# Dimming-discrete-multi-tone (DMT) for simultaneous color control and high speed visible light communication

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**Abstract:** Visible light communication (VLC) using LEDs has attracted significant attention recently for the future secure, license-free and electromagnetic-interference (EMI)-free optical wireless communication. Dimming technique in LED lamp is advantageous for energy efficiency. Color control can be performed in the red-green-blue (RGB) LEDs by using dimming technique. It is highly desirable to employ dimming technique to provide simultaneous color and dimming control and high speed VLC. Here, we proposed and demonstrated a LED dimming control using dimming-discrete-multi-tone (DMT) modulation. High speed DMT-based VLC with simultaneous color and dimming control is demonstrated for the first time to the best of our knowledge. Demonstration and analyses for several modulation conditions and transmission distances are performed, for instance, demonstrating the data rate of 103.5 Mb/s (using RGB LED) with fast Fourier transform (FFT) size of 512.

**OCIS codes:** (230.3670) Light-emitting diodes; (060.4510) Optical communications; (060.4080) Modulation.

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## References and links

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## 1. Introduction

The prosperity of light-emitting diode (LED) technologies has made LED a competitive illumination choice compared to traditional fluorescent light sources. LED has larger modulation bandwidth; hence it encourages the applications of simultaneous illumination and high speed visible light communication (VLC) [1–3].

Generating human-comfortable white light is a critical issue for LEDs. One common technique used is mixing red (R), green (G), and blue (B) LEDs to generate white light. According to CIE 1931 system, illumination source with arbitrary color can be generated by adequately mixing different ratios among R, G, and B LEDs. Additionally, wavelength-division multiplexing (WDM) technique can be used to triply increase the VLC bandwidth by using RGB LEDs. This is especially beneficial for the bandwidth limited VLC system.

Dimming technique is advantageous for energy efficiency [4], and it also provides high quality color performance [5]. Color control can be performed in the RGB LEDs by using dimming technique. It is highly desirable to employ dimming technique to provide simultaneous color control and high speed VLC services. Variable pulse position modulation (VPPM), pulse width modulation (PWM), and on-off keying (OOK) modulation are typically proposed as dimming choices for LEDs [6, 7]. These modulation schemes are not suitable for high speed VLC because of the limited bandwidth of LED. Discrete multi-tone (DMT) is one main technique to provide high data rate VLC due to its high spectral efficiency [8]. PWM-DMT is proposed for dimming the DMT signal [9]. It also states that the PWM rate should be at least higher than twice the frequency of the highest DMT subcarrier [9]. This is nearly impractical in a bandwidth limited VLC system for high speed communication. When compared with ref [10], our proposed scheme can adjust the power level. Hence, there is no need to adjust the DMT symbol rate and constellation set. Besides, our proposed scheme has low latency since the dimming-DMT system is transmitting signals continuously even during the "dimming time-slot". In this work, a novel modulation scheme, named dimming-DMT is proposed and demonstrated. By using RGB LEDs, color control with triple data rate can be further obtained. Here, simultaneous high speed DMT-based VLC with color control is demonstrated for the first time to the best of our knowledge. Demonstration and analyses for several modulation conditions and transmission distances are performed, for instance, demonstrating the data rate of 103.5 Mb/s (using 3 x 34.5 Mb/s) with fast Fourier transform (FFT) size of 512.

## 2. Principles

Figure 1(a) shows the encoding and decoding processes of dimming-DMT. In the encoding process, the binary digital sequence is first parallelized and mapped into a specific quadrature amplitude modulation (QAM) symbol. Specific number of pilot is inserted. Inverse fast Fourier transform (IFFT) is then used to transform the signal from frequency domain into time domain. The IFFT size is determined by the brightness requirement for the LED. The signal is further serialized to generate a complete DMT symbol. To mitigate multipath interference, moderate cyclic prefix (CP) is added. Each DMT symbol is then normalized. The average power of each DMT symbol is further modulated to provide another dimension of modulation; hence achieving the dimming-DMT symbol. Figures 1(b) and 1(c) show the schematic time traces of typical DMT symbols and dimming-DMT symbols respectively. Figure 1(b) denotes a "flat" signal power over time. Then, we can modulate this "average power" to provide another dimension of modulation and dimming control (indicated in Fig. 1(c)). The dimming-DMT signal is converted to analog signal through a digital-to-analog converter (DAC). Decoding of the dimming-DMT is a reverse process of the encoding process. After the dimming-DMT is received by the photo-diode (PD), it is converted into digital signal by an analog-to-digital converter (ADC). The average power of each dimming-DMT symbol is calculated by the comb pilots and compensated to unity to achieve the DMT

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symbols. Each DMT symbol is transformed into frequency domain and mapped into original binary sequence. Then the encoding functions (i.e. the dimming-DMT symbols) are applied to the R, G, and B LEDs separately. Hence the intensities of the 3 color channels (R, G and B LEDs) can be control separately to achieve different overall color control. The bit pattern used was pseudo-random sequence, and no special channel coding scheme was applied.

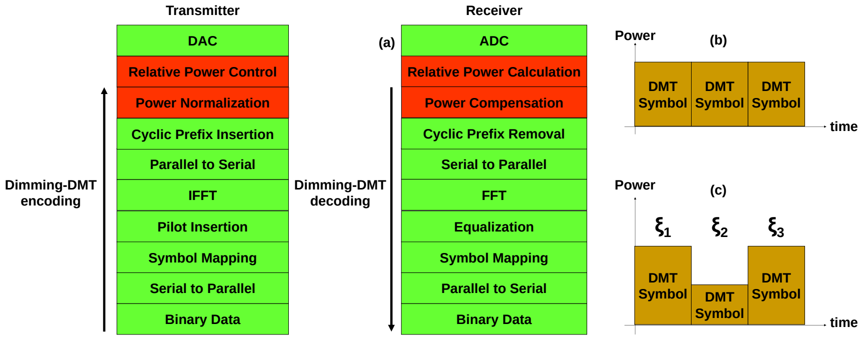

Fig. 1. (a) Encoding and decoding processes of dimming-DMT. (b) Time trace of typical DMT signals. (c) Time trace of dimming-DMT signals.

Figure 2 shows the proposed architecture to achieve simultaneous color control and high speed VLC. First, the color required is mapped into the CIE 1931 color space coordinate. Then, the average intensity for each R, G, and B LEDs is calculated. Based on the calculated value, the FFT size and the modulating power of each dimming-DMT symbol can be determined. Typically, the FFT size should be known between the transmitter and the receiver to ensure the proper decoding of the signal. For bi-directional communication condition, this is not a serious problem. For unidirectional communication condition, the FFT size should be fixed, and the adjustable variable is only the average power of each dimming-DMT symbol. The dimming-DMT encoding process described in Fig. 1(a) is then employed in the transmitter. After the DAC, dimming-DMT signal is injected into each R, G, and B LEDs. At the receiver end, filters with different wavelengths are put in front of each PD to select the R, G, and B channels. The decoding process of dimming-DMT is described in Fig. 1(a).

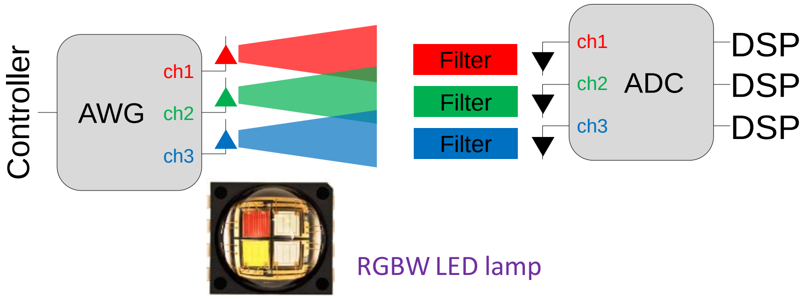

Fig. 2. Architecture for simultaneous color control and high speed VLC. Inset: red-green-blue-white (RGBW) LED.

Dimming range of dimming-DMT is analyzed here. Assuming the brightness of a LED is normalized to be within “0” and “1,” where “0” denotes totally darkness of the LED, and “1” denotes the brightest level of the LED. We define Q as the effective transmitted number of dimming-DMT symbols within the human eyes response interval, N the FFT size, $\xi_q$ the dimming-level of the q-th dimming-DMT symbol, f the root mean square (RMS) LED injection alternative current (AC) at $\xi_q = 1$, B the direct current (DC). $\xi_q$ is a parameter between “0” and “1,” which respectively denotes the minimum and maximum dimming condition. Two functions, “max()” and “min(),” are defined respectively to denote the maximum and minimum values of a parameter. It is obvious that the brightest dimming of “1” is achievable while all the LEDs' intensities are adjusted to their highest levels. Hence, we have the dimming range stated in Eq. (1),

$$D \in \left[ \frac{\min(B) + f \cdot \min(\xi_q) \cdot \min(Q)}{\max(B) + f \cdot \max(\xi_q) \cdot \max(Q)}, 1 \right]. \tag{1}$$

We assume the dimming-DMT symbol rate and the effective human eyes response time are fixed. We obtain Eq. (2),

$$D \in \left[ \frac{\min(B) + f \cdot \min(\xi_q) / \max(N)}{\max(B) + f \cdot 1 / \min(N)}, 1 \right]. \tag{2}$$

We assume the LED is always electrically driven in the forward-base region. The maximum ratio for DC over RMS amplitude of AC is $\sqrt{2}$ . For power compensation requirement, the minimum FFT size is 4, and a reasonable FFT size of 512 can be set as the maximum value of N. In our experiment result, the minimum $\xi_q$ for bit error rate (BER) < 3.8 x $10^{-3}$ is 0.3. Hence, we obtain Eq. (3),

$$D \in \left[ \frac{\sqrt{2} \cdot f \cdot 0.3 + f \cdot 0.3/512}{\sqrt{2} \cdot f + f \cdot 1/4}, 1 \right] \approx [0.26, 1]. \tag{3}$$

Two things should be noticed. First, minimum $\xi_q$ may change at different bias conditions because of the non-linear transfer function of LED. Hence, the above dimming range is only for reference. Second, for ideal dimming-DMT, the DC component can be directly adjusted in the encoding process, which means the output signal from the DAC should be a direct-couple signal. However, for typical high speed arbitrary waveform generator (AWG), the adjustable DC range is normally limited. Hence, we do not integrate the DC component in the dimming-DMT symbol. Hence, in Eqs. (1)–(3), the analyses are all based on separating DC and AC conditions. In practical case, the human eyes response time should be much slower than that the electrical devices. We can achieve the dimming-DMT by synchronizing DC and AC signal supplies. Even in the ideal case described in Fig. 2, Eqs. (1)–(3) still hold true.

## 3. Experiments and discussions

The experimental setup was similar to Fig. 2. Due to the limited output channels of the AWG available in the laboratory, the signal performances among the R, G, B LEDs were measured separately. A bias-tee was used to combine the DC power and Dimming-DMT signal from the AWG. Dimming-DMT with FFT sizes of 512, 128, and 32 were measured respectively at different transmission distances and dimming-ratios. Dimming-ratio is the ratio of minimum dimming-level over maximum dimming-level within Q dimming-DMT symbols. The LED used in the experiment was an integrated RGB and white (W) LED lamp from Cree XLamp (shown in inset of Fig. 2). At the receiver, the signal was received by a PIN PD from Thorlab PDA10A. After the PD, the signal was received by a real-time sampling scope and decoded offline. The achieved data rate among different FFT sizes were respectively 34.5 Mb/s, 32.5 Mb/s, and 24.2 Mb/s. The power radiated by the LEDs was estimated by the emission spectra of the LEDs, the response spectrum of the PD, and the scope value. The displayed color was estimated by the emission spectra of the LEDs, the CIE 1931 color matching functions, and the relative power radiated by the R, G, and B LEDs.

Figures 3(a)–3(c) respectively show the signal performance among different dimming-ratios for FFT size of 512, 128, and 32. It can be seen that the FFT size of 128 has the best signal performance. The relatively poor performances of the 512 and 32 FFT cases may result from non-optimized comb choice and multipath interference respectively. The analyses for performance differences among different FFT sizes will be discussed in the following paragraph. It can be seen that for dimming-ratio higher than 0.3, the BER is under the forward error correction (FEC) error-free threshold of 3.8 x $10^{-3}$.

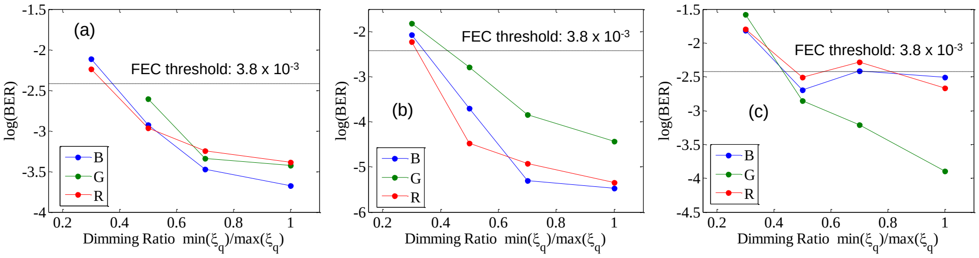

Fig. 3. The signal performance for different dimming-ratios. The distance between LEDs and PD was set to be 10 cm. (a) FFT size of 512. (b) FFT size of 128. (c) FFT size of 32.

Figure 4 shows the signal-to-noise ratio (SNR) of different DMT subcarriers among 512, 128, and 32 FFT cases. It is seen that all three cases have lower SNR at high frequency subcarriers. This may mainly be caused by limited bandwidth of LEDs. 32 FFT case has even worse SNR at high frequency subcarriers. This may result from the short occupied interval for the dimming-DMT signal. This may enhance the multipath interference. As for the 512 FFT case, it is seen that the anomalous SNR degradation appears at low frequency subcarrier. This may result from improper choice of comb subcarrier. In 512 FFT case, the low frequency band may suffer from low frequency noise reported in ref [11, 12]. While the comb subcarrier is not chosen properly, the linear compensation between subcarriers may deviate from real channel response. This may cause the low frequency SNR degradation phenomenon in 512 FFT case. The direct evidence can be seen from the cosmetic constellations for 512 FFT case. The phase shift phenomenon of each constellation is caused by the imperfect prediction of low frequency channels. This can be mitigated by optimizing the comb subcarrier choices and the equalization algorithms.

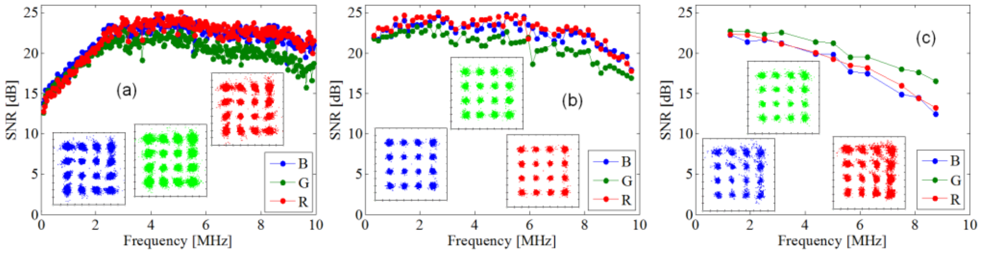

Fig. 4. The SNR performance for different DMT subcarriers. The dimming-ratio was set to be 1, and the transmission distance was 10 cm. (a) FFT size of 512. (b) FFT size of 128. (c) FFT size of 32. Inset: constellation for each R, G, and B channels.

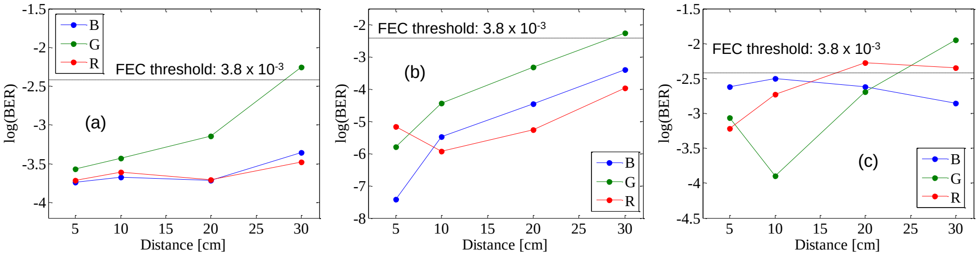

Fig. 5. The signal performance for different transmission distances. The dimming-ratio was set to be 1. (a) FFT size of 512. (b) FFT size of 128. (c) FFT size of 32.

Figure 5 shows the signal performances for different transmission distances among 512, 128, and 32 FFT cases. The dimming-ratio is set to be 1 because different dimming-level equally denotes different SNR conditions. It is seen that, within 30 cm transmission distance,

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nearly all cases can achieve FEC error-free threshold of 3.8 x $10^{-3}$. Further transmission distance can be achieved by using LEDs with higher illumination and with better choice of the focusing lenses.

Figure 6 shows the time traces of dimming-DMT among different dimming-ratios. It can be seen that the time trace at maximum dimming-ratio is like typical DMT. For lower dimming-ratio, the time trace shows low amplitude at low dimming-level symbols.

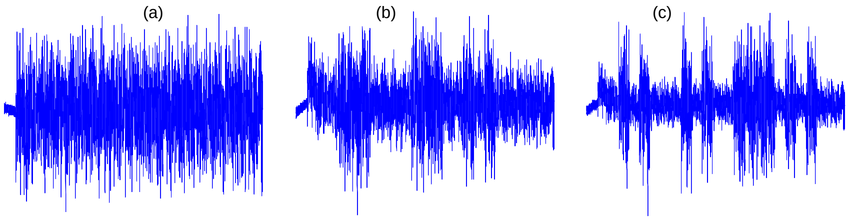

Fig. 6. The time traces of dimming-DMT signals among different dimming-ratios. (a) Dimming-ratio is 1. (b) Dimming-ratio is 0.5. (c) Dimming-ratio is 0.3.

Figure 7(a) shows respectively the LED emission response and the PD response. To obtain the radiation power of each color LED chip, we can estimate it by the measured value from the oscilloscope. Correction parameters for each R, G, and B scope values can be obtained by integrating among the overlap areas of the curves of Fig. 7(a). Figure 7(b) shows the curves for R, G, and B LEDs emission spectra and the CIE 1931 x, y, and z color matching functions. By the six curves and the radiated power of each R, G, and B LEDs, we can get the x, y coordinate of the color. One coordinate of the color generated by the R, G, and B LEDs is shown in Fig. 7(c) on the CIE 1931 color gamut.

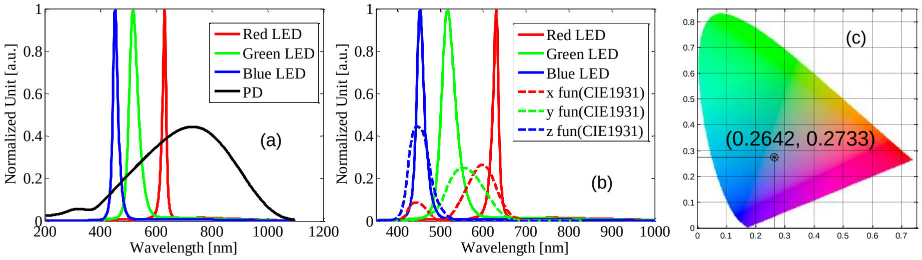

Fig. 7. (a) The spectra of R, G, and B LEDs, and PD. (b) The spectra of R, G, and B LEDs, and the CIE 1931 x, y, z color matching function. (c) The coordinate of one generated color on CIE 1931 color gamut.

## 4. Conclusion

A novel modulation scheme named dimming-DMT was proposed and demonstrated. By using the dimming-DMT, the high speed VLC and color control can be achieved simultaneously. In this work, the dimming range of dimming-DMT was analyzed. Signal performances among different FFT sizes and different transmission distances were compared and analyzed. In the transmission distance of 30 cm and using FFT size of 512, VLC data rate of 103.5 Mb/s (3 x 34.5 Mb/s) was demonstrated. The RGB system may increase the complexity and cost, we believe that the triple increase in data rate as well as color control (a "fancy" function) may justify the additional cost introduced to the RGB VLC system.

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