

PAPER

Experimental Investigation of Modulation Method for Visible-Light Communications

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SUMMARY We have developed a new modulation method—inverted pulse position modulation (I-PPM) and subcarrier inverted pulse position modulation (SC-I-PPM)—that provides superior LED brightness for visible-light communications. In addition, the new modulation method SC-I-PPM is not affected by background light. In this paper, we investigated several modulation methods in details and set up a standard with which to evaluate the performance of modulation methods. Several modulation methods are subjected to experiments to clarify their performance. Experiments show that subcarrier modulation suppresses the influence of background light and that our new modulation best maintains LED brightness.

key words: visible-light communication, optical wireless communication, LED, modulation, PPM

1. Introduction

The rapid diffusion of portable communication terminals such as cellular phones has elevated the importance of indoor wireless communication and wireless local-area networks. We note that Light Emitting Diodes (LEDs) offer many advantages in terms of lower power consumption, longer life, and the ability to be downsized. They are expected to become the dominant light source in future illumination systems. Our laboratory developed an indoor visible-light communication system that uses LED light, not only for illumination but also for optical wireless communication [1], [2]. The image of visible-light communication system is shown in Fig. 1. This system has the following advantages:

- We can use the large illumination power for wireless communication.
- Propagation area is limited; it is safe system free of eavesdropping.
- Illumination exists everywhere; we can build a ubiquitous environment easily.

The problem is offsetting the impact of background lights, such as fluorescent lamps, on communications. It is important that stable data transmission be provide even if the background light is strong. The modulation method used must offer high robustness to background light. Since the LED light used for communication must also provide stable illumination, the LED's output should be as bright as possible.

Since the performance of existing modulation methods

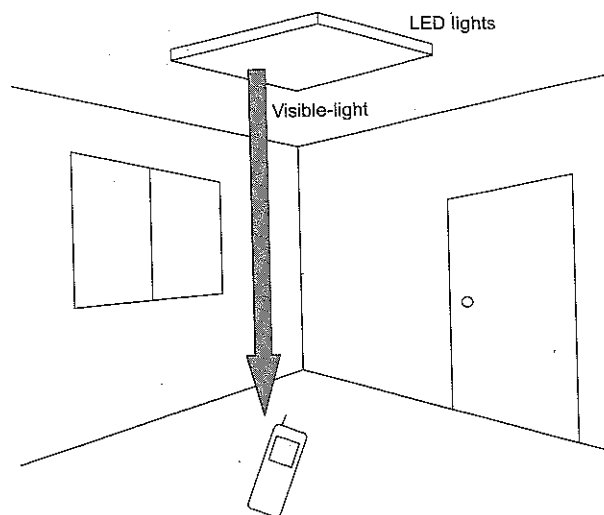


Fig. 1 Visible-light communication system using LED light.

has not been clarified, this paper conducts several experiments on the effect of background light and LED brightness. Furthermore, we present two new schemes, inverted pulse position modulation (I-PPM) and subcarrier inverted pulse position modulation (SC-I-PPM), for visible-light communication. A standard that can evaluate the performance of modulation methods is introduced.

This paper is organized as follows. In Sect. 2, we describe the optical channel. Section 3 describes modulation methods for visible-light communication including the new schemes. Section 4 introduces the evaluation standard and describe experimental conditions. Section 5 describes the performance of the modulation methods examined. In Sect. 6, we discuss the relationship between received power and communication area analytically. In Sect. 7, we set out our conclusions.

2. Optical Channel

We assume that the noise is AWGN (Additive White Gaussian Noise) and also assume that interference is generated by background light. The optical wireless channel model is expressed as follows [3], [4]:

$$Y(t) = RX(t) \otimes h(t) + N(t) + I(t), \quad (1)$$

where $Y(t)$ represents the received signal current, R is the detector responsivity, $X(t)$ represents the transmitted optical pulse, $h(t)$ is the impulse response, $N(t)$ represents

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the AWGN, $I(t)$ represents the interference from the background light, and symbol \otimes means convolution. The average optical power P_t is given by

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

The optical power loss is expressed by the channel DC gain

$$H(0) = \int_{-\infty}^{\infty} h(t) dt, \quad (3)$$

where the average received power at the receiver is

$$P_r = H(0)P_t. \quad (4)$$

3. Modulation Methods

3.1 Pulse Position Modulation (PPM)

PPM is widely used in intensity-modulation optical communication systems, such as fiber optic communication systems, satellite systems, and wireless infrared communication systems because of its high average power efficiency. The symbol interval of duration T is divided into L sub-intervals and to signify the i -th symbol, the optical intensity is "on" during the i -th sub interval and "off" everywhere else [3], [4]. In other words, bits are transmitted by the position where the pulse exists. Figure 2 shows a block diagram of an L-PPM transmitter.

The input bits with bit rate R_b are grouped in blocks of length $\log_2 L$ at a symbol rate of $1/T = R_b / \log_2 L$, and from each block one of L possible signals is chosen to be transmitted. The output of the unit amplitude encoder block of Fig. 2 during the k -th baud interval $t \in [kT, (k+1)T)$ is given by $p_{i[k]}(t - kT)$, where $i[k] \in \{1, 2, \dots, L\}$ denotes the position of the "on" sub-interval during the k -th baud interval, and where $\{p_i(t)\}$ is a family of pulse shapes given by

$$p_i(t) = \begin{cases} 1, & t \in [(i-1)T/L, iT/L) \\ 0, & \text{elsewhere} \end{cases}, \quad i \in \{1, 2, \dots, L\}. \quad (5)$$

$b(t)$ which is the transmitted value at slot k is expressed as follows:

$$b(t) = p_{i[k]}(t). \quad (6)$$

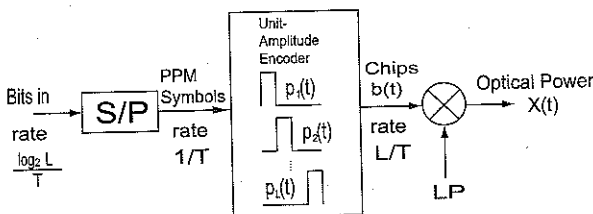


Fig. 2 Block diagram of L-PPM transmitter.

The output of the encoder is scaled by a factor LP to ensure that the resulting intensity $X(t)$ has an average value of P .

$$X(t) = LP \sum_k b(t - kT). \quad (7)$$

3.1.1 Conventional PPM

Figure 3 shows transmitted waveforms with conventional PPM ($L=2, 4$). When we set the amplitude of transmitted waveforms to A , average transmitted power of 2PPM is $A/2$, that of 4PPM is $A/4$, and that of L-PPM is A/L .

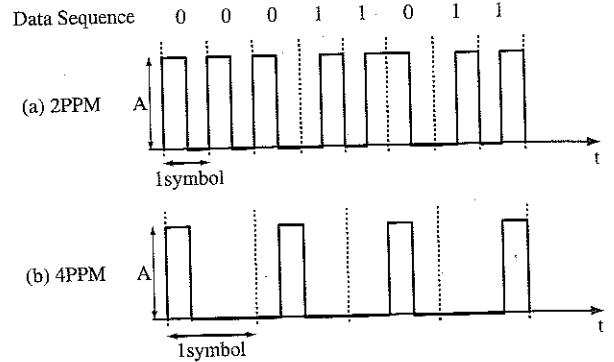


Fig. 3 Transmitted waveforms with (a) 2PPM, and (b) 4PPM.

3.1.2 Inverted PPM (I-PPM)

In the case of conventional PPM, we set only one pulse among L sub intervals. Average transmitted power, i.e. LED brightness, falls to $1/L$ when the peak amplitude is not changed. Of course, LED brightness can be made to equal with other modulation methods if we increase the amplitude L times, but this is not practical given that all LEDs have some peak power constraint.

We present new modulation method, I-PPM, that yields higher LED brightness than conventional PPM. The I-PPM waveform is made by inverting the pulse position. The optical intensity is "off" during the i -th sub interval and "on" everywhere else. We propose to change $p_i(t)$ as follows:

$$p_i(t) = \begin{cases} 0, & t \in [(i-1)T/L, iT/L) \\ 1, & \text{elsewhere} \end{cases}, \quad i \in \{1, 2, \dots, L\}. \quad (8)$$

Fig. 4 shows a transmitted waveform with I-PPM ($L=4$). When the amplitude of the transmitted waveform is A , average transmitted power of I-4PPM is $3A/4$. I-4PPM makes the LED three times as bright as conventional 4PPM.

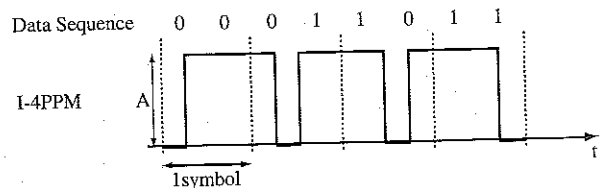


Fig. 4 Transmitted waveform with I-4PPM.

3.2 Subcarrier Pulse Position Modulation (SC-PPM)

As in PPM and I-PPM, the power spectra of transmitted signals are concentrated in the DC and low-frequency bands because of the use of rectangular pulses. Background light sources such as sunlight and fluorescent lamps have strong power spectrum in the same DC and low-frequency bands and so are likely to interfere with communications. Especially, the effect of fluorescent lamp will be extremely large because its spectrum has both the DC and low-frequency component, while the spectrum of sunlight contains only the DC component. In principle, subcarrier modulation can be made immune to fluorescent lamp noise by setting the subcarrier frequency high enough [4]. We can apply subcarrier modulation to visible-light communications.

3.2.1 SC-PPM

Figure 5 shows the transmitted waveform with SC-PPM ($L=4$). We replace the rectangular pulses with a subcarrier. This shifts the power spectrum of the signal to a higher frequency band. The signal component can be separated from the background light component by placing a suitable filter at the receiver side. When the amplitude of the transmitted waveform is A , average transmit power is $A/8$.

$p_i(t)$ is expressed by:

$$p_i(t) = \begin{cases} 1 - \cos(\omega t), & t \in [(i-1)T/L, iT/L] \\ 0, & \text{elsewhere} \end{cases}, \quad (9)$$

$i \in \{1, 2, \dots, L\}$.

where ω denotes subcarrier frequency.

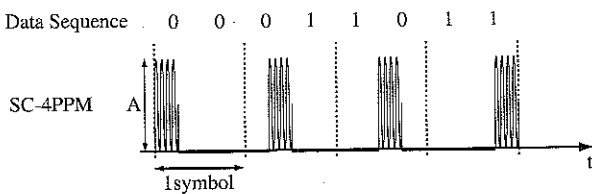


Fig. 5 Transmitted waveform with SC-4PPM.

3.2.2 SC-I-PPM

Figure 6 shows the transmitted waveform with SC-I-PPM ($L=4$). We can apply subcarrier technique to I-PPM. When the amplitude of the transmitted waveform is A , average transmit power is $7A/8$. The SC-I-4PPM approach enables the LED to be seven times brighter than is possible with SC-4PPM.

$p_i(t)$ is expressed by the following equation:

$$p_i(t) = \begin{cases} 1 - \cos(\omega t), & t \in [(i-1)T/L, iT/L] \\ 1, & \text{elsewhere} \end{cases}, \quad (10)$$

$i \in \{1, 2, \dots, L\}$.

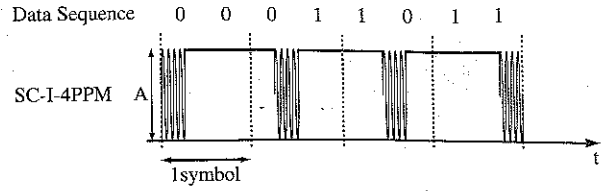


Fig. 6 Transmitted waveform with SC-I-4PPM.

3.3 Subcarrier Frequency Shift Keying (SC-FSK)

Figure 7 shows the transmitted waveform with SC-FSK. A bit stream is modulated to yield a radio frequency subcarrier, and this modulated subcarrier is used to modulate the instantaneous power of the transmitter. In SC-FSK, bits are transmitted by changing the frequency of the subcarrier.

With 2-level frequency shift keying the transmitted intensity is given by:

$$X(t) = P + P \sum_k p_{i[k]}(t - kT) \quad (11)$$

where $\{p_i(t)\}$ is a family of pulse shapes given by:

$$p_i(t) = \begin{cases} \cos(\omega_i t), & t \in [0, T] \\ 0, & \text{elsewhere} \end{cases}, \quad (12)$$

$i \in \{1 \text{ or } 2\}$.

where ω_i represents subcarrier frequency.

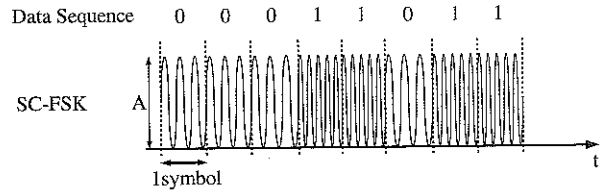


Fig. 7 Transmitted waveform with SC-FSK.

3.4 Subcarrier Phase Shift Keying (SC-PSK)

Figure 8 shows the transmitted waveform with SC-PSK. In SC-PSK, bits are transmitted by changing the phase of the subcarrier. With binary phase shift keying the transmitted intensity is given by:

$$X(t) = P + P \sum_k a_k p(t - kT) \quad (13)$$

where $a_k \in \{\pm 1\}$ represents the data sequence; $p(t)$ is the transmit pulse shape given by:

$$p(t) = \begin{cases} \cos(\omega t), & t \in [0, T] \\ 0, & \text{elsewhere} \end{cases} \quad (14)$$

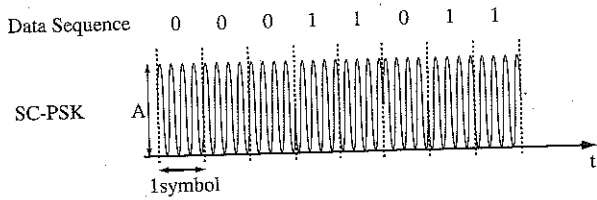


Fig.8 Transmitted waveform with SC-PSK.

4. Experiments

4.1 Conditions

We clarified the impact of background light through experiments. Table 1 shows the conditions of the experiments. A picture of the LED and fluorescent lamp used are shown in Figs.9 and 10, respectively. The LED was a "LXHL-PW01" manufactured by LUMILEDS. Diameter of LED was 5.8 mm. The transmitted optical power from the LED was 40 mW in the experiment on the same average power. We chose an inverter type fluorescent lamp as the background light. The fluorescent lamp was a "HHPFZ5251" manufactured by Matsushita Electric Works. Diameter of the fluorescent lamp was 55 cm. Since this fluorescent lamp is driven by electric ballast, this type is most likely to interfere with visible-light communication links. Figure 11 shows the experimental set up. We set the fluorescent lamp at 410 cm from the receiver. The received power from the fluorescent lamp was -13.6 dBm/cm^2 . At the receiver side, the signal was detected by a Photo Diode (PD). Figure 12 shows the transmitter and receiver setup. At the transmitter side, we used an arbitrary waveform generator to create the modulated signal, and transmitted data from the LED. At the receiver side, the received signal was amplified by 40 dB, converted into a digital signal, and recorded in an oscilloscope. After that, we demodulated the signal by digital processing with decision in a PC. We did not use an Automatic Gain Control (AGC). Figure 13 shows the frequency spectrum of each modulation method. In this figure, the DC component is not shown. The spectra of 2PPM, 4PPM and I-4PPM are the same except for the DC component. Figure 14 shows the frequency spectrum of the fluorescent lamp measured at 10 cm using the PD listed in Table 1. The fluorescent lamp emitted strong power from DC to several hundreds of kHz, which overlaps the spectrum of baseband modulation PPM and I-PPM. We performed measurements while changing the distance between the transmitter and receiver (100–400 cm), under the conditions with and without background light.

4.2 Standard Evaluation Method

In order to rank modulation schemes, we must first define a suitable evaluation method. Our approach is to use the same average power and the same peak power as defined below.

Table 1 Conditions.

Modulation	2PPM, 4PPM I-4PPM, SC-2PPM, SC-4PPM, SC-I-4PPM SC-FSK, SC-BPSK
Bit Rate	100 [kbps]
Subcarrier Frequency	1.5 [MHz] (SC-FSK 1.5 [MHz] \pm 300 [kHz])
Transmitted Bits	16000 (16k) [bits]
LED	White LED LXHL-PW01 Radiation Angle 70 [degrees]
PD	Si PIN PD (Physical Area 19.6 [mm ²])
Sampling Frequency	50 [MHz]
Antialiasing Filter	10 [MHz] Low Pass Filter
Digital Filter	300 Taps FIR Filter

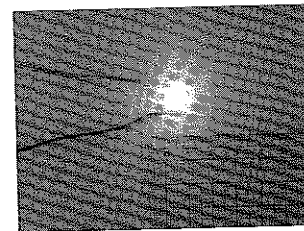


Fig.9 LED.

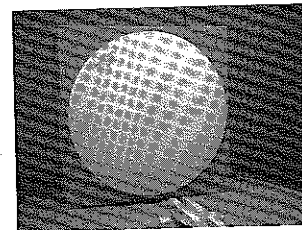


Fig.10 Fluorescent lamp.

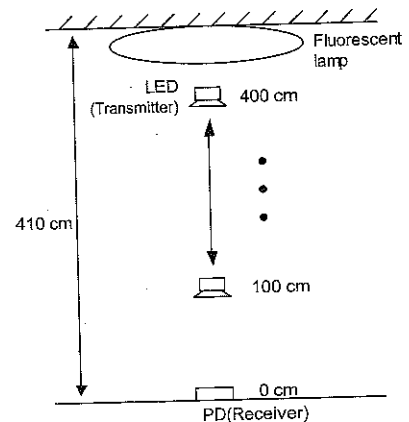


Fig.11 Experimental setup.

4.2.1 Same Average Power

Modulation methods are generally evaluated under same average power in optical wireless communication systems [3],

[4]. The average power constraint is a fundamental limit related to the conservation of energy and imposes a bound on the current that LED can consume per unit time. When we set the same average power among all modulation schemes, the LED has the same luminosity, a key critical target if we need to compare modulation schemes. Therefore we performed experiments under the condition of same average power.

4.2.2 Same Peak Power

The peak power constraint is particularly important in visible-light communications, because the LED has a peak power limit. Maximum current of existing LEDs is strictly regulated. The peak current indicates magnitude of load on the LED. It is of value to clarify the performance of modulation schemes under the same burden on the LED. Then,

we need to evaluate under the condition that peak power i.e. amplitude of each modulation is equal.

5. Results

5.1 Same Average Power

Figure 15 shows the performance of baseband modulation under same average power. Dashed (solid) lines show the performance without (with) background light. The Bit Error Rate (BER) of all baseband modulation schemes examined is degraded by background light. This is because the spectra of baseband modulation and fluorescent lamp overlap. The results show that baseband modulation schemes are not adequate when background light is strong.

Figure 16 shows the performance of subcarrier modulation under same average power. In this figure, the dashed and solid lines overlap. Subcarrier modulation is free from

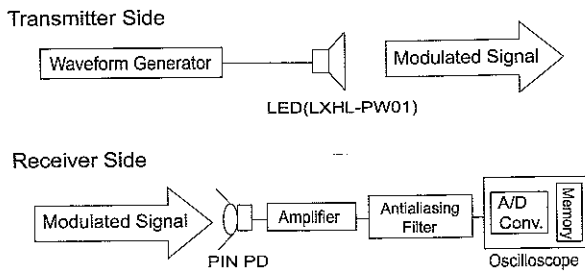


Fig. 12 Experimental equipment.

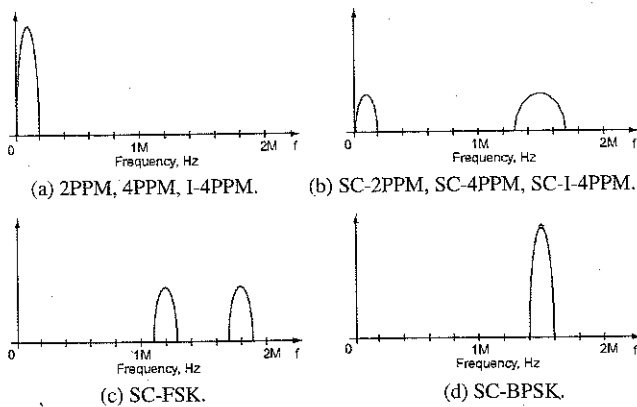


Fig. 13 Frequency spectrum of each modulation.

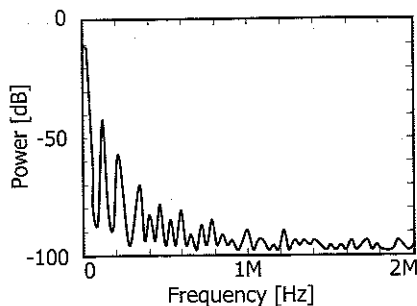


Fig. 14 Frequency spectrum of fluorescent lamp.

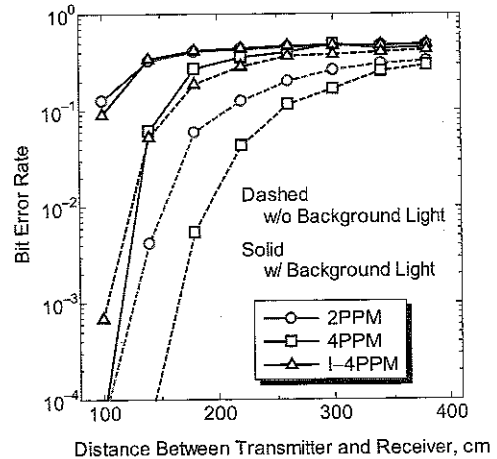


Fig. 15 BER of baseband modulation under same average power.

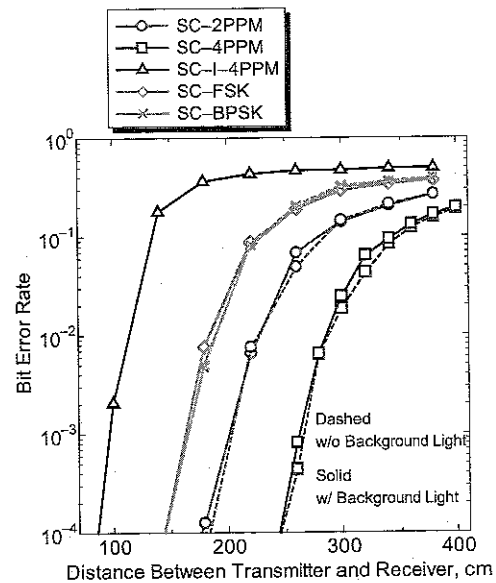


Fig. 16 BER of subcarrier modulation under same average power.

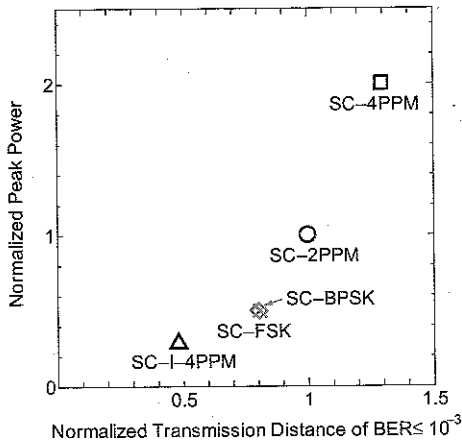


Fig. 17 Transmission distance versus peak power.

the effect of background light. This is because the spectra of the fluorescent lamp and subcarrier modulation do not overlap, see Fig. 13, Fig. 14. We can separate the signal component from the interference component easily by setting a band pass filter at the receiver side. Subcarrier modulation is useful for visible-light communication systems because data transmission is possible even if there is strong background light.

In this experiment, we set same average power among all modulation schemes, peak power is not considered. It is necessary to discuss both average and peak power to rank modulation schemes. We examine it in Fig. 17. Figure 17 shows the transmission distances that yielded the BER of at least 10^{-3} as a function of peak power. We consider only subcarrier modulation because baseband modulation is likely to be affected by background light and so is not suitable for visible-light communication. The vertical axis represents the peak power as normalized against that of SC-2PPM. It is preferable to have the lowest possible peak power in order to reduce the electrical stress placed on the LED. If the peak power is too large, the degradation speed of LED performance will be rapidly. SC-4PPM offers superior communication performance, but it requires high peak power. In contrast, SC-I-4PPM is inferior to other modulation in communication performance, but it is suitable for LED and drive circuit because it does not require high peak power. In other words, SC-I-4PPM is easy to implement even if the peak power constraint of the LED is severe. This is a great advantage for SC-I-4PPM from the point of view of electrical stress on the LED and implementation.

5.2 Same Peak Power

Figure 18 shows the performance of baseband modulation under same peak power. Along with same average power, baseband modulation allows the BER to be degraded by background light.

Figure 19 shows the performance of subcarrier modulation under same peak power. As with the case of same average power, the dashed and solid lines overlap. These results

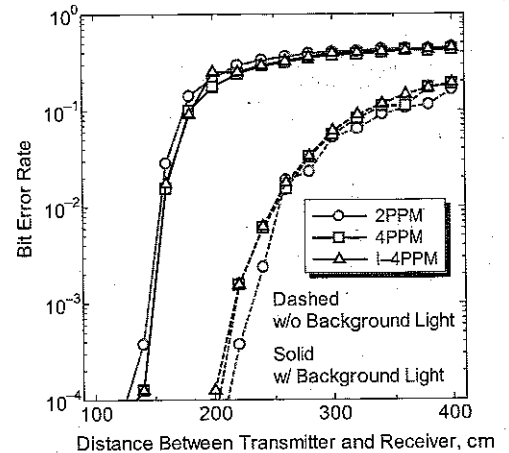


Fig. 18 BER of baseband modulation under same peak power.

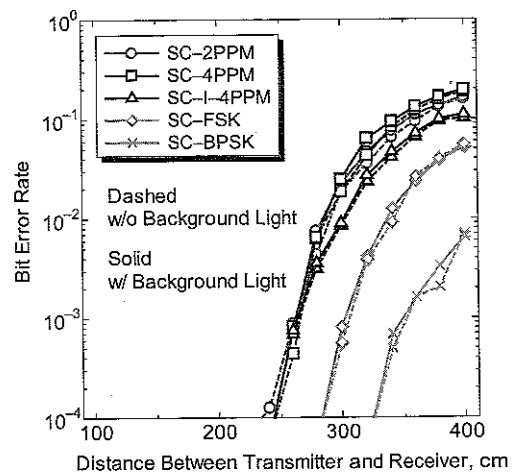


Fig. 19 BER of subcarrier modulation under same peak power.

show that subcarrier modulation is robust against fluorescent lamp noise if the subcarrier frequency is high enough.

In this experiment, we set same peak power among all modulation schemes, average power i.e. luminance of LED is not considered. We examine the luminance in Fig. 20. Figure 20 plots the transmission distances that yield BERs better than 10^{-3} versus LED luminance normalized by that of SC-2PPM. SC-BPSK yields the longest communication distance. SC-BPSK is the best modulation for communication link. On the other hand, SC-I-4PPM yields the highest LED luminance. In visible-light communication system, luminosity is very important because the main function of LEDs is not communication but illumination or indication. From the point of view of luminance, the proposed SC-I-4PPM has a great advantage over other modulation schemes.

The above result show that we should choose the modulation scheme according to the intended application. Without detailed specifications of the application, such as the expected room size, desired transmission distance, function of LED: illumination or indication, it is not possible to isolate a single modulation scheme as the definitive choice. All we

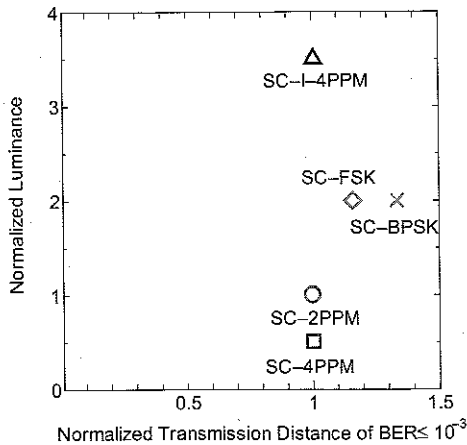


Fig. 20 Transmission distance versus luminance.

can do is point out relative advantages and disadvantages of modulation schemes in terms of communication distance and LED luminance, and leave it to the system designer to choose the scheme that best matches needs. For instance, we should choose SC-BPSK when we want make data communication over long distances and SC-I-4PPM when we want to make LEDs as bright as possible for illumination.

6. Discussion

The experiments in the previous section showed that data transmission distances of over 1 m as possible even if we use only one LED. However, practical illumination configurations will consist of many LEDs, so the communication area will be large. In this section, we discuss the relationship between received power and communication area. In this chapter, we ignore the effect of background light.

6.1 Analysis of Experimental Result

The channel DC gain $H(0)$ is expressed by [3], [4]:

$$H(0) = \frac{(m+1)A}{2\pi d^2} \cos^m(\phi) T_s(\psi) g(\psi) \cos(\psi) \quad (15)$$

where A is the physical detection area of the PD, d is the distance between LED and PD, ψ is the angle of incidence. $T_s(\psi)$ is the signal transmittance of the optical filter, and $g(\psi)$ is the concentrator gain. m is the order of Lambertian emission, which is given by the semiangle at half power of the LED $\Phi_{1/2}$ as

$$m = \frac{-\ln 2}{\ln(\cos \Phi_{1/2})} \quad (16)$$

In this experiment, the parameters were $\phi = 0$, $\psi = 0$, $T_s(\psi) = 1$, $\Phi_{1/2} = 70$ deg. Therefore, the received power on the optical axis is given by

$$P_{r \text{ optical axis}} = P_t \cdot \frac{(m+1)A}{2\pi d^2} \quad (17)$$

We set $P_t = 40$ mW in the experiment when we set the

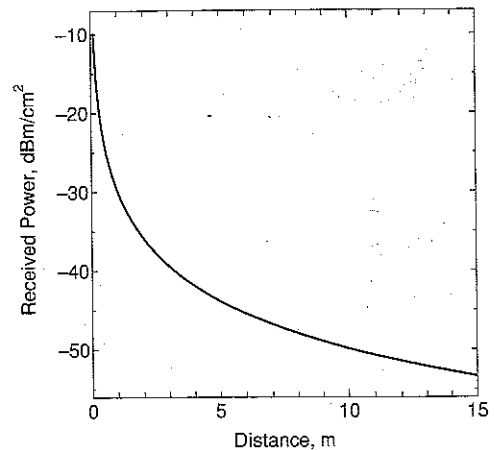


Fig. 21 Received power.

same average power for all modulation methods; the received power is as shown in Fig. 21.

Figures 15 and 16 show that the communication area is about 1 to 2.5 m, and there is some difference among the modulation methods. From the results of experiments and our analysis of received power, we need -40 to -30 dBm/cm² to achieve $\text{BER} \leq 10^{-3}$. In other words, the area where in the received signal power exceeds -30 dBm/cm² is the communication area. We used an amplifier with 40 dB gain in this experiment. In practice, we can increase the communication area by using a higher gain amplifier. For instance, the receiver of the typical infrared remote control uses an amplifier with over 60 dB gain.

6.2 Practical Environment

We assume that LED arrays will be used not only for illumination but also for communication. We analyzed the illuminance and received power at points 0.7 m from the floor in an indoor room model. A service area of 5.0 m \times 5.0 m is assumed in this analysis. We set four LED lights on the ceiling which was 3.0 m from the floor. Each light array consisted of 400 (20 \times 20) LEDs. The space between each LED was 2 cm. We set the transmitted optical power from 1 LED to 128.5 mW, the center luminous intensity was 9.41 cd. These are measured values of LXHL-PW01. Figure 22 shows the distribution of illuminance. From this figure, the illuminance ranges from 400 to 1300 lx. Acceptable illuminance, 300 to 1500 lx by ISO, is obtained in all places in the room. Therefore, these LED arrays will provide adequate room illumination. Figure 23 shows the received power at each point. Received power exceeds -8 dBm/cm² over the whole room. We showed in the previous subsection that communication is available when the received power exceeds -30 dBm/cm², so data transmission is possible anywhere in the room. Therefore, these LED arrays realize both good illumination and complete communication coverage at the same time.

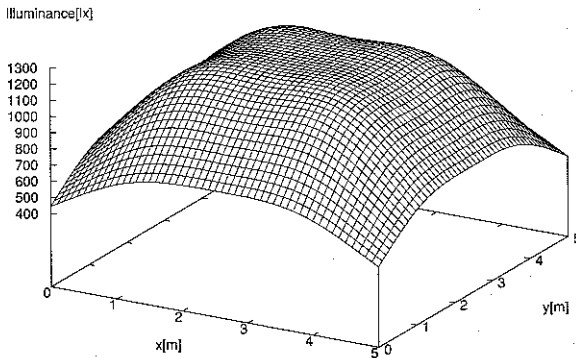


Fig. 22 Illuminance distribution.

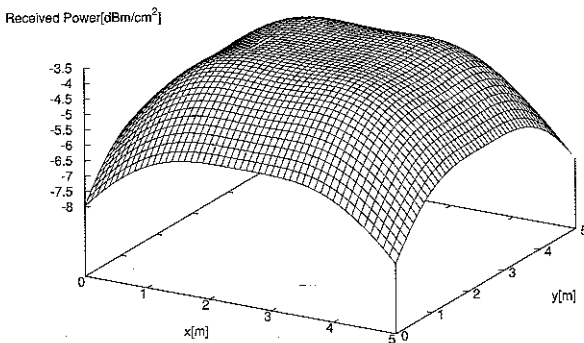


Fig. 23 Received power distribution.

7. Conclusion

We have developed two new modulation schemes: I-PPM and SC-I-PPM. I-4PPM provides three times as much luminosity as conventional 4PPM, while SC-I-4PPM offers seven times the luminosity of SC-4PPM.

We clarified the performance of modulation methods for visible-light communication through experiments. The results show that subcarrier modulation offers much greater immunity to background light than baseband modulation. With subcarrier modulation, data transmission can be free of the influence of background light sources such as fluorescent lamp.

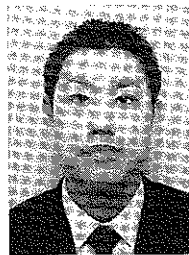
The modulation scheme adopted depends on the intended function of the LED lights and constraints. For example, we should choose SC-4PPM for best communication performance, and SC-I-4PPM for minimizing the load on LED devices under the average power constraint. We should choose SC-BPSK for best communication performance, and SC-I-4PPM for the best illumination performance i.e. LED luminosity. Furthermore, we showed that communication is possible over the whole room if we use LED illuminations as transmitters. Visible-light communication system will be feasible by adopting best suited modulation method.

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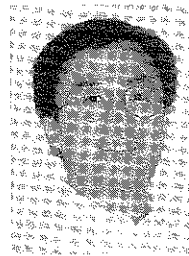
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