Indoor Visible Communication utilizing Plural White LEDs as Lighting

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***Abstract*—Future electric lights will be composed of white LEDs (Light Emitting Diodes). Indoor wireless optical communication systems utilizing white LED lights have been proposed from our laboratory and we have been studying about it. Generally, plural lights are installed in our room. Therefore, their optical path difference must be considered. In this paper, the influence of an optical path difference has been investigated and two approaches against this problem are introduced. One uses OOK-RZ (Of-Off Keying, Return-to-Zero) coding and the other uses optical OFDM (Orthogonal Frequency Division Multiplexing). From the results of computer simulations, we have found that these approaches are feasible for the wireless optical communication systems utilizing white LED lights.**

I. Introduction

In the 21st century, high speed data transport will play an important roll in our life. We will be able to have many kinds of information, which are so called multimedia information, at any place and any time. Of course, the high speed data will come not only to offices but also to our homes. Therefore the concept of wireless home link (WHL) has been proposed and drawing considerable attention [1]. The electrical appliances will be wireless-linked with each other in the 21st century. Using WHL, we will be able to access the worldwide Internet with these appliances anywhere in our home.

Wireless optical communication can be considered as a candidate for WHL [2]. It is suitable for WHL which requires high speed wireless link. The wireless optical link is suitable for a non-public network, or a consumer communication network, such as WHL which is the topic here because they do not require any licenses. Moreover, lightwaves are obstructed only by physical obstacles, and it is easy to prevent the interference from adjacent rooms. Wireless optical communication occupies no radio frequency spectrum and it can be used where electromagnetic interference is strictly prohibited (hospitals, air planes, and so on). Therefore the transmission by lightwaves is more suitable for indoor wireless networks than the one by radio waves.

On the other hand, white LEDs (Light Emitting Diodes) are also drawing much attention [3]. They are considered as lighting for the next generation. However, it was impossible to obtain white LEDs until recently due to the lack of highly efficient blue and green LEDs. Now, InGaN based highly efficient blue and green LEDs have become commercially available. Using these LEDs, it is possible to fabricate white LEDs by mixing the three primary colors (red, green and blue). The white LEDs have bright output, high power efficiency and long lifetime. They will play a principal part instead of incandescent or fluorescent lights in our home.

We have proposed a wireless optical communication system utilizing white LEDs for wireless home link [4,5]. In this system, lighting equipment is able to have a capacity for wireless optical communication. The proposed system has the following advantages:

- Communication throughout the whole room will be enabled by high power lighting equipment.
- Lighting equipment with white colored LEDs is easy to install and nice looking.

In this system, an optical path difference must be considered when plural lights are utilized. Thus here, the influence of an optical path difference has been investigated and two approaches against this problem are introduced. One uses OOK-RZ (On-Off Keying, Return-to-Zero) coding and the other uses optical OFDM (Orthogonal Frequency Division Multiplexing) [6]. Through computer simulations, we found that these approaches are feasible for the wireless optical link utilizing white LEDs.

This paper is organized as follows. In section 2, the proposed indoor wireless optical link is introduced and a computer simulation model is described. The influence of an optical path difference is discussed in section 3 and section 4 presents the computer simulation results in the assumed channel model. And finally, we give our conclusions in section 5.

II. System Description

A. Proposed System

We have proposed a wireless optical communication system utilizing indoor LED lights and have been studying about it. The proposed system image is drawn in Fig. 1.

Information arriving at home flows into a home network and is taken out from optical access points in each room. These access points are composed of white LEDs and have a function

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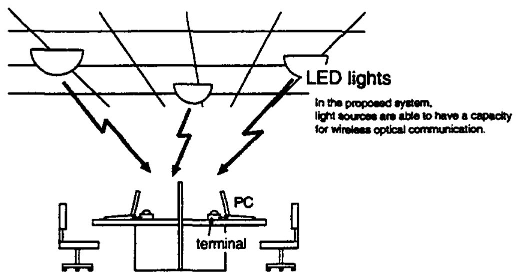

Fig. 1. A proposed system image in a room: wireless optical communication system also working as indoor lighting.

of lighting simultaneously. White LEDs in the access points do not only illuminate our room but also modulate electric signals into visible lightwave signals and these signals are emitted into the air. Since blinking of modulated lightwaves is very fast, we cannot sense it. Therefore, the function of lighting is not spoiled by a wireless optical communication. In this system, IM-DD (intensity modulation & direct detection) is applied as optical modulation and a directed LOS (line-of-sight) link is assumed. In the directed LOS link, an optical path is not obstructed. Transmitted optical pulses from LED lights are received at a user terminal. The user terminal is composed of PDs (Photo Diodes) and can convert optical pulses into electric signals.

In the proposed system, the consideration for illuminance of LED lights is required. Generally, illuminance of lights is standardized by ISO (International Organization for Standardization). In this standard, illuminance of $200 \sim 1000$[lx] is required for our offices to work. From the results of our numerical analyses [4, 5], sufficient communication and illuminance are possible with $600 \sim 1000$ white LEDs.

B. Wireless Optical Channel

In this paper, we assume a wireless optical channel and this is applied to computer simulations.

In an optical link, the channel DC gain is given by [2] as:

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

where A is the physical area of a detector in a 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 a field of vision at a receiver. The optical concentrator $g(\psi)$ can be given as:

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

where n denotes the refractive index.

C. Noise Model

Secondly, in this paper, we assume that the noise model is an Additive White Gaussian Noise (AWGN) model. In an optical channel, originally, the quality of transmission is dominated by shot noise [2, 7]. 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 [8]. Accordingly, the wireless optical channel model is expressed as follows:

$$y(t) = x(t) \otimes H(\tau) + n(t), \tag{3}$$

where $y(t)$ represents the received signal current and $x(t)$ represents the transmitted optical pulse and $n(t)$ represents the AWGN noise with the symbol $\otimes$ denoting convolution.

In the proposed system, a directed LOS path is assumed. Thus transmitted pulses are not obstructed and the relation $H(\tau) = H(0)$ stands. The received optical power P_r is derived by the transmitted optical power P_t as follows:

$$P_r = H(0) \cdot P_t. \tag{4}$$

Furthermore, multipath fading can be neglected in wireless optical channel. In our channel model, information carrier is lightwave whose frequency is about 10^{14}[Hz]. Hence, the Doppler frequency of fading is higher than the data rate. Moreover, detector dimensions are of the order of thousands of wavelengths, leading to efficient spatial diversity that prevents multipath fading. Due to the above reasons multipath fading can be neglected.

III. Optical Path Difference

A. Influence of an optical path difference

In the proposed system which utilizes multiple lights, an optical path difference must be considered. This is caused by delay time due to plural transmitters as shown in Fig. 2. When two transmitters are assumed to be used, a ratio of delay to pulse width is

$$\frac{t_d}{1/R_b} = \frac{R_b \cdot (\sqrt{(w-x)^2 + h^2} - \sqrt{x^2 + h^2})}{c}. \tag{5}$$

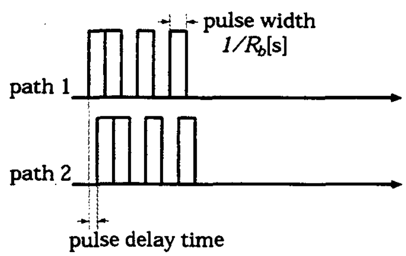

Fig. 2. Pulse delay due to an optical path difference.

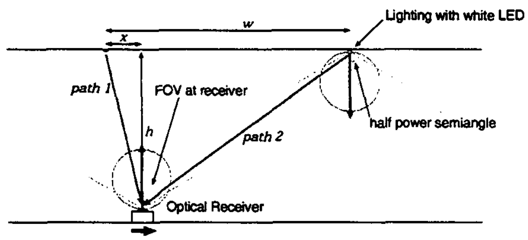

Fig. 3. Calculation of an optical path difference.

where c is the speed of light and R_b[bps] is the rate of optical pulses. The meaning of other abbreviations is shown in Fig. 3.

Fig. 4 shows a BER performance of an optical subcarrier BPSK system. In this simulation, the situation described in Fig. 3 is assumed. The parameters listed in Table I are applied. Optical signals are arrived at a terminal through two directed LOS paths. The width between two transmitters w is 10.0[m] and the height of room h is 3.0[m]. The terminal positions x are 0.0,2.0,5.0[m]. From this figure, it is found that the delayed signal degrade the performance when a terminal is distant from a optical transmitters. When the teminal is set just under a transmitter, the floor can be seen and we cannot communicate. At this time, the delay time is 9.46[ns] and the DUR is 8.66[dB].

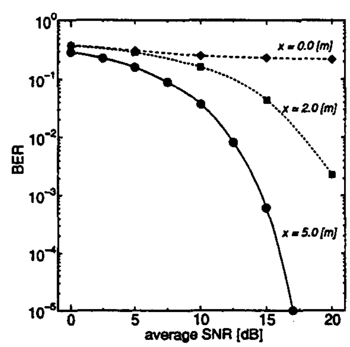

Fig. 4. BER performance of single carrier BPSK under LOS path, R_b = 100[Mbps].

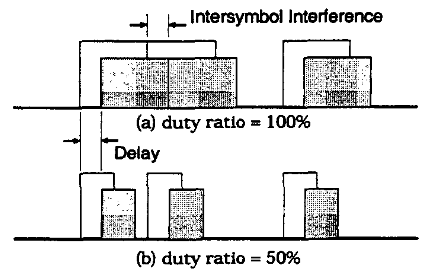

Fig. 5. OOK-RZ coding can alleviate a delay effect.

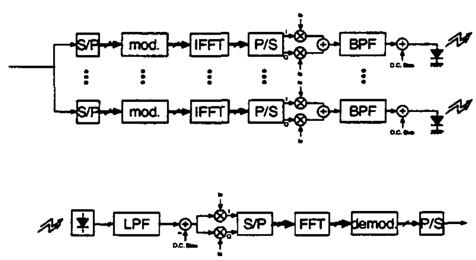

Fig. 6. A computer simulation model of an optical OFDM system.

B. OOK-RZ and Optical OFDM

In this paper, two approaches against this problem are discussed. An OOK-RZ (On-Off Keying Return-to-Zero) coding is considered as a candidate for alleviating the optical path delay. Ordinary OOK utilizes the continuous pulses, whereas "1" pulses have a period being zero in OOK-RZ coding. This is shown in Fig. 5. Thus, the ratio r is defined in this paper as:

$$r = \frac{\text{“1” period}}{\text{symbol duration}}. \tag{6}$$

As shown in Fig. 5, the OOK-RZ coding has a guard time and can alleviate a delay effect. These pulses require a wide transmission bandwidth. However, this is not significant because an optical carrier has wide bandwidth available.

Another approach is the one using OFDM (Orthogonal Frequency Division Multiplexing). In an optical OFDM system, the delay is absorbed by a guard interval of an OFDM symbol. The system is shown in Fig. 6, in which T transmitters are assumed. The original data bits are copied to each transmitters, which is composed of LEDs. In each transmitter, an information sequence is converted to N parallel symbols with S/P (serial to parallel) converter and modulated in each branch. Then the modulated parallel symbols are converted into the sum of N different subcarriers by IFFT (Inverse Fast Fourier Transform) and guard intervals are inserted. This is the way how OFDM

TABLE I

SIMULATION PARAMETERS.

Semiangle at half power	60.0[deg.]
FOV of a terminal	74.0[deg.]
Optical Power of each light	15.0[dBm]
Index of optical concentrator	1.5
Physical area of a PD	1.0[cm^2]
Primary modulation	OOK-RZ, OFDM-BPSK
Original data rate	100,400[Mbps]
O/E conv. efficiency	0.53[A/W]
Optical channel	directed LOS path (only AWGN channel)
background light noise (assumed to be an AWGN)	0.0[dBm] (1.0[mW])
O/E conversion efficiency	0.53

signals are generated. These signals are converted into optical intensity by an O/E (optical to electrical) converter, and finally emitted into the air. At a terminal, the received lightwave is converted into an electrical waveform by a PD. This waveform, which is an OFDM modulated signal, is demodulated by OFDM demodulator and the original data bits are retrieved.

IV. Simulation Results

In this section, we will discuss the computer simulation results. Table I shows the general simulation parameters. The channel is assumed to be an indoor channel as described in section II. Intensity Modulation and Direct Detection (IM-DD) are used as optical modulation schemes. The error property does not depend on the wavelength of carriers because this system adopts IM-DD. Noise in an optical transmission is assumed to be an AWGN and its power is 0.0[dBm]. An O/E conversion efficiency of a PD is 0.53[A/W].

In the beginning, we will examine the influence of an optical path difference. Figs. 7 and 8 show the BER performance of an OOK-RZ coding versus the received optical power at a user terminal. The horizontal axis shows the received optical power and the vertical axis shows the BER. In Fig. 7, the original data rate is 100[Mbps], whereas for Fig. 8, 400[Mbps].

A pulse ratio r on an OOK-RZ coding is 50, 75, 100% of the original data rate. The average transmitted power per symbol is fixed even though a pulse ratio varies. The following three cases are assumed as an optical path difference:

1. D/U ratio = 0.00[dB], delay = 0.00[ns]. (This represents the case with no delay.)
2. D/U ratio = 2.60[dB], delay = 2.90[ns]. ($w = 10.0$[m], $h = 3.0$[m], $x = 4.5$[m] in Fig. 3)
3. D/U ratio = 2.60[dB], delay = 5.90[ns]. ($w = 10.0$[m], $h = 3.0$[m], $x = 4.5$[m] in Fig. 3 with delay 3.0[ns], which is required for transmission on an electric wire.)

From Fig. 7, we can find that the difference of a pulse ratio does not affect the performance when delay time is 0.00[ns], that is a case without delay. On the other hand, large delay degrades the performance of an OOK coding (pulse ratio = 100%), whereas an OOK-RZ coding alleviates the influence of delay. Fig. 8 shows us that a delay path degrades the performance seriously. Moreover the improvements by using an OOK-RZ coding are not clear. This is because although OOK-RZ is applied, the symbol duration of 400[Mbps] pulses is 2.5[ns], and the pulse width of an OOK-RZ coding is almost similar to the delay time.

Now, we will discuss the influence of an optical path difference in case of applying the optical OFDM.

In the following simulations, the number of carriers is 8. Figs. 9 and 10 show the BER performance of an optical OFDM system. Two transmitters are assumed to be used and delay and DUR configurations are the same as mentioned previously. In Fig. 9, the original data rate is 100[Mbps], whereas the date rate in Fig. 10 is 400[Mbps].

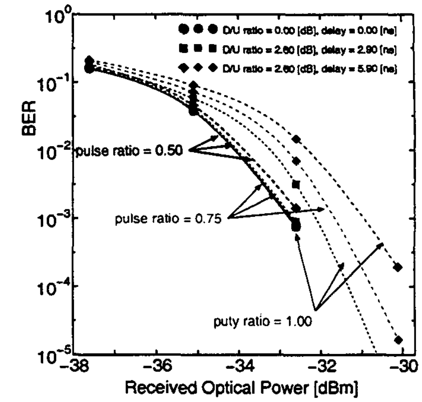

Fig. 7. BER vs. received optical power; an OOK-RZ coding is assumed, pulse ratio is 50, 75, 100% of the original data rate, R_b = 100[Mbps].

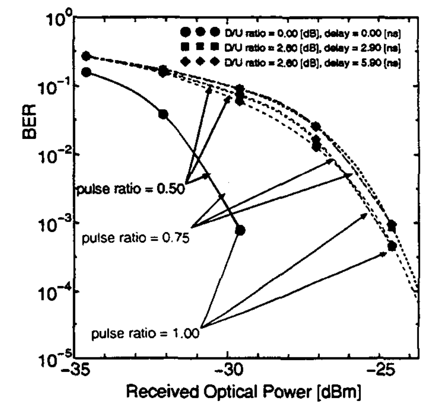

Fig. 8. BER vs. received optical power; an OOK-RZ coding is assumed, pulse ratio is 50, 75, 100% of the original data rate, R_b = 400[Mbps].

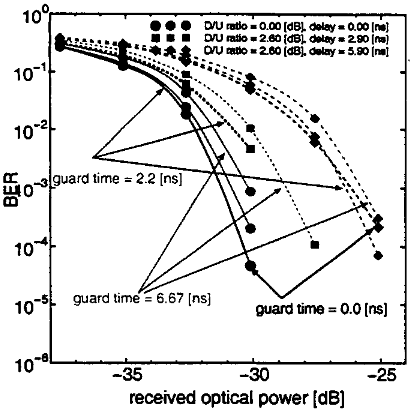

Fig. 9. BER vs. received optical power; the number of subcarriers is 8, original data rate is 100[Mbps] (effective OFDM symbol duration is 80.0[ns]).

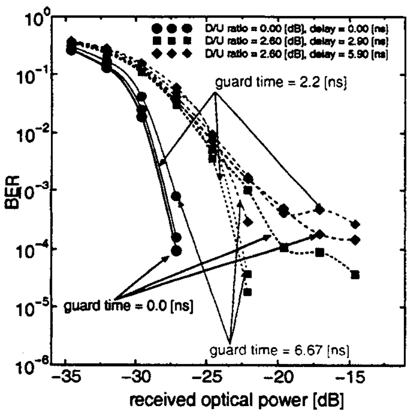

Fig. 10. BER vs. received optical power; the number of subcarriers is 8, original data rate is 400[Mbps] (effective OFDM symbol duration is 20.0[ns]).

Fig. 9 shows the BER performance at 100[Mbps]. A floor cannot be seen in this figure. This is because OFDM symbol duration is 80[ns] when the data rate is 100[Mbps]. Therefore delay time is much smaller than the OFDM symbol duration and the influence of delay is almost negligible. Consequently, a guard interval is not required because it degrades the power efficiency. The performances at 400[Mbps] are shown in Fig. 10. A floor can be seen in the case using OFDM without guard intervals when there is a delayed signal (i.e., delay $= 2.90, 5.90$[ns]), whereas a floor cannot be seen in the performance of OFDM with guard interval. These results show us that the guard interval of optical OFDM can improve the performance in our proposed system.

V. Conclusion

Indoor wireless optical communication systems utilizing white LED lights have been proposed in our laboratory. An optical path difference, however, must be considered in this system when plural lights are assumed to be utilized. In this paper, the influence of an optical path difference has been investigated and two approaches to reduce the delay has been introduced.

It was found from the computer simulation results that delay due to an optical path difference affects the performance when the original data rate is high. A high data rate transmission will be required in the future and thus this delay problem needs to be solved. An OOK-RZ coding mitigates the influence of delay when the data rate is 100[Mbps], whereas improvement of performance cannot be seen so much at 400[Mbps]. When optical OFDM is utilized, delay does not give a large impact at 100[Mbps] and a guard interval will not be required. At 400[Mbps], optical OFDM with guard intervals inserted improves the performance. In conclusion, OOK-RZ is effective when the data rate is relatively low. OFDM with guard intervals has the effect for an optical path difference in high speed data transmission. Further research on these would make an LED light communication feasible.

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