View angle of LED	65 deg.
FOV	70 deg.
Detector Area	1.0 cm^2
Photo detector reponsivity	0.45 A/W
Number of LED lamps	3
Model room size	5 m x 5 m x 3 m
F-ID1	1.0 MHz

When we used 1 MHz, 3 MHz, and 5 MHz for F-ID1, F-ID2, and F-ID3, respectively, the received signal at (3, 3) on the bottom is depicted in Fig. 4



(a)



(b)

Fig. 4. Received signal at (3, 3) on the bottom: (a) time domain, and (b) frequency domain

Fig.4(a) shows the received signal in the time domain, from this figure, we can see several frequency components exist in the received signal. Fig. 4(b) depicts the received signal in the frequency domain, and we can easily check the frequency components. As shown in Fig. 4(b), except F-IDs there exist other frequency components at 2 MHz, 4 MHz, and 6 MHz. It is due to the nonlinear property of the photo detector. However, we can remove these unwanted signals by using BPF as referred in previous section.

By detecting phase difference between transmitted signals, TDOA information is acquired. Then, using (13), the distance value is easily obtained. Fig. 5 shows the result of trilateration at (3, 3) on the bottom. As we can see in Fig. 5, a point of intersection of three circles also indicates (3, 3).

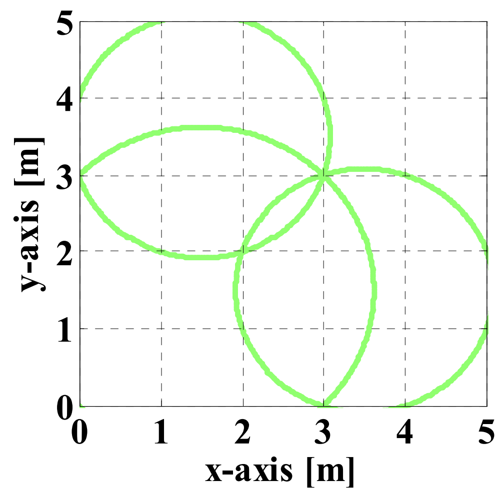


Fig. 5. The result of trilateration at (3, 3)

We evaluated the performance of location error at every point on the bottom xy-plane. Fig. 6 shows the result of location error.

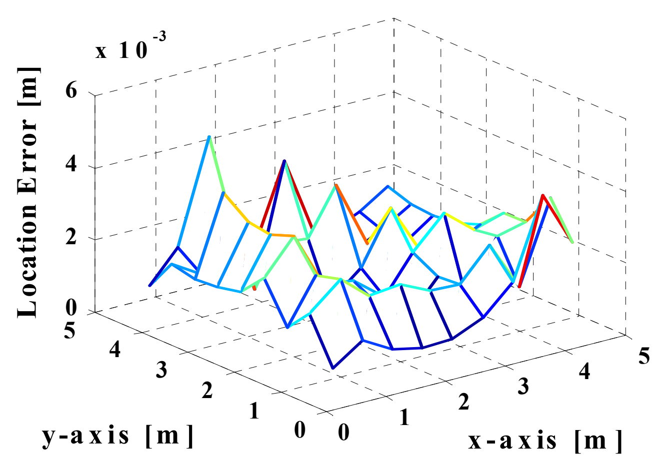


Fig. 6. Location Error on the bottom xy-plain

Among 81 points on the bottom xy-plain, the maximum location error was 4.5 mm and the mean of location errors was 1.8 mm. Using this method, we can estimate location very accurately. Fig. 7 depicts the effect of F-ID1 on the location error.

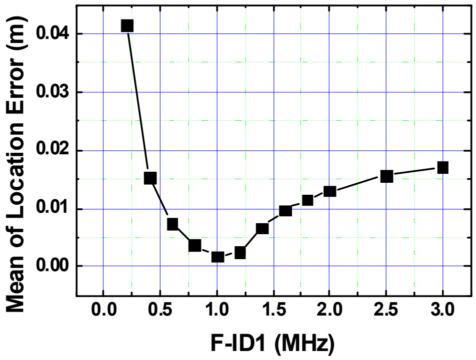


Fig. 7. Effect of F-ID1 on the performance

As shown in Fig. 7, when F-ID1 is 1 MHZ, the best performance was achieved. When F-ID1 is less than 1 MHz the mean of location errors is increased because the frequency is inversely proportional to a resolution, and it is directly related to the location error. On the other hand, in the region above 1 MHz, an optical wireless channel is distorted for F-ID3 whose frequency is 5 times of F-ID1, and the location error is increased. Based on these results, 1 MHz is the best choice for F-ID1.

V. Conclusion

We proposed an indoor localization method based on TDOA using LED ceiling lamps. A unique frequency address was assigned to each LED lamp, and using LED properties such as lighting and switching, assigned frequency-ID were transmitted while LED ceiling lamps were utilized for illumination.

TDOA localization algorithm was used to estimate the target position. The localization method was performed via computer simulation. Three LED lamps were employed in simulation model space with dimensions of 5 m x 5 m x 3 m. The maximum and mean values of location errors during simulation were 4.5 mm and 1.8 mm, respectively.

This proposed positioning system possibly represents an effective candidate for future indoor localization under LED ceiling light environments. Moreover, not only can indoor robotic behavior be improved, but smarter mobile networking can be realized using the proposed positioning technology.

References

[1] J. Hightower and G. Borriello, “Location sensing techniques”, Technical Report UW CSE 2001-07-30, Department of Computer Science and Engineering, University of Washington, 2001.

[2] C. Drane, M. Macnaughtan, and C. Scott, "Positioning GSM telephones," *IEEE Commun. Mag.,* vol. 36, no. 4, pp. 46-54, 59, Apr. 1998.

[3] P. Kontkanen, P. Myllymaki, T. Roos, H. Tirri, K. Valtonen, and H. Wettig, "Topics in probabilistic location estimation in wireless networks," *in Proc. 15th IEEE Symp. Pers., Indoor, Mobile Radio Commun., Barcelona, Spain,* vol. 2, pp. 1052-1056, Sep. 2004.

[4] R.Want, A. Hopper, V. Falcao, and J. Gibbons, “The active badge location system,” *ACM Trans. Inf. Syst.*, pp. 91-102, Jan. 1992.

[5] A. Harter, A. Hopper, P. Steggles, A. Ward, and P. Webster, "The anatomy of a context-aware application," *MOBICOM 1999*, August 1999.

[6] N. B. Priyantha, A. K. L. Miu, H. Balakrishnan, and S. Teller, "The cricket compass for context-aware mobile applications," *7th ACM Conf. MOBICOM* July 2001.

[7] P. Bahl and V. N. Padmanabhan, “RADAR: An in-building RF-based user location and tracking system,” *in Proc. IEEE INFOCOM 2000*, Mar., vol. 2, pp. 775-784.

[8] J. Hightower, R. Want, and G. Borriello, "SpotON: An indoor 3D location sensing technology based on RF signal strength," *Univ. Washington, Seattle, Tech. Rep. UW CSE* 2000-02-02, Feb. 2000.

[9] S. Gezici, Z. Tian, G. V. Giannakis, H. Kobaysahi, A. F. Molisch, H. V. Poor, and Z. Sahinoglu, “Localization via ultra-wideband radios: A look at positioning aspects for future sensor networks,” *IEEE Signal Process. Mag.*, vol. 22, no. 4, pp. 77-84, Jul. 2005.

[10] J. Hallberg, M. Nilsson, and K. Synnes, "Positioning with bluetooth," *in Proc. IEEE 10th Int. Conf. Telecommun.,* vol. 2, pp. 954-958, Mar. 2003.

[11] J. H. Reed, K. J. Krizman, B. D. Woerner, and T. S. Rappaport, "An overview of the challenges and progress in meeting the E-911 requirement for location service," *IEEE Commun. Mag.* vol. 36, no. 4, pp. 30-37, Apr. 1998.

[12] H. Liu, H. Darabi, P. Banergee, and J. Liu, "Survey of wireless indoor positioning techniques and systems," *IEEE Trans. Syst., Man, Cybernet.,* vol. 37, no. 6, Nov. 2007.

[13] K. Pahlavan, X. Li, and J. Makela, "Indoor geolocation science and technology," *IEEE Commun. Mag.*, vol. 40, no. 2, pp. 112-118, Feb. 2002.

[14] T. Tamura, T. Setomoto and T. Taguchi, "Fundamental characteristics of the illuminating light source using white LED based on InGaN semiconductors," *Trans. IEE Japan*, vol. 120-A, no. 2, pp. 244-249, 2000.

[15] T. Komine, Y. Tanaka, S. Haruyama and M. Nakagawa, "Basic study on visible-light communication using light emitting diode illumination," *Proc. of 8th International Symposium on Microwave and Optical Technology (ISMOT 2001)*, Montreal, Canada, pp. 45-48, 2001.

[16] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," *IEEE Transactions on Consumer Electronics,* vol. 50, no. 1, pp. 100-107. 2004.

[17] Y. Tanaka, T. Komine, S. Haruyama, and M. Nakagawa, "Indoor visible communication utilizing plural white LEDs as lighting," *in the 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2001),* San Diego, CA, pp. F81-F85, Sept. 2001.

[18] H. Le-Minh, L. Zeng, D. C. O'Brien, O. Bouchet, S. Randel, J. Walewski, J. A. R. Borges, K.-D. Langer, J. G. Grubor, K. Lee, and E. T. Won, "Short-range visible light communications," *Wireless World Research Forum*, 2007.

[19] J. Grubor, J.-O. Gaete, J. Waleski, S. Randel, and K.-D. Langer, "High-speed wireless indoor communication via visible light," *ITG Fachbericht*, pp.203-208, 2007.

[20] J. M. Kahn, J. R. Barry, M. D. Audeh, J. B. Carruthers, W. J. Krause, and G. W. Marsh, "Non-directed infrared links for high-capacity wireless LANS," *IEEE Personal Commun. Mag.*, 1994.

[21] F. R. Gfeller and U. H. Bapst, “Wireless in-house data communication via diffuse infrared radiation,” *Proc. IEEE*, vol. 67, no. 11, pp. 1474–1486 (1979).

[22] J. M. Kahn and J. R. Barry, “Wireless infrared communication,” *Proc. IEEE,* vol. 85, pp. 265–298, 1997.

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