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Experimental demonstration of 62.5 Mbps VLC link for healthcare infrastructures by incorporating limiting amplifier as an amplification scheme

Sushank Chaudhary*, Xuan Tang**, Xian Wei
Quanzhou Institute of Equipment Manufacturing, Haixi Institutes, Chinese Academy of Sciences, China

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ABSTRACT
The ongoing pandemic situation of COVID-19 has alarmed global public healthcare and epidemic response mechanisms to a significant extent. In this context, communication services can play an important role in hospitals to drive emergency response mechanisms accurately. Visible light communication (VLC) can become an excellent solution to provide communication services in hospitals as it uses low-cost LEDs to transmit information in the form of light signals which can not interfere with medical equipment and does not impact patient health. However, low bandwidth of LEDs is one of the major challenges, which limits the transmission capacity and distance in VLC system. In this work, we propose a post-amplification scheme based on low-pass filter and limiting amplifier to overcome the inherent bandwidth limitation of commercial LEDs. A 62.5Mbps non-return to zero on-off keying (NRZ-OOK) modulation-based VLC link with error-free transmission can be achieved over a transmission distance of 6 m.

1. Introduction
The pandemic situation of COVID-19 has alarmed global public healthcare and epidemic response mechanisms to a significant extent. Since it spreads primarily through contact with any infected person, even doctors and medical professionals attending COVID-19 patients can face the danger of infection. Communication and data exchange systems can play an important role in screening infected individuals and supporting frontline medical staffs. Since, Visible Light Communication (VLC) uses low-cost Light-emitting diode (LEDs) to transmit information in the form of light signals; it does not interfere with the medical equipment with zero effect on patient’s health. LED based VLC is a promising technology for short-range indoor applications [1,2], thus making it useful for healthcare infrastructures. This technology can be incorporated into any existing lighting fixtures including street and traffic lights, homes, and offices. Visible light range can provide a transmission bandwidth $B_T$ of hundreds of GHz. However, the commercial LEDs impose a rather lower bandwidth limit, e.g., <5 and < 20 MHz for white LEDs and RGB LEDs, respectively. The bandwidth limitation has been addressed using pre- and post-equalization circuits, micro LEDs, and advanced detection circuits [3,4]. In addition, the $B_T$ has been enhanced by adopting advanced modulation formats such as single carrier frequency domain equalization (SCFDE), multi-band carrier-less amplitude and phase modulation, orthogonal frequency division multiplexing (OFDM) and OFDM/offset quadrature amplitude modulation (OQAM) [5–7] at the cost of increased complexity both at the transmitter (Tx) and receiver (Rx). On the other hand, on-off keying (OOK) is the simplest and cost-effective modulation format to transmit binary 1 and 0 as positive and negative voltages. In 2009 [8], pre-equalization circuit was used in transmitting 100 Mb/s, non-return to zero on-off keying (NRZ-OOK) data with 50 MHz and 3 dB bandwidth. In 2014 [9], authors have used RLC equalizer to increase VLC bandwidth and reported transmitting data with a range of 84.44Mb/s-190 Mb/s without any blue filter. White LED was used in another study [10] at a short distance of 0.6 m to transmit 550 Mb/s of real-time data. In 2016 [11], authors have transmitted 150Mbps data over 6 m VLC link with bit error rate (BER) of $1.3 \times 10^{-6}$ by using Red LED and OOK modulation format. However, transmitter and receiver have used a second-order L-C-R equalization circuit for extending the bandwidth. In another work [12], boost LED driver is demonstrated for transmitting 266kbits data over 2 m VLC link by employing OOK encoding scheme. In 2017 [13], an active on-chip tracking system is proposed for transmitting 600Mbps data over 60 cm VLC link by

* Corresponding author.
** Corresponding author.
E-mail addresses: sushankchaudhary@gmail.com (S. Chaudhary), xtang@fjirsm.ac.cn (X. Tang).

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employing NRZ-OOK encoding scheme. A recent study [14] reported using NRZ-OOK encoding scheme with a cascaded T-bridge pre-equalization circuit to transmit 1 Gbps data over 1.5 m VLC link with $7.36 \times 10^{-4}$ BER.

Many researchers [15–17] have used limiting amplifier (LA), a scheme to reduce unnecessary voltage, as pre- and/or post-amplification
scheme to improve transmission bandwidth of optical communication systems. However, limiting amplifier remains an unexploited area in VLC. The current study is an experimental research aiming at using limiting amplifier as a post-amplification scheme for 62.5 Mbps data transmission over 6 m VLC link.

The rest of the paper is divided as follows: Section II describes the working principle of LA, Section III describes the experimental setup and results followed by Section IV which presents the conclusion of this work.

2. Working principle of LA

LA transits between trans-impedance circuit and clock and data recovery (CDR) circuit. A prototype of LA was proposed in 2013 [18] for increasing gain and bandwidth. LA can detect 11.9 mV signal by utilizing large extinction ratio, 18dBm received average optical power, 0.75A/W photodiode responsivity, and 1kΩ transimpedance amplifier (TIA) gain. With higher gain (>40 dB), LA can provide larger voltage signals for the subsequent CDR and decision circuits. Most amplifiers provide linear response to small input signals. However, output signals can be altered by nonlinear effects in case of large signals.

For instance, constant tail current switching through a single transistor can limit the output signal at a differential stage by clipping it. LA cannot evade limiting or clipping the output signal. Fig. 1(a) and (b) represent the basic architecture and DC transfer function of LA [18]. LA operates in linear regime ($v_{out}$ proportional to $v_{in}$) for small input signals ($v_{out}$) and in limiting regime ($v_{out}$= constant) for large signals.

3. Experimental setup and results

The experimental setup of the proposed NRZ-OOK VLC system by incorporating limiting amplifier is shown in Fig. 2. At the transmitter side, OptiSystem™ is used to generate 62.5Mbps NRZ-encoded data in a computer. The NRZ-OOK digital-encoded data is uploaded into RIGOL DG-5352 arbitrary wave generator (AWG) which has the overall bandwidth of 350 MHz. The sampling rate of AWG is set at 125 MHz. AWG performs the conversion of digital data into analog signal. The output of AWG is modulated with d.c bias by using Tee Bias from Mini-Circuits™. A programmable battery source (RIGOL DP832A) is used to generate d.c bias of 25 mW. The output of Tee Bias is fed to commercially available Blue LED from Epileds™ for intensity modulation.

Fig. 3 shows the measured frequency response of the blue LED. It shows that -3dB attenuation is achieved at ≥4.40 MHz.

The receiver is fixed at a distance of 6 m from the LED. Convex lens is used to focus the beam of light towards avalanche photo diode (APD) from Thorlabs. The distance between the lens and APD is 10 cm. The output of APD is fed to RIGOL MSO 4054 real-time oscilloscope operating at a sample rate of 125 MHz. The oscilloscope captures the waveform which can be further processed for post-amplification in the computer. Table 1 illustrates the system parameters used for this experiment. The post-amplification scheme comprises of LA followed by low-pass filter with a cut-off frequency of 125 MHz. The amplifier is used to increase the output signal from APD between the range of 0.1V and ~0.1V while clipping the unwanted signal out of this range. We have compared the performances of low-pass Gaussian filter and low-pass Butterworth filter.

![Fig. 3. Measured frequency response of LED](image)

| Table 1 System parameters. |
|----------------------------|
| Parameters | Value |
| LED bandwidth | <5 MHz |
| Input power | 25 mW |
| APD active Area | 0.8 mm² |
| APD peak response | 0.45 A/W |
| LA gain | 40 dB |
| LA maximum output voltage | 0.1 V |
| LA minimum output voltage | -0.1 V |
| LA transition time | 20 ps |
| LA noise power | -60 dBm |

![Fig. 4. Measured results (a) BER versus Vpp (b) Q Factor versus Vpp.](image)
The transfer function of low-pass Gaussian filter is expressed mathematically as:

\[ H(f) = \alpha e^{-\left(\sqrt{2}\right) \left( \frac{f}{f_c} \right)^N} \]  

where \( H(f) \) is the filter transfer function, \( \alpha \) is the parameter insertion loss, \( f_c \) is the filter cut-off frequency, \( N \) is the parameter order, and \( f \) is the frequency.

Similarly, the transfer function of low-pass Butterworth filter is expressed mathematically as:
When Vpp is 12V, the value of BER for both low-pass Gaussian filter and low-pass Butterworth filter is slightly better than that of low-pass Gaussian filter as shown in Fig. 4(a). Similarly, the value of Q factor for low-pass Gaussian filter is noted as 3.62 dB whereas in case of low-pass Butterworth filter, the value of required Vpp for transmission of such data is also optimized. The reported results show the successful transmission of 62.5 Mbps data at the Vpp of 12V with the acceptable BER. Furthermore, the BER can be improved with the increase of Vpp.

\[ H(f) = \frac{1}{1 + (j2\pi f fc)^n} \]

where, \( fc \) is the filter cut-off frequency, \( n \) is the parameter order, and \( f \) is the frequency.

We have varied the value of voltage peak-to-peak (Vpp) from AWG to measure the corresponding Bit Error Rate (BER) and Quality factor (Q factor) for low-pass Gaussian filter and low-pass Butterworth filter as shown in Fig. 4.

When Vpp is 12V, the value of BER for both low-pass Gaussian filter and low-pass Butterworth filter is calculated as below \( 10^{-3} \). However, when Vpp is increased further the performance of low-pass Butterworth filter is slightly better than that of low-pass Gaussian filter as shown in Fig. 4(a). Similarly, the value of Q factor for low-pass Gaussian filter is noted as 3.49 dB at the Vpp value of 12V as shown in Fig. 4(b). Moreover, if Vpp is increased further up to 20V, significant improvement of BER and Q factor is noticed for both filters. This shows that at least 12V of Vpp is required to receive the accepted BER value as per FEC limits.

Fig. 5 shows the measured time domain signal without filter and with low-pass Gaussian and Butterworth filters. It is noted that the signal without filter contains more noise as compared to the one with the use of filters. Both filters are used to remove the noise and unwanted frequency components from the output of photodetector. When Vpp is increased from 12V to 20V, the electrical time domain signal is further enhanced with less noise. Similarly, Fig. 6 shows the measured eye diagram at the receiver side for without LA and with LA in conjunction with low-pass Gaussian filter and low-pass Butterworth filter at Vpp = 12V and Vpp = 20V, respectively.

4. Conclusion

In this work, we have experimentally demonstrated the transmission of 62.5 Mbps data over 6 m VLC link by incorporating LA and low-pass filter technique for healthcare infrastructures. For low-pass filter technique, we have used Gaussian and Butterworth filters. The performance of low-pass Gaussian filter is slightly better than that of low-pass Butterworth filter. The value of required Vpp for transmission of such data is also optimized. The reported results show the successful transmission of 62.5 Mbps data at the Vpp of 12V with the acceptable BER. Furthermore, the BER can be improved with the increase of Vpp.

Author statement

Sushank Chaudhary: Conceptualization, Methodology, Software, Writing Original Draft. Xuan Tang: Validation, Resources, Supervising. Xian Wei.: Formal Analysis, Data curation, Investigation.

Declaration of competing interest

The authors declare that they have no conflict of interest with anyone.

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