2 Gb/s µLED-APD Based Visible Light Communications Using Feed-forward Pre-equalization and PAM-4 Modulation

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Abstract *Feed-forward pre-equalization is investigated to extend the transmission capability of µLED-based links, providing better receiver sensitivities up to 5dB compared with post-equalization. Error-free 2Gb/s free-space VLC over 0.6m is demonstrated using a PAM-4 modulated blue µLED and an APD receiver.*

Introduction

Visible light communication (VLC) links for intra-room data communications have been investigated intensively recently as light-emitting diodes (LEDs) can provide high-speed data transmission as well as illumination. Such LED-based optical wireless systems are a potential solution to the spectrum crunch in radio frequency systems as they can make use of hundreds of THz of un-regulated bandwidth[1]. Moreover, VLC systems demonstrate important advantages, namely high security, cost-efficiency and energy-efficiency[1].

Low-cost VLC links are typically based on the use of intensity modulation and direct detection (IM/DD) schemes with the major challenge for higher speed transmission being the limited modulation bandwidth of the LEDs. Therefore various techniques have been investigated to compensate this LED bandwidth limitation and therefore improve the achievable data rate. Modulation schemes with high spectral efficiency, such as orthogonal frequency division multiplexing (OFDM) and pulse amplitude modulation (PAM), have also been studied[2]. High data rate multiple-input multiple-output (MIMO) optical wireless communications have also been proposed to achieve higher capacity[3]. Optical spatial modulation (OSM) can also demonstrate an enhanced link rate[4].

Equalization has been investigated to extend the link bandwidth and improve the data rate. Multiple-resonant equalization has been proposed and 80 Mb/s data transmission has been achieved with a bit-error-rate (BER) $<10^{-6}$ using a pre-equalized white LED[5]. VLC post-equalization circuits, which reshape the channel response, have also been studied, achieving non-return-to-zero (NRZ) data transmission up to 340 Mbit/s[6]. Moreover, simulation studies on an adaptive equalization system using decision feedback equalizer have shown the potential to achieve 1 Gb/s data transmission using 4 feed-forward taps and 2 decision feedback taps[7].

In this work, feed-forward equalization (FFE) is proposed for use at the VLC transmitter in conjunction with a PAM modulation scheme in order to achieve high data rates of > 1 Gb/s in free-space VLC links. Simulation results demonstrate that such pre-equalization provides up to 5 dB better receiver sensitivity compared with post-equalization as the receiver noise is not enhanced in the former case. Moreover, experimental results demonstrate that simple 2-tap and 3-tap feed-forward equalization is able to remove the inter-symbol-interference (ISI) caused by the limited link bandwidth of a line of sight (LOS) VLC system, greatly improving the link performance. Micro-pixelated LEDs (µLEDs) are used as they exhibit higher modulation bandwidth than conventional large-size LEDs[8]. Furthermore, four-level PAM (PAM-4) is used at the transmitter, as it exhibits double the spectral efficiency of NRZ modulation. An avalanche photodiode (APD) is used at the receiver since APDs have been shown to provide an additional link power budget[9]. Using a 3-tap feed-forward pre-equalizer, error free 2 Gb/s transmission is achieved over a 0.6 m free-space VLC link. The results prove that feed-forward pre-equalization with only a few taps can improve the µLED-based link performance greatly, providing a cost-effective solution for high speed VLC links.

Feed-forward equalization and simulation results

Equalization has been used in radio communication systems to compensate for ISI.

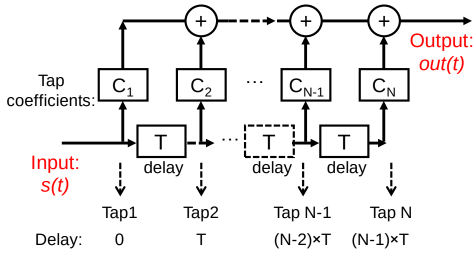


Fig. 1: Schematic of the feed-forward equalizer.

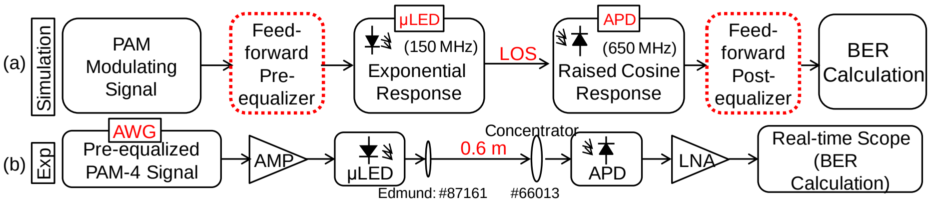


Fig. 2: (a) VLC system simulation model and (b) experimental setup of the pre-equalized PAM-4 VLC link.

A feed-forward equalizer is a linear equalizer and can be implemented using a transversal filter[10] (Fig. 1). The output of the equalizer is the sum of a set of input signals which are delayed and weighted by the tap coefficients and it can be written as

$$out(t) = \sum_{n=1}^{N} C_n \times s[t-(n-1)T]$$

where *s(t)* is the equalizer input, C_n are the tap coefficients, T is the tap delay and N is the number of taps. In this work, a symbol-spaced equalizer is employed at the transmitter side of the proposed VLC system. A simulation model is built to compare the performance of the proposed pre-equalizer with a feed-forward post-equalizer for a LOS VLC system. The link model is based on the characteristics of the components used in the experimental demonstration with their key parameters noted in Fig. 2a. The BER curves are used to compare the performance of the link using the two equalization schemes at different data rates.

Fig. 3 shows the optimized tap coefficients and the eye-diagram of the pre-equalized modulating and respective detected PAM-4 signal for a 1.6 Gb/s VLC link using 2 taps. The

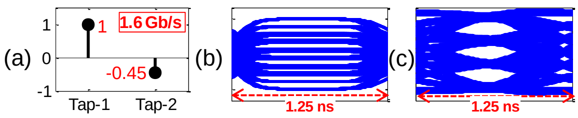


Fig. 3: Simulated (a) tap coefficients and eye-diagrams of the (b) pre-equalized and (c) received PAM-4 signals.

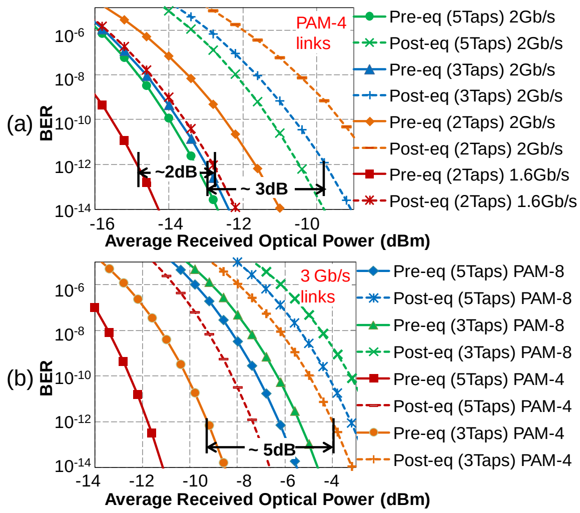


Fig. 4: Simulated BER performance of (a) PAM-4 VLC links at different data rates and (b) 3 Gb/s VLC links for different PAM schemes using pre- and post-equalization with varying number of taps.

comparison of the BER curves (Fig. 4) shows that pre-equalization outperforms post-equalization for all the VLC links studied. This is due to the fact that feed-forward post-equalization amplifies both received signals and the noise, resulting in a noise enhancement penalty[9], which does not exist in the pre-equalized link. It is found that pre-equalization provides an improved receiver sensitivity for PAM-4 links over the respective post-equalized links of 2 dB, 3 dB and 5 dB at 1.6 Gb/s, 2 Gb/s and 3 Gb/s respectively. Moreover, simulation results (Fig. 3b) demonstrate that 3 Gb/s transmission is feasible using a pre-equalized PAM-4 link with only a few taps. Furthermore, it is found that PAM-4 works better than PAM-8 in such links as the multi-level penalty is smaller (Fig. 4b). The simulation results clearly demonstrate the advantage of using pre-equalization and PAM-4 in free-space VLC links.

Experimental setup and results

The experimental setup employed for a LOS high-speed PAM-4 VLC link is illustrated in Fig. 2b. An arbitrary waveform generator (AWG) is used to generate the pre-equalized modulating signals. The output of the AWG is amplified to 2V peak-to-peak in order to modulate a 450 nm µLED (square 20×20 µm^2 aperture). The µLED is driven with a DC bias of 5V. The output beam is collected using an aspheric lens, while at the receiver side an aspheric lens is employed as a concentrator. The transmitted signal is detected with an APD detector (First Sensor AD800-11), while a low noise amplifier (LNA) amplifies the detected signal. A digital storage oscilloscope is used to capture the received waveform and respective eye-diagram. The BER of the link is

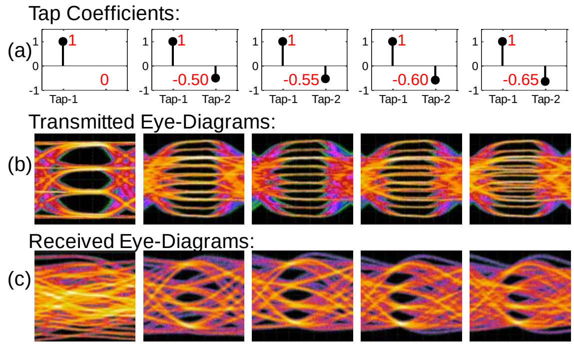


Fig. 5: (a) Tap coefficients and eye-diagrams of the (b) pre-equalized PAM-4 modulating and (c) respective received signal for the 1.6 Gb/s VLC link.

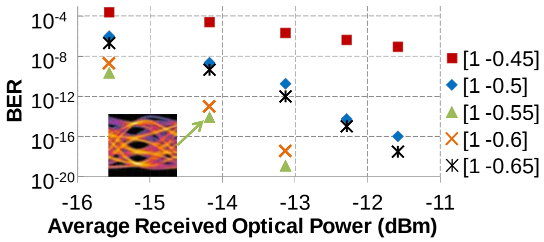


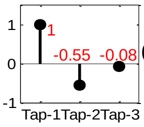
Fig. 6: BER plots of the 1.6 Gb/s pre-equalized PAM-4 link over 0.6 m for various tap coefficients.

calculated offline based on the captured waveforms and the measured APD noise.

A 1.6 Gb/s VLC link is implemented using a 2-tap FFE pre-equalizer and an 0.8 GS/s PAM-4 modulating signal. Fig. 5 shows the eye-diagrams of the pre-equalized PAM-4 signal generated by the AWG (Fig. 5b) and the respective eye diagrams (Fig 5c) of the signal detected at the APD for various FFE tap coefficients (Fig. 5a). The un-equalized PAM-4 modulating signal and the corresponding eye diagram of the received signal are also shown.

It can be observed that the received eye diagram for the un-equalized PAM-4 link is completely closed and therefore, the transmitted information cannot be recovered at the receiver. However, the received pre-equalized eye-diagrams have 4 clearly distinguishable levels, demonstrating that the proposed 2-tap FFE can mitigate the ISI and overcome the limited link bandwidth. The BER performance is also calculated for various tap coefficients (Fig. 6). Error-free transmission with a BER<10^{-12} is achieved, with the tap coefficient of (1, -0.55) providing the best BER performance. The link sensitivity for achieving 1.6 Gb/s transmission with a BER < 10^{-12} is found to be -15 dBm.

A 2 Gb/s free-space VLC link is also tested using the same setup but now with a 3-tap pre-equalizer. The tap coefficients are optimized to achieve the largest eye opening. The eye diagrams of the transmitted pre-equalized PAM-4 signal and the received signal are shown in Fig. 7. The eyes are open indicating that the

(a) 

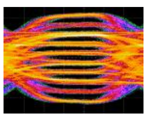
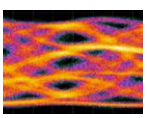
(b) 
(c) 

Fig. 7: (a) Optimized tap coefficients and eye-diagrams of the (b) pre-equalized and (c) received PAM-4 signals.

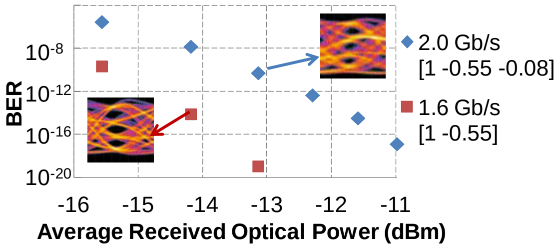


Fig. 8: BER plots for the 1.6 Gb/s and 2 Gb/s PAM-4 VLC link with optimized tap coefficients.

transmitted signal can be recovered. The BER performance obtained for the 2 Gb/s pre-equalized PAM-4 link is shown in Fig. 8. Error-free transmission (BER<10^{-12}) is achieved for an average received optical power of > -12.2 dBm.

Conclusions

The use of pre-equalization in VLC links is proposed in order to mitigate the ISI caused by the limited link bandwidth. Feed-forward equalization in conjunction with PAM modulation is demonstrated to enable high speed (> 1 Gb/s) data transmission in free-space VLC links without using complicated digital signal processing. Simulation results show that the use of pre-equalization and PAM-4 offers better receiver sensitivity of up to 5 dB when compared with post-equalization. Error-free (BER<10^{-12}) 2 Gb/s data transmission over 0.6 m of free-space VLC link using a blue µLED and an APD detector is demonstrated. The results showcase the potential benefits of pre-equalisation and PAM-4 modulation in high-speed VLC systems.

Acknowledgements

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