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Visible Light Communication

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1. Introduction

The visible light communication (VLC) refers to the communication technology which utilizes the visible light source as a signal transmitter, the air as a transmission medium, and the appropriate photodiode as a signal receiving component.

The visible light communication technology has a short history compared with other communication technology, for example, public old telephone service, Ethernet, high-speed optical communication, wireless cellular communication, IrDA, etc.

It is due to that the development and commercialization of light emitting diodes (LEDs) which emits the light in visible wavelength range have been successful for illumination in recent decade. It is said that the illumination LEDs will replace the conventional illumination lightings such as incandescent bulbs and fluorescent lamps since they have the characteristics of long lifetime, mercury free, color mixing, fast switching, etc.

By utilizing the advantage of fast switching characteristic of the LEDs compared with the conventional lightings, i.e., modulating the LED light with the data signal, the LED illumination can be used as a communication source. Since the illumination exists everywhere, it is expected that the LED illumination device will act as a lighting device and a communication transmitter simultaneously everywhere in a near future.

There have been researches on application of visible LEDs. The audio system using visible light LEDs was reported in Hong Kong by G. Pang et al. (Pang, 1999) and the visible light communication with the power line communication was reported in Japan by Komine et al. It can be considered that the active research has been started since 2005. Still the VLC system is not close to commercialization, but in the basic research.

From the above technical backgrounds, the technical issues will be described in system viewpoint with the recent developments and research results. The VLC link configuration is explained in Section 2. The VLC transmitter (Section 3) and the VLC receiver (Section 4) are described. Section 5 is about VLC considerations including LED characteristics and data format considering the illumination perspectives, including the international efforts on standardization for helping commercialization. The chapter will be concluded with Section 6.

2. System description

2.1 Channel configuration

The optical wireless communication (OWC) is a general term for explaining wireless communication with optical technology. Usually, OWC includes infrared (IR) communication for short range (Knutson, 2004) and free-space optics (FSO) communication (FSO website) for longer range.

The visible light communication (VLC) denotes a communication technology which uses visible light as optical carrier for data transmission and illumination. Nowadays, light-emitting diode (LED) at visible wavelengths (380 nm ~ 780 nm) has been actively developed (Schubert, 2003) and can be used as a communication source and, naturally, the silicon photodiode which shows good responsivity at visible wavelength region is used as receiving element. The transmission channel is the air, whether it is indoor or outdoor.

At present, the researches on VLC are focused on indoor applications. The indoor VLC channels are classified adopted from the conventional IR communication (Kahn, 1999) and (Ramirez-Iniguez, 2008), since the link configurations of VLC are similar to IR communication. The different characteristics come from the different operating wavelength and wavelength-dependent devices (visible LED, silicon photodetector, etc), and the fact that the VLC has the dual nature of communication and illumination. The other physical principles related to optics can be applied similarly, including the light transmission and reflections.

The link configurations are classified into four basic types (Ramirez-Iniguez, 2008), according to the existence of obstacles in light path and the directionality of the transmitter to the receiver.

The basic link types include the directed line-of-sight (LOS), the non-directed LOS, the directed non-LOS, and the non-directed non-LOS. The decision that the link is directed or non-directed depends on whether the transmitter has the direction to the receiver. The decision that the link is LOS or non-LOS depends on whether there exist a barrier to block the transmission of light between a transmitter and a receiver.

In a VLC system, the non-directed LOS link is important since the general illumination operates for LOS environment and it is not focused or directed.

From now on, we concentrate on indoor application of VLC and non-directed, line-of-sight (LOS) link, since the indoor application is expected to be developed in a near future.

Fig. 1 shows the simplified geometry for an indoor, non-directed LOS link, with the transmitter on the ceiling and the receiver on the bottom surface.
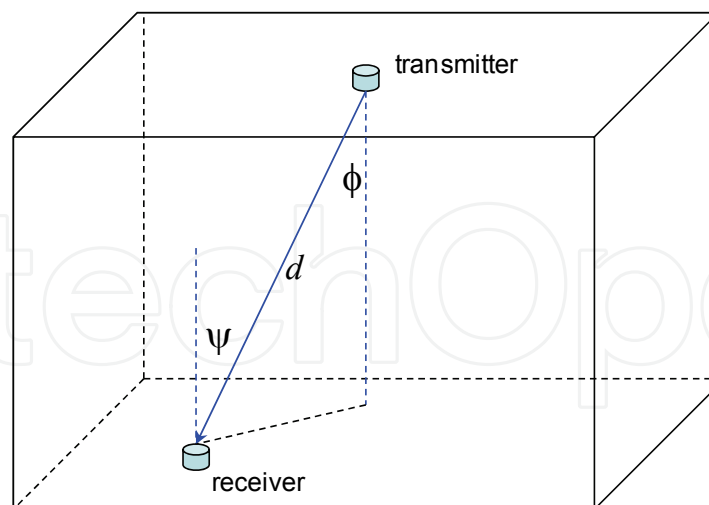

Fig. 1. Geometry for an indoor, non-directed LOS VLC link

Following the analysis for the directed LOS link (Kahn, 1997), the received optical power P at a receiver is expressed as

$$P = P_t \cdot \frac{(m+1)}{2\pi d^2} \cdot \cos^m(\phi) \cdot T_s(\psi) \cdot g(\psi) \cdot \cos(\psi) , \qquad 0 \le \psi \le \Psi_C , \qquad (1)$$

where P_t is the transmitted power from an LED, ϕ is the angle of irradiance with respect to the axis normal to the transmitter surface, ψ is the angle of incidence with respect to the axis normal to the receiver surface, d is the distance between an LED and a detector's surface. $T_s(\psi)$ is the filter transmission. $g(\psi)$ is the concentrator gain. Ψ_C is the concentrator field of view (FOV), i.e., semiangle at half power. m is the order of Lambertian emission, and is given with the transmitter semiangle (at half power) $\Phi_{1/2}$ as

$$m = -\ln 2 \,/\, \ln(\Phi_{1/2}). \tag{2}$$

Here, $m = 1$ in the case of $\Phi_{1/2} = 60°$ (Lambertian transmitter). From the axial symmetry in Fig. 1, we can set as $\phi = \psi$. A concentrator and an optical filter can be used in front of the photodetector. At the time of experiment, it was not optimized for the beam profile from the LED. With $\Psi_C \approx 90°$, $g(\psi) \approx n^2$, where n is the refractive index of the CPC.

2.2 Comparison with IR communication

To have a clear notion about VLC, it is needed to compare it with the infrared communication technology. The differences between VLC and infrared communication are listed in Table 1.

	Visible light communication	Infrared communication
Data rate	>100Mb/s possible (LED dependent)	4 Mb/s (FIR), 16 Mb/s (VFIR)
Status	Research and standardization in IEEE	Standardization (IrDA)
Distance	~meters	~3 meters
Regulation	No	No
Security	Good	Good
Carrier wavelength (frequency)	380~780 nm visible light (multiple wavelengths)	850 nm infrared
Services	Communication, illumination	Communication
Noise source	Sun light, Other illumination	Ambient light
Environmental	Daily usage Eye safe (visible)	Eye safe for low power (invisible)
Applications	Indoor & vehicular communication, Optical ID	Remote control, Point-to-point connection

Table 1. Comparison of short-range wireless communication technologies. (FIR: fast infrared, VFIR: very fast infrared)

The infrared communication is standardized by the IrDA (Infrared Data Association) and the IrDA is still developing advanced application of infrared communication. The data rate for infrared communication (Knutson, 2004) includes 4 Mb/s (FIR), 16 Mb/s (VFIR), and etc. On the other hand, the VLC data rate is dependent on the LED's modulation bandwidth and the standardization on physical layer specifications has not yet been published. Some of

researches have reached around 20 Mb/s. Since the resonant-cavity LEDs shows the modulation bandwidth > 100 Mb/s, it is expected that the VLC system with > 100 Mb/s data rate is possible by using the high-speed LEDs and appropriate multiplexing techniques. The transmission distance for VLC is possible up to several meters due to its illumination requirement. Since the infrared communication is used for a remote controller, the maximum distance is ~ 3 meters. The VLC transmitter emits multiple-wavelength light from red to violet and the exact analysis will become more complex than infrared communication. Due to the wavelength of the light source, the noise sources will be different. For infrared communication, noise comes from ambient light containing infrared light. In the case of VLC, the sunlight and other illumination light can be noise sources. Also, the visible light is in our daily lives and we can detect it with human eye. Therefore, the VLC is eye safe. The infrared communication has the long history and many applications have been developed and are listed in (IrDA website). On the other hand, the VLC has shorter history and the small number of applications has been proposed. Nevertheless, the illumination exists everywhere and the VLC using the illumination infrastructure can be used easily.

By utilizing the characteristics of VLC link, it is expected to be candidate infrastructure for indoor/outdoor public ubiquitous communication technology in the near future.

3. VLC transmitter

The technical considerations for VLC transmitter are mentioned. The main components of VLC transmitter are visible LEDs Fig. 2 shows a configuration of a VLC link and an VLC transmitter is shown. The VLC transmitter is different from conventional communication transmitter in viewpoint that it must act as a communication transmitter and an illumination device simultaneously. Therefore, we must consider the following two requirements simultaneously.
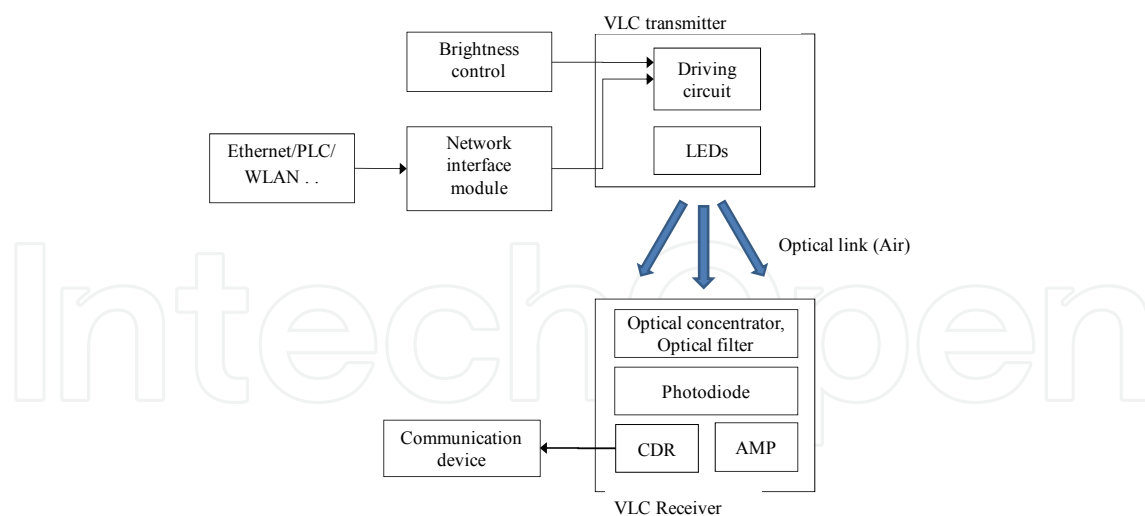

Fig. 2. Configuration of a VLC link. (CDR: clock and data recovery, AMP: amplifier, PLC: power line communication, WLAN: wireless LAN)

Firstly, the VLC transmitter for communication usually uses visible LEDs as a modulation device on optical carrier at visible light. For data modulation on the LEDs, the modulation bandwidth of visible LEDs must be considered. The visible LEDs are usually high-brightness LEDs and the manufacturers do not develop the high-brightness LEDs for communication applications.   There were research reports on measured modulation

bandwidth of high-brightness LEDs (Lee, 2007). Still, most of visible LEDs for illumination have the modulation bandwidth around tens of megahertz. Although the data rate using visible LEDs would be limited to tens of megahertz, the VLC will find the appropriate low data rate applications, for example, optical ID, simple message delivery, etc.

There was a research on increasing the modulation bandwidth of arrayed white LEDs using multiple-resonant modulation for VLC system (Minh, 2008). The experiment demonstrated the VLC system with 16 LEDs to achieve 25 MHz bandwidth and low error rate data transmission at 40 Mb/s.

Secondly, the VLC transmitter must act as an illumination as well. The illumination requirement is that the illuminance must be 200 – 1000 lx for indoor office illumination according to ISO recommendation (Tanaka, 2003). The high-brightness LEDs operates with the forward current > 100 mA and it is quite large, compared with usual communication devices. Thus, to modulate data on the high-brightness LEDs while maintaining the illumination level makes the VLC transmitter design more complex than the conventional communication transmitter design. Transmitting low rate data transmission with illumination simultaneously was reported in (Choi, 2010), where pulse position modulation (PPM) data was transmitted over pulse width modulation (PWM) dimming control signal.

3.1 LED characteristics

For appropriate VLC transmitter design, the LED characteristics needs to be understood.

The general characteristics of LED are well described in (Schubert, 2003). Here, we focus on the high-brightness LED for visible wavelength range.

There are two types of visible wavlength LEDs. One category is single color LED, for example, red (R), green (G), blue (B) LEDs. The other category is white LED, which uses phosphors for converting the emission wavelength from the original active area. We will discuss the white LEDs later in this section. Typically, red, green, and blue LEDs emits a band of spectrum, depending on the material system. Red LEDs emits the wavelength around 625 nm, green LEDs around 525 nm, and blue LEDs around 470 nm.

The output optical power versus the input current into the LED is one of important parameter. The linear dependence of the output optical power on the input current makes the LED operation easy and is closely related to the data modulation performance. The output optical power depends on the ambient temperature. Depending on the material system, the temperature dependence of the output optical power varies. Generally, the temperature increases, the output optical power decreases.

On the other hand, the white LED draws much attention for the illumination devices. Comparing the LED illumination with the conventional illumination such as fluorescent lamps and incandescent bulbs, the LED illumination has many advantages such as high-efficiency, environment-friendly manufacturing, design flexibility, long lifetime, and better spectrum performance.

Most of white LEDs is comprised of LED chip emitting short wavelength and wavelength converter (for example, phosphor). The short wavelength light from the LED chip is absorbed by the phosphor and then the emitted light from the phosphor experiences wavelength shift to a longer wavelength. As a result, the many wavelength components are observed outside the LED. A white light can be generated from a blue LED with appropriate phosphor. The emission spectrum of a phosphor based LED has the strong original blue specrum and the longer wavelengths shifted by the phosphor.

From the illumination viewpoint, the RGB or white LEDs can be used for VLC. However, we consider the response time of each LED from the communication viewpoint, since the

response time is directly related to the maximum data rate to be transmitted by the LED. Basically, the phosphor based white LED has longer rise/fall times due to phosphor absorption/re-emission times. It is noted that each LED can find its appropriate applications for VLC systems.

3.2 Brightness control of LED

For LED illumination, dimming, i.e., brightness control, is needed. Several dimming control methods are widely used (Garcia, 2009) and new methods have been proposed (Doshi, 2010). AM dimming is the way of LED dimming which controls the DC forward current injected into the LED. By changing the DC forward current, the emitted luminous flux is controlled. It is very simple to implement, but it could cause a change of the chromaticity coordinates of the emitted light.
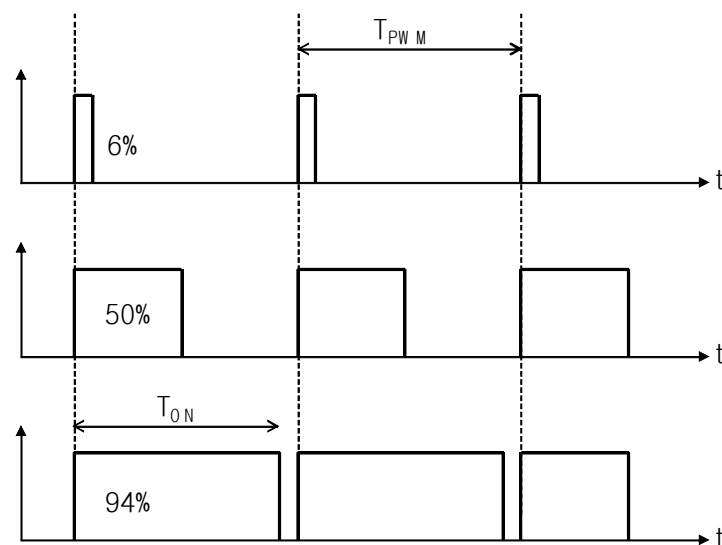

Fig. 3. Waveform of pulse width modulation (PWM) signal for dimming control
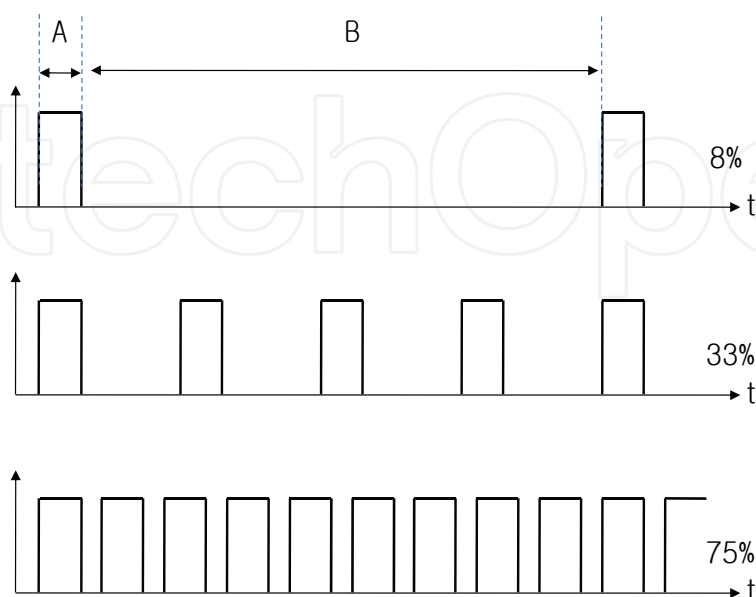

Fig. 4. Waveform of pulse frequency modulation (PFM) signal for dimming control

The pulse width modulation (PWM) method controls the width of the current pulse, thus the average current into the LED, as shown in Fig. 3. While the PWM pulses have a constant amplitude, the pulse width varies according to the dimming level (duty ratio) within the PWM period. Since the PWM pulses have a constant amplitude, the spectrum of the emitted light from the LED is constant.

The pulse frequency modulation (PFM) method controls the frequency of the contant width pulses as shown in Fig. 4, and thereby, the average current into the LED.

The bit angle modulation (BAM, also known as binary code modulation) method is shown in Fig. 5, which is invented by Artistic License Engineering Ltd., uses the binary data pattern encoding the LED dimming level (Artistic License website). Each bit in the BAM pulse train matches to the binary word. For example, in the 8-bit BAM system, the most significant bit (MSB), b7, matches to the pulse with the width of $128=2^7$, the sixth bit, b6, matches to the pulse with the width of $64=2^6$. Similarly, b5 to 2^5 pulse width, b4 to 2^4 pulse width, b3 to 2^3 pulse width, b2 to 2^2 pulse width, b1 to 2 pulse width. The least significant bit (LSB), b0, matches to the pulse width of a unit width. The BAM is simple to implement and reduces the potential to flicker.
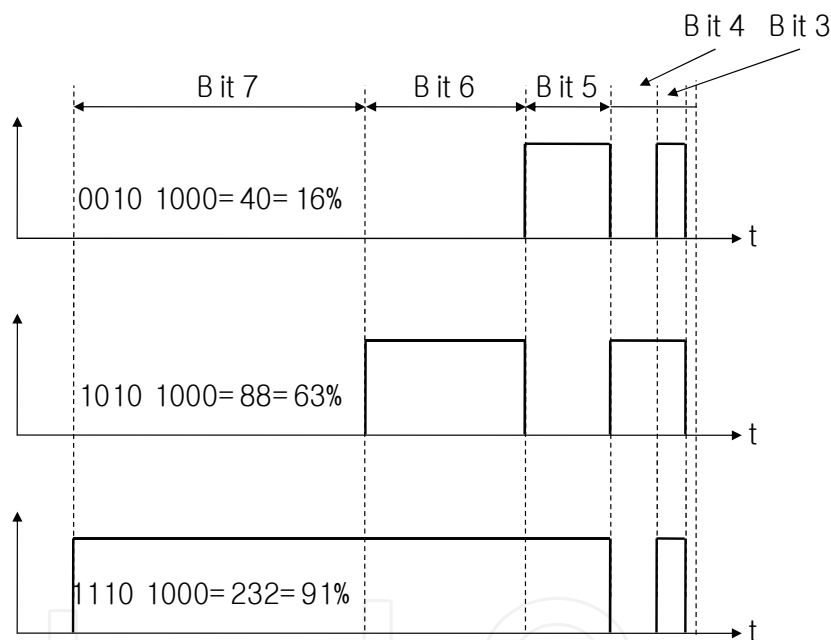

Fig. 5. Waveform of bit angle modulation (BAM) signal for dimming control

The multiphase PWM method is proposed (Doshi, 2010) to reduce the output current transients and electromagnetic interference (EMI) generated by the power circuit, which are associated with visible flicker and audible noise in the power circuit. It is achieved by shifting the individual PWM signals for different LED.

Recently, the signal formats considering the brightness control and data communication simultaneously have been introduced for VLC (Linnartz, 2009) (Choi, 2010) (Bai, 2010). Usually, the brightness of LED light depends on average current into the LED light. The above methods are based on PWM dimming techniques.

3.3 LED driver circuit

Usually, the VLC transmitter employs direct modulation of visible LEDs since the VLC system needs cheap transmitter design. To utilize LEDs as a communication source and as

an illumination simultaneously, it is required to add the digital data signal over the dimming control signal. To modulate the LEDs, the drive current is fed into the LEDs with the appropriate DC bias.

For modulating an LED or LD directly, a transistor is switched for feeding the LED or an FET can be used (Ramirez-Iniguez, 2008). Also, the integrated circuit (IC) based driver chip can be used. We can get application diagrams for such IC based LED driver from the driver chip manufacturer (Maxim website).

Since the drive current contains the DC current for illumination or the dimming current for data signal, a bias Tee can be used for mixing the DC current and digital data for low data rate application.

To design an appropriate driver circuit for VLC system, the following items must be considered:

- Current requirement of LED(s) : modulation depth and bias current
- Rise and fall times of LED(s) and component(s) : related to maximum bit rate
- Illumination compatibility with communication
- Design approach : whether driver IC is used or not
- Power dissipation and thermal design of the transmitter

4. VLC receiver

The VLC receiver is composed of receiving optical elements including optical concentrator and optical filter, photodiode, amplifier, and signal recovery circuit, as shown in Fig. 2. Basically, the VLC system is designed to employ direct detection at the photodiode.

The optical concentrator is used to compensate for high spatial attenuation due to the beam divergence from the LEDs to illuminate large area. By using the appropriate concentrator, the effective collection area can be increased. The methods using compound parabolic concentrator (CPC) and imaging lens for infrared communications are described in (Kahn, 1997) and (Ramirez-Iniguez, 2008). Since the wavelength range is different from the infrared communication, the specific design parameters for the VLC system will be changed from the design for the infrared communication.

The VLC system is vulnerable to the sunlight and other illuminations, and therefore, it is important to employ appropriate optical filter to reject unwanted DC noise components in the recovered data signal.

The photodiodes with good responsivity to visible light are silicon p-type-insulator-n-type photodiode (Si PIN-PD) and silicon avalanche photodiode (Si APD). The silicon material photodiode operates from 400 nm to 1200 nm, which includes the visible wavelength range. There are many photodiodes whose bandwidths are over 200 MHz and is much wider than the VLC LED transmitter.

There are several types of signal amplification circuits. Among them, high impedance amplifier and transimpedance amplifier are briefly described. The high impedance amplification is simple to implement. The series resistor is connected to the anode of the photodiode and the high input-impedance amplifer senses the voltage across the series resistor and amplifies it. The transimpedance amplifier provides current-to-voltage conversion by using shunt feedback resistor around an inverting amplifier

Generally, the noise in the VLC receiver is similar to the usual optical communication receiver, for example, the thermal noise from the load resistor and the photodiode, the shot noise in the photodiode, the excess noise from the amplifier. The main noise components are the sunlight and the other illumination light.

5. VLC considerations

5.1 Multiple wavelengths

The system design and analysis on IR are based on the assumption that the IR source emits a monochromatic light. Most of researches on VLC have been performed also on the same assumption. The optical power [Watt] of monochromatic light at wavelength λ is related to the illuminance $I(0)$ as :

$$P_{rec} = \frac{I(0)\cos^m(\phi)}{683V(\lambda)D_d^2\cos(\psi)},\qquad(3)$$

where $V(\lambda)$ is the eye sensitivity function (Schubert, 2003). Referring to Fig. 1, ϕ is the angle of irradiance with respect to the axis normal to the transmitter surface and ψ is the angle of incidence with respect to the axis normal to the receiver surface. D_d is the distance between an LED and a detector's surface. The constant 683 in the denominator comes from the conversion equation between radiometric [Watt] and photometric unit [lx]:

$$Photometric\ unit\left[lx\right] = radiometric\ unit\left[Watt\right] \times 683\left(\frac{lm}{W}\right) \times V(\lambda)\qquad(4)$$

According to the photometry (Schubert, 2003), at the wavelength of 555 nm (green color), we have the eye sensitivity $V(550) = 1$; and at the wavelength of 720 nm (red color), the eye sensitivity is given as $V(720) = 0.001$.

However, practically, the illumination LED is a multiple-wavelength source in visible range, for example, 380 nm ~ 780 nm. Therefore, the calculations of the illuminance and received optical power must involve the integration over wavelengths occupied by the light in the eye sensitivity function. The received optical power is given as

$$P_{rec} = \frac{I(0)\cos^m(\phi)}{683D_d^2\cos(\psi)\int\limits_{380}^{780} V(\lambda)P(\lambda)d\lambda}\qquad(5)$$

$P(\lambda)$ is the power spectral density (Schubert, 2003).

5.2 Optical interference noise

The noise sources in VLC system include the sunlight, the incandescent light and the fluorescent light. Moreira et al. measured the average background current for a couple of typical optical interferences (Moreira, 1997). The background current was detected with a 0.85 cm² silicon PIN photodiode in a differential structure.

Table 1 shows the measured background currents from 60 Watt incandescent bulb at 1 m distance and from eight 36 Watt fluorescent lamps at 2.2 meters distance in a 5 m × 6 m room. From the Table, the background current of the sunlight is the largest one. Also, the background current of the incandescent bulb is larger than that of the fluorescent lamps. If the optical filter is used, the backgound current can be reduced effectively by filtering out appropriate wavelength components. Specifically, the optical filter works effectively for fluorescent lamps due to its optical spectrum.

	without optical filter	with optical filter
Direct sunlight	5100	1000
Indirect sunlight	740	190
Light from an incandescent bulb	84	56
Light from a fluorescent lamp	40	2

Table 2. Background current from the optical interferences (Moreira, 1997)

In (Moreira, 1997), the interference signal from the incandescent bulbs has the Fourier series expression given by

$$i_{incandescent}(t) = \frac{I_B}{A_1} \sum_{i=1}^{\infty} a_i \cos(2\pi \cdot 100it + \phi_i) \,, \tag{6}$$

where a_i and ϕ_i are the relative amplitude and phase of each harmonic of 100 Hz. A_1 is the constant that relates the interference amplitude with I_B. The constants a_i, ϕ_i, and A_1 can be estimated from the measurement data for a specific incandescent bulb.

The reference (Moreira, 1997) provides the mathematical equations for the other interference signals from incandescent bulbs and fluorescent lamps, and the related constants. For a specific photodiode and receiver circuit, the equation needs to be estimated for more exact analysis.

5.3 Recent research

Most of researches on optical wireless communication (OWC) have been performed in the field of infra-red (IR) communication. The modulation formats for optical wireless communication system have been reported such as on-off keying (OOK) (Dickenson, 2004), dual-header pulse interval modulation (DH-PIM) (Aldibbiat, 2005), subcarrier PSK intensity modulation (Lu, 2004), multiple-subcarrier modulation (Ohtsuki, 2003). From the fact that the IR and visible light are light with different wavelength spectra, the modulation formats for IR system can be adopted in VLC considering geometrical environment, mobility and multi-user connectivity.

Recently, the VLC research has been started actively in Japan. Nakagawa laboratory in Keio University has published many research papers on VLC, including the fundamental analysis (Komine, 2004) and the interconnection of VLC with power line communication (Komine, 2003). The Korea Photonics Technology Institute (KOPTI) published a research on measurement results for modulation bandwidth of high-brightness LEDs to prove the feasibility of VLC from the source bandwidth (Lee, 2007). The research group in Oxford University reported the multiple resonant equalization technique for enhancing LED bandwidth for VLC (Minh, 2008).

Recently, Linnartz et al. published the code-time division multiple access – pulse position modulation (CTDMA-PPM) and code-time-division multiple access – pulse width modulation (CTDMA-PWM) for tagging each LED lamp by transmitting PPM and PWM coded data in high-power LED system, respectively (Linnartz, 2010). The scheme is proposed for illumination, transmission of identifiers and lighting control. As stated in Section 3.2, the signal formats for brightness control and data communication simultaneously have been reported (Choi, 2010) (Bai, 2010).

5.4 Standardization activities

In Japan, the visible light communication consortium (VLCC) is organized for collaboration between industrial companies, universities, and research institutes (VLCC website). The VLCC member includes NEC corporation, Panasonic Electric Works, Nippon Signal, Toshiba corporation, Samsung Electronics, NTT DoCoMo, Casio Computer, Nakagawa Laboratories, Sumitomo Mitsui Construction, Sharp corporation, etc. The VLCC concentrates on activating technology exchange, system development, demonstration, and standardization of VLC inside Japan.

In Europe, the working group 5 of the wireless world research forum (WWRF) deals with VLC technology as one of next-generation wireless access technology (WWRF website). The WWRF has published a white paper on killer application of VLC, market forcast, and technology roadmap.

In IEEE, 802.15 in IEEE 802 LMSC (LAN/MAN Standards Committee) has organized the study group on VLC and the group is now the task group 7 (TG7) (TGVLC website).

In South Korea, the telecommunications technology association (TTA) (TTA website) supports standardization of VLC for Korean standard and international standard.

6. Conclusion

In this chapter, the key ideas on visible light communication (VLC) have been reviewed in relationship with optical wireless communication and infrared communication. The channel characteristics for VLC system were mentioned comparing it with infrared communication and the VLC transmitter and receiver are described including the basic characteristics of LED. Also, the considerable topics have been described including LED dimming, optical devices, and the effect of multiple wavelengths. The recent research results and standardization activities are summarized.

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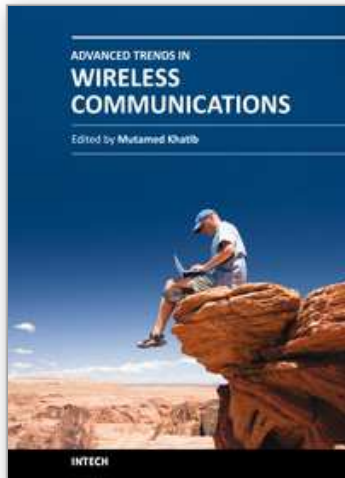
Advanced Trends in Wireless Communications

Edited by Dr. Mutamed Khatib

ISBN 978-953-307-183-1

Hard cover, 520 pages

Publisher InTech

Published online 17, February, 2011

Published in print edition February, 2011

Physical limitations on wireless communication channels impose huge challenges to reliable communication. Bandwidth limitations, propagation loss, noise and interference make the wireless channel a narrow pipe that does not readily accommodate rapid flow of data. Thus, researches aim to design systems that are suitable to operate in such channels, in order to have high performance quality of service. Also, the mobility of the communication systems requires further investigations to reduce the complexity and the power consumption of the receiver. This book aims to provide highlights of the current research in the field of wireless communications. The subjects discussed are very valuable to communication researchers rather than researchers in the wireless related areas. The book chapters cover a wide range of wireless communication topics.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Chung Ghiu Lee (2011). Visible Light Communication, Advanced Trends in Wireless Communications, Dr. Mutamed Khatib (Ed.), ISBN: 978-953-307-183-1, InTech, Available from:
http://www.intechopen.com/books/advanced-trends-in-wireless-communications/visible-light-communication

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