Indoor Channel Characteristics for Visible Light Communications

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***Abstract*—In this letter, we present indoor multipath dispersion characteristics for visible light communications (VLC). Since the VLC uses a wide spectrum between $380\ \mathrm{nm}$ and $780\ \mathrm{nm}$, the conventional narrowband model for infrared may not apply. We generalize the Barry's model by including wavelength-dependent white LED characteristics and spectral reflectance of indoor reflectors. We perform a computer simulation to compare the power delay profile of the VLC with that of infrared communications. From our studies, we show that the VLC provides a larger transmission bandwidth than infrared communications.**

***Index Terms*—Optical wireless communications, visible light communications, LED-lighting, and spectral reflectance.**

I. INTRODUCTION

VISIBLE light communication (VLC) is a short-range optical wireless communication utilizing LED lighting, so that the LED lights can provide both illumination and communication.

Many studies on channel characteristics for infrared (IR) have been made since the first study by Gfeller and Bapst in 1979 [1]. A computer simulation using a recursive method is presented in [2]. Characterization of wireless channel by measuring in various rooms is reported in [3]. All of these studies have assumed a narrowband near-monochromatic IR light source, so that the reflectance of reflectors is modeled as a constant, with no dependence on wavelength.

Several results about the VLC channel based on the recursive algorithm are presented [4], [5] where constant value of reflectance was also used for all wavelengths as in IR. There are some experimental studies of the VLC channel in [6], [7], but little attention has been given to the reflectance in the visible spectrum. Few attempts have been made to observe the features of power spectral distribution of reflected LED light and spectral reflectance of indoor finishing materials.

In this letter we extend the recursive algorithm of [2] to account for the wideband nature and power spectral distribution of the visible light source, and for the wavelength-dependent nature of reflectors.

II. MULTIPATH CHANNEL CHARACTERISTICS

In indoor environments, the received optical signal experiences time dispersion due to reflections from walls and other objects. Although specular reflections can occur from a mirror or other shiny object, most reflections are typically diffuse in nature, and most are well-modeled as Lambertian [1]–[3]. We assume that interior materials or indoor fixtures are purely diffusive.

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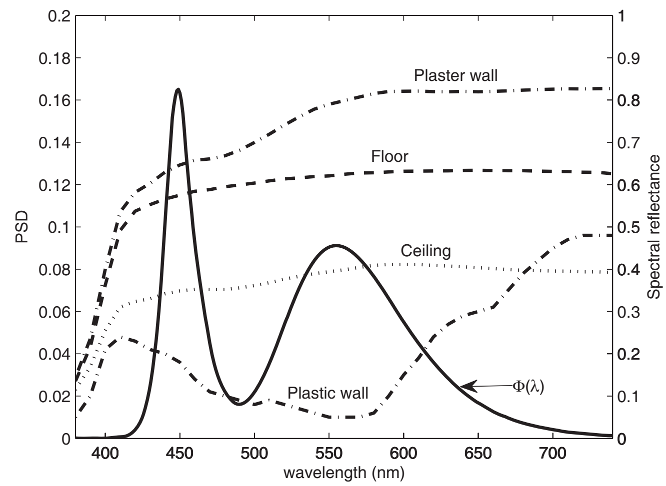

Fig. 1. The PSD (solid line, which corresponds to the left axis) is compared to the measured spectral reflectance (which corresponds to the right axis) of plaster and plastic wall (dash-dot line), floor (dash line), and ceiling (dot line).

A. *Optical source and indoor reflector*

The phosphor based white LEDs radiate wideband visible light. The radiant power from the white LEDs is widely distributed over the visible spectrum (from $380\ \mathrm{nm}$ to $780\ \mathrm{nm}$). Power spectral distribution (PSD), denoted as $\Phi(\lambda)$, describes the radiant power per unit wavelength of an illuminator [8]. The measured PSD for LED lighting (Kumho Electric, Inc.) is shown in Fig. 1. On the other hand, an IR LED source has narrow emission spectrum and emits invisible monochromatic light, at peak wavelength of $850\ \mathrm{nm}$ or $950\ \mathrm{nm}$ that depends on the type of the chemical compound being used. The full width at half maximum (FWHM) spectral bandwidth is approximately $40\ \mathrm{nm} \sim 50\ \mathrm{nm}$ for commercial IR LEDs (Vishay Semiconductors: TSFF5410).

Spectral reflectance, denoted as $\rho(\lambda)$, is the reflectivity varying its value as a function of wavelength. In general, the reflectivity of the IR band is higher than that of the visible band [9]. We have measured the spectral reflectance of some building materials by using a spectrophotometer (Konica Minolta: CM-2500d). The spectral reflectances compared to the PSD, are also illustrated in Fig 1. Each reflector has distinct spectral reflectance, and each reflectance ranges between 0.1 and 0.8 as the wavelength changes. This wide variety is generated by the combinations of colors, textural patterns, and other physical features. For the IR communications, Gfeller and Bapst made rough measurements of the reflectance at

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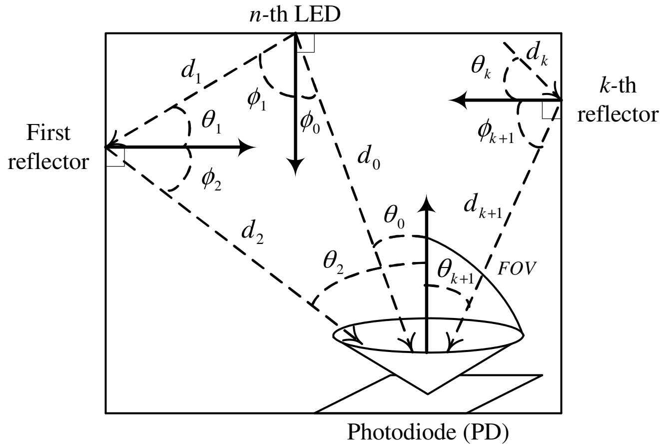

Fig. 2. Geometry of the n-th LED and a PD with reflectors.

wavelength 950 nm [1]. They found that indoor materials reflect infrared radiation ranging from 0.4 to 0.9. For example, the reflectance of plaster wall is about 0.8.

B. Multipath dispersion under wideband optical source

Multipath propagations due to many reflections cause time spreading of the received signal, and the PDP can be used to analyze the effect of multipath dispersion between transceivers. The PDP model for the recursive algorithm [2] consists of path-loss, time delay, and reflected power. The path-loss and the time delay are related to a distance between transceivers. The reflected power at IR is greater than that at the visible light spectrum since the indoor materials have higher reflectance at IR.

For the IR communications, the reflected power can be described as the product of incident power and the reflectance on a surface at the peak wavelength of incident ray, because infrared ray has a narrow spectral bandwidth, and most power is concentrated on its peak wavelength.

On the contrary, to describe the power of reflected light for the VLC, we propose a method that includes both the PSD of an optical source and the spectral reflectance of a reflector. According to [2], multiple-bounces PDP with multiple optical sources is:

$$h(t) = \sum_{n=1}^{N_{\rm LED}} \sum_{k=0}^{\infty} h^{(k)}(t;\Phi_n), \tag{1}$$

where $N_{\rm LED}$ is the total number of LEDs, and we assume that the transmitted power from each LED has equal power. The response after k-bounces to the n-th LED source is:

$$h^{(k)}(t;\Phi_n) = \int_S \left[L_1 L_2 \ldots L_{k+1}\, \Gamma_n^{(k)}\ \mathrm{rect}\left(\frac{\theta_{k+1}}{FOV}\right) \times \delta\left(t - \frac{d_1 + d_2 + \ldots + d_{k+1}}{c}\right)\right] d\mathcal{A}_{\rm ref},\ k \geq 1, \tag{2}$$

where

$$L_1 = \frac{\mathcal{A}_{\rm ref}(m+1)\cos^m \phi_1 \cos\theta_1}{2\pi d_1^2},$$
$$L_2 = \frac{\mathcal{A}_{\rm ref}\cos\phi_2\cos\theta_2}{\pi d_2^2}, \cdots,$$
$$L_{k+1} = \frac{\mathcal{A}_{\rm PD}\cos\phi_{k+1}\cos\theta_{k+1}}{\pi d_{k+1}^2}$$

represent path-loss terms for each path. The integration in (2) is performed with respect to the surface S of all reflectors, and $\mathcal{A}_{\rm ref}$ is the area of the reflecting element. The mode number of a radiation lobe, $m = -1/\log_2(\cos\phi_{1/2})$, is a measure of the directivity of the light beam and related to the viewing angle ($2\phi_{1/2}$) of an LED. The angles of irradiance and incidence are written by ϕ_k and θ_k respectively. Received power is inversely proportional to the square of the distance d_k, which is the distance between source and destination as shown in Fig. 2. The photodiode (PD) detects light whose angle of incidence is less than field of view (FOV). The field of view is the acceptance angle of the detector. The rectangular function $\mathrm{rect}(x)$ is given by:

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

The constant term of c is the speed of light.

Let $\Gamma_n^{(k)}$ in (2) denote the power of reflected ray after k-bounces from the n-th LED. To calculate the reflected power exactly, we define it as:

$$\Gamma_n^{(k)} = \int_\lambda \Phi_n(\lambda)\rho_1(\lambda)\rho_2(\lambda)\ldots\rho_k(\lambda)d\lambda. \tag{4}$$

The simplified form with lower accuracy can be described by:

$$\overline{\Gamma}_n^{(k)} = P_n\ \overline{\rho}_{n,1}\ \overline{\rho}_{n,2}\ \cdots\ \overline{\rho}_{n,k}, \tag{5}$$

where $\overline{\rho}_{n,k} = \frac{1}{P_n}\int_\lambda \Phi_n(\lambda)\rho_k(\lambda)d\lambda$ is the average reflectance, and $P_n = \int_\lambda \Phi_n(\lambda)d\lambda$ is the radiant power from the n-th LED source. For $k = 1$, (4) and (5) have the same value as:

$$\Gamma_n^{(1)} = \overline{\Gamma}_n^{(1)} = \int_\lambda \Phi_n(\lambda)\rho_1(\lambda)d\lambda, \tag{6}$$

however, the differences are obvious in higher-order reflection.

Finally, the PDP for line-of-sight (LOS) is given as:

$$h^{(0)}(t;\Phi_n) = L_0\ P_n\ \mathrm{rect}\left(\frac{\theta_0}{FOV}\right)\delta\left(t - \frac{d_0}{c}\right), \tag{7}$$

where

$$L_0 = \frac{\mathcal{A}_{\rm PD}(m+1)\cos^m\phi_0\cos\theta_0}{2\pi d_0^2}.$$

C. Simulation results and discussions

We evaluate the PDP to verify the effect of the wavelength-dependent variability of the reflectance. We consider multipath environment in an empty room. The indoor topology for simulation is a cubic room (5.0 m $\times$ 5.0 m $\times$ 3.0 m) with plaster or plastic walls. An LED ($2\phi_{1/2} = 120\ °$) is located on the center of the ceiling (2.5 m, 2.5 m, 3.0 m), and a photo-detector is located on the corner of the floor (0.5 m, 1.0 m, 0.0 m) pointing upward. The FOV and the area of a PD ($\mathcal{A}_{\rm PD}$) are $85\ °$ and 1 cm^2, respectively. The bin width of the power histogram is $\Delta t = 0.2$ ns. The spatial resolution, which is related to the area of the reflecting element is the same as Configuration A in [2].

To compare the VLC with the IR communication, we assumed that 1 W optical power is transmitted for both cases. Two types of walls are considered; plaster and plastic. The measured data of the spectral reflectance (see Fig. 1) is used for the VLC simulation, and extrapolated value at 800 nm

TABLE I
SIMULATION RESULTS FOR SINGLE OPTICAL SOURCE.

	Received power [μW]			
	IR		VLC	
	Plaster walls	Plastic walls	Plaster walls	Plastic walls
$k = 1$	0.524	0.303	0.467	0.063
$k = 2$	0.496	0.260	0.211	0.015
$k = 3$	0.241	0.087	0.107	0.003
Total	1.261	0.650	0.785	0.081
	Time dispersion parameters [ns]			
$\overline{\tau}$	18.78	16.44	16.42	13.20
σ_τ	8.34	6.52	6.20	0.56

TABLE II
SIMULATION RESULTS FOR MULTIPLE LED SOURCES.

	Received power [μW]			
	Plaster walls		Plastic walls	
$k = 1$	87.82		15.43	
$k = 2$	42.00		3.13	
$k = 3$	20.93		0.52	
Total	150.75		19.08	
	Time dispersion parameters [ns]			
	$\overline{\tau}$	σ_τ	$\overline{\tau}$	σ_τ
Multiple LOS only	12.50	1.98	12.50	1.98
Multiple LOS + diffuse	15.79	6.41	12.63	2.08

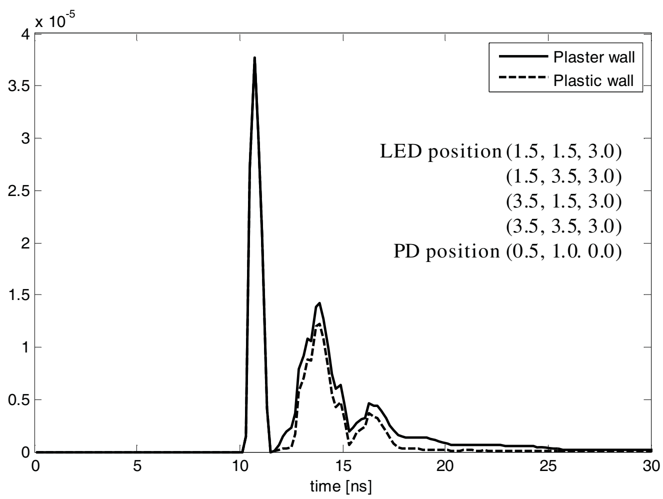

Fig. 3. The PDPs with respect to the plaster walls and the plastic walls for multiple sources.

(Floor: 0.63, Ceiling: 0.40, Plaster wall: 0.83, and Plastic wall: 0.48) is used for the IR case.

The simulation results for received optical power accounting for up to three-bounces are given in Table I. The power from LOS light for all the cases is $1.232\ \mu$W. For the IR case, the received power from reflected paths tends to add to a significant amount [2] regardless of the type of the indoor walls. However, for the VLC case, the received power from reflected paths is smaller than that of the IR case, and it largely depends on building materials.

Indoor VLC systems normally use multiple LED lighting fixtures, because there are more than two lightings in homes and offices. Moreover, LED lamps consist of clusters of white LED chips. This is the one of the differences compared with the IR transmitter. For multiple optical sources, we assume that four LED lightings (0.6 m $\times$ 0.6 m square type) are installed on the ceiling. An LED lighting consists of 100 LED chips, and each chip radiates 0.45 W [4]. Four lightings transmit same signals at the same time. The other parameters are same as the single source. The power from LOS light for multiple sources is $231.47\ \mu$W. The detailed results are listed in Table II. The PDPs are also illustrated in Fig. 3. The first peak signals come from the nearest LED lighting. The other peak signals due to the other lightings and dispersed signals from the reflected paths are observed.

It is known that the temporal dispersion of a PDP can be expressed by the channel root mean square (RMS) delay spread that affects the channel bandwidth, and mitigating the reflections decreases the RMS delay spread [10]. The time dispersion parameters are calculated with the truncation length (T_{tr}), which can be calculated by $\int_0^{T_{tr}} h(t)dt = 0.97 \int_0^{\infty} h(t)dt$. The mean excess delay ($\overline{\tau}$) and the RMS delay spread (σ_τ) are listed at the bottom of Table I and Table II. For single optical source, the RMS delay spread of the VLC case is smaller than that of the IR case, due to weak power from reflected paths. These results show that the VLC can provide a larger transmission bandwidth. For multiple sources environment, it is noted that the bandwidth can be approximately determined by the multiple strong LOS components. Notably in the plastic wall, the RMS delay spread for the LOS components only and including the diffuse components are 1.98 ns and 2.08 ns, respectively.

III. CONCLUSION

A new approach is proposed to calculate the accurate PDP for the VLC. We have analyzed the indoor multipath dispersion characteristics by considering the spectral reflectance in the visible spectrum with respect to single and multiple phosphor based white LEDs. From our studies, the total received power from reflected paths and the RMS delay spread of the VLC cases are smaller than those of the IR cases, which means the VLC has a larger optical transmission bandwidth. For multiple optical sources, the channel bandwidth is limited in some environments due to strong LOS components.

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