Overcoming Bandwidth Limitation of LED by Using Multilevel Differential PAM in VLC

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Abstract— We propose a novel modulation and de-modulation method to reduce the complexity of transmitter and receiver which is named multilevel differential pulse amplitude modulation (MD-PAM). The proposed modulation scheme transmits different PAM signals with same amplitude and unit time delay using different multiple LED chips. Optical signals from each LED chips are superposed during through the optical wireless channel and directly detected at the single optical receiver. Received signal is demodulated using signal power difference which is changed by light intensity. As a result, we experimentally confirmed that 100-Mbit/s transmission was possible using two LED chips which have 25 MHz modulation bandwidth, respectively.

1. INTRODUCTION

Commercial white light-emitting diodes (LEDs) have the great advantage to become the main device for indoor and outdoor illumination and already used for lighting source of numerous devices due to their energy efficiency, eco-friendly, and small size than previously light sources like as incandescent, uorescent light, and so on. LEDs also provide a cost-effective solution for transmitters of optical wireless communication systems [1–5]. In the infrared range, such systems provide wireless local-area-network connectivity in the order of several Mbps and above, in both line of sight and the diffuse regime. It is also possible to modulate the visible light emitted by lighting LEDs, hence providing illumination and wireless connectivity, simultaneously. These systems are usually referred to as optical wireless visible light communication (OWVLC) systems. However, narrow modulation bandwidth of commercial white LED is limitation of OWVLC. Modulation bandwidth of commercial white LED is limited about several MHz by characteristics of device. Therefore, using a simple modulation format which is non-return-zero on-off-keying (NRZ-OOK), the data rate reaches only to several Mbps. Thus, several studies have been carried out to overcome the intrinsic bandwidth limitation of LED. First of all, for the white lighting, most devices for illumination use a blue LED which illuminates a layer of yellow phosphor. These two colors are mixing and creating a white light. However, modulation bandwidth is typically lower than 3 MHz by slow time constant of the yellow phosphor material, thus optical blue filtering techniques have been reported to improve the modulation bandwidth [4, 5]. However, blue filtering also removes a large portion of the signal power, depending on the color spectrum emitted from the LED package, thus optical power loss is additionally occurred. Secondly, to enlarge modulation bandwidth and compensate the channel response, electrical pre-, post-equalizer circuits are adopted. The characteristic of pre- and post-equalizer have high pass filter (HPF). Thus, power loss is occurred and additional electric amplifier is required to compensate the power loss. Thirdly, to obtain the additional optical wireless channel, wavelength division multiplexing (WDM) based on RGB LED and optical color filter at receiver or polarization division multiplexing (PDM) based on polarizer is researched [6, 7]. However, proposed methods are also loss of optical power is occurred according to color filtering or polarization filtering. Fourthly, high-speed wireless connectivity is implemented using spectrally efficient modulation methods: quadrature-amplitude-modulation (QAM) with orthogonal frequency division multiplexing (OFDM) or discrete multi-tone (DMT) with water-filling algorithms [8, 9]. The transmission capacity can be increased significantly, because spectral efficiency is maximized. However, these modulation methods need additional digital signal processing such as fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT), thus hardware and computational complexity of transmitter and receiver is increasing. In addition, modulated signals have a high peak-to-average power ratio (PAPR). Such a high PAPR necessitates the linear devices to have large dynamic range which is difficult to accommodate because light source can saturate and clip the peak at the high values. Thus, a RF devices and lighting source with nonlinear characteristics will cause undesired distortion. In addition, peaking the LED increased its temperature, which in turn leads to undesired color shift and reduced LED lifetime. Last, spatial modulation (SM) is introduced [10, 11]. Generally, SM is required different channel gain or transmitted signal power is required. One of the special form of the GM is generalized space shift keying (GSSK). In this case, with an array of N_t LEDs, GSSK can send Nt bits/symbol. However, it is required different channel gain with $2^{N_t - 1}$ levels. Thus, additional time synchronization between different LEDs are required. Another method is superposed pulse amplitude modulation (SPAM). The SPAM is using characteristics of optical wireless channel. Superposed different signals from different LEDs are detected single receiver. The modulation order is also Nt bit/symbols, however it is also required different intensity ranges of $V, 2V, 4V, 2^{N_t - 1}V$ to obtain 2^N-SPAM. Thus, nonlinearity of device can be occurred where high signal power required LED.

In this paper, we propose a novel modulation and de-modulation format to reduce the complexity of transmitter and receiver which is named multilevel differential pulse amplitude modulation (MD-PAM). The proposed modulation scheme transmits different PAM signals with same amplitude and unit time delay using multiple LED chips, respectively. Optical signals from every LED chips are linearly accumulated during through the optical wireless channel and directly detected at the single optical receiver. Received signal is demodulated using received signal power difference which is changed by light intensity. As a result, we experimentally confirmed that 100-Mbit/s transmission was possible using LED which has 25 MHz modulation bandwidth.

2. OPTICAL WIRELESS CHANNEL CHARACTERISTICS

Generally, OWVLC use intensity modulation and direct detection (IM/DD) which is traditional modulation method using optical wired and wireless communication system. The single LED produces an instantaneous optical power waveform which is expressed X and it was always positive values with average transmitted power can be describe as

$$P_t = \lim_{x \to 0} \frac{1}{2T} \int_{-T}^{T} X(t) dt \tag{1}$$

where T is time period of transmitted optical signal. The produced electrical power which is converted from optical receiver is decided by response to all light incident on its effective area. For now we assume an ideal channel H_0, and we represent the light as

$$P_{opt} = h_0 X(t) + P_{amb} \tag{2}$$

where $H_0 X(t)$ is the light intensity from single LED and P_{amb} is and unwanted light component from all other light sources and it can include LEDs. The optical receiver converts this light into a current and it can be changed received signal power PRF. Random nature of photo-electronic interactions within the optical receiver, the additional noised component $N(t)$ is generated. This noise component is random and distribution pattern is same with Poisson distribution. Thus, current and its variance are proportional to the total irradiance. The received signal power PRF can be describe as two different terms: a positive signal composed by P_t and P_{amb}, and noise component which is zero-mean fluctuation, or shot noise and it can be describe as

$$P_{RF} = R(H_0 X(t) + P_{amd}) + N(t) \tag{3}$$

where R is the responsivity of the used optical receiver including effective area. The additional noise component including shot noise is appropriate to model $N(t)$ as white and Gaussian distribution. Thus, we can expect that if different LEDs generate optical signals which component is P_{amb}, received optical and electrical signals are linearly accumulated.

3. EXPERIMENTS AND RESULTS

The modulation bandwidth of the commercial white LEDs is not over the 10 MHz and it was the intrinsic characteristics of the LED. Fig. 1 shows the frequency response of electrical-optical-electrical system using white LED (OSRAM LE UW S2W). The 3 dB bandwidth of used avalanche photodiode (APD) is 100 MHz which obtain data-sheet from HAMAMATSU, thus bandwidth limitation is caused by used LED. From Fig. 1, the 3 dB bandwidth of the used LED is approximately 1.5 MHz, so the expected data rate cannot over the 10 Mbps when using NRZ-OOK. In this experiment, the modulation bandwidth can be enhanced up to 25 MHz by using a pre-equalizer.

Multiple optical signal transmitting is enabled in the optical wireless channel and superposed light intensity can be detected at the receiver part. The operation principle of proposed modulation format is shown in Fig. 2. The generated pseudorandom binary sequence (PRBS) signals are

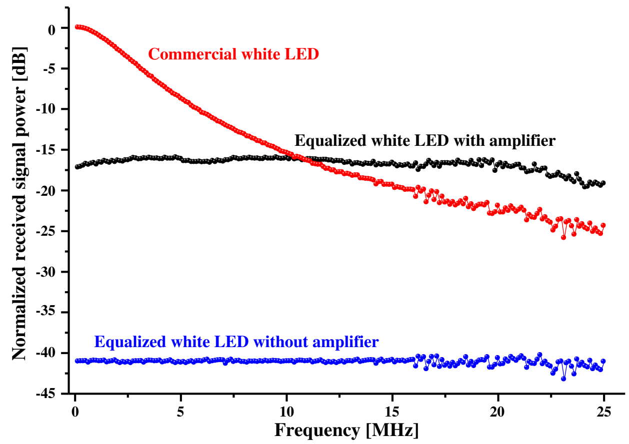


Figure 1: Frequency response of used commercial white LED.

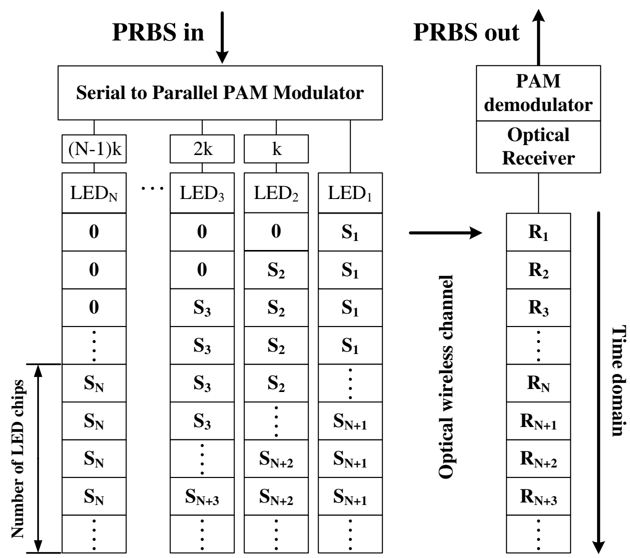


Figure 2: Block diagram of proposed MD-PAM algorithms.

modulated using PAM modulator and distributed in parallel to N different LED chips. When wanted total transmission rate is PRBS, the symbol period of transmitted signal when modulation format is M-PAM is τ which can be calculated by $\log_2 M = PRBS$. The distributed and modulated signal at each LED chip can be described as

$$S_i[N(t-1)+i+k] = MPAM[N(t-1)+i], \quad 0 \leq k < N \quad \text{and} \quad 0 < i \leq N \tag{4}$$

where S_i is a transmitted signal at the ith LED chip, t is a unit time, and k is an arbitrary constant. The required modulation bandwidth of proposed system of each LED chip is decreases by $PRBS = \log_2 M$; thus, the bandwidth limitation of the LED can be overcome and frequency efficiency at the view of LED is 2 bits/Hz. The received optical intensity $R(t)$ becomes then linearly superposed while passing through the optical wireless channel. The received signal power variation for unit time is determined by a single LED device, thus, the demodulated signal $D(t)$ can be obtained by

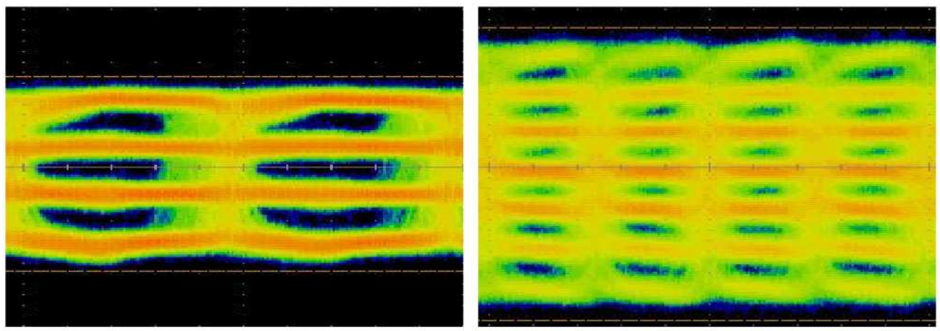
$$D(t) = \begin{cases} R(t) & \text{if } t = 1 \\ R(t) - R(t-1) & \text{if } 1 < t \leq N \end{cases} \tag{5}$$

during first symbol duration. However, after first duration, demodulation method is slightly different because received signal is affected by previous symbol when received optical power difference is zero. Thus, demodulation method can be describe as

$$D(t) = R(t) - R(t-1) + D(t-N) \tag{6}$$

The random bits were generated by offline process and the generated 4-PAM signals are distributed to different two port of an arbitrary waveform generator (AWG). The electrical signals are transmitted to each LED chip using bias-tee. The time delay between different two channels is given by digital signal process. After the pre-equalizer the signal is transferred to each LED chip. The light intensity of a single LED device was changed by the 4-PAM signal and the superposed optical signals are detected by APD. The generated electrical signals were captured by a mixed signal oscilloscope. After synchronization, the received signals were demodulated.

The BER measurements have been done for the signal performance evaluation. When 100 Mbps PRBS signals are generated, the assigned symbol rate per single LED chip is 25 MSymbol/s according to proposed modulation method. The received eye-diagram of the single LED is shown in Fig. 3(a). When the Ch1 and Ch2 transmitted at the same time, received signals are accumulated and it is shown Fig. 3(b). Demodulation is possible using distinguishable levels and threshold values. After demodulation, BER 10^{-3} is achieved which is FEC limitation.



(a) (b)

Figure 3: Eye-diagram of received signal (a) single LED only, (b) two different LEDs, simultaneously.

4. CONCLUSIONS

We propose and experimentally demonstrate the MDPAM with white LEDs based OWVLC. A commercial white LED with a modulation bandwidth of 1.5 MHz was used for the lighting source. The experiment is performed using a single LED light source which is composed of four chips for the transmission distance of 0.8 m. Two LED chips are separately modulated using MPAM and accumulated light is detected by a single APD. We achieved BER 10^{-3} for 100-Mbit/s. In addition, proposed system expect that the transmission rate can be linearly increased as we increase the number of LEDs. Thus, the possible transmission data rate can be extremely increased even using a low frequency response LED transmitter.

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