A 100 Mb/s Visible Light Communications System Using a Linear Adaptive Equalizer

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Abstract—This paper presents experimental results demonstrating a > 100 Mb/s visible light communications (VLC) system using linear adaptive equalizers for the first time. In order to achieve high transmission speeds, generally the research community has adopted spectrally efficient modulation formats such as discrete multi-tone and equalizers are overlooked. The reason for this is unclear as equalizers offer a substantial capacity for removing inter-symbol interference. As a result, in this paper we implement a line-of-sight VLC link with an ~8 MHz bandwidth and a linear feedforward equalizer; the number of taps is varied in order to gain insight into the system performance using varying complexity. The 120 Mb/s transmission speed ultimately achieved offers a bit-rate to bandwidth gain of ~15 times.

Keywords— Equalizers, light emitting diodes, visible light communications

I. INTRODUCTION

VLC is a technology that is coming under an ever increasing focus for research as a solution to the last-metre bottleneck imposed by ultra-high capacity optical fibre backbone networks. Due to congested and over-allocated spectrum, radio frequency (RF) technologies simply cannot provide the required bandwidth ubiquitously at low costs [1].

As such, it is necessary to ensure that high transmission speeds are readily available through VLC systems in order to satisfy such demand. Thus, the vast majority of research is focused on improving transmission speeds. There has been substantial success within the research community as data rates in the low Gb/s region are now readily available using a variety of different transmitters. In [2], red, green and blue wavelengths are multiplexed. The modulation format selected for each channel is orthogonal frequency division multiplexing (OFDM), which offers higher spectral efficiency than unequaledized time-domain modulation formats such as pulse amplitude modulation (PAM). Each wavelength multiplexed channel offers ~30 MHz bandwidth, thus leading to a bit rate gain of around ~33 times for each channel. OFDM was also selected as the modulation format in [3] which had a modulation bandwidth ~60 MHz and thus a bit rate gain of 50 times, which is a remarkable result.

While OFDM has shown considerable potential for driving up transmission speeds in VLC systems, equalizers have been largely ignored. The reason for this is unknown; especially considering that depending on fast Fourier transform size and data rate, OFDM hardware implementation can be relatively complex in comparison to an equalizer in the form of a finite impulse response (FIR) filter, trained with the least mean squares algorithm. Thus the BER performance capabilities of using such an equalizer are unknown. To the best of our knowledge, in this work we demonstrate a digital linear adaptive VLC system that can offer > 100 Mb/s transmission speeds for the first time. Previously in [4] it had been demonstrated that transmission speeds of up to 170 Mb/s were available using decision feedback and artificial neural network equalizers, which are more complex than the linear LMS equalizer. Here we show a transmission speed of 120 Mb/s (~70% of [4]) using a significantly less complex equalizer.

White light is required for home/office illumination and is commonly produced in one of two ways; firstly using a red, green and blue light-emitting diode (LED) as in [2]. This method offers a capacity improvement by introduction of additional channels. The disadvantage of this method is achieving the correct white balance and the additional expense and complexity associated with the introduction of colour filters at the receiver. The more popular method to produce white light is an off-the-shelf solution using packaged white phosphor LEDs (WPLEDs) that consist of blue LED chips encapsulated by a yellowish phosphor. This method has a significant associated downside; the temporal response of the phosphor is in the μs region, limiting the overall bandwidth to a few MHz, despite the faster response of the blue LED that can be in the GHz region [5]. The faster blue component can be extracted using a blue filter at the receiver, thus increasing the bandwidth by up to one order of magnitude, for the cost of an ~30 dB power penalty [5]. The WPLED under test in this work is a Philips Luxeon Rebel DS64 that has a measured bandwidth of 4.5 MHz (white) and 8 MHz (blue). It is well known that in order to improve the link capacity, the bandwidth is the key parameter to optimize. Therefore we adopt the blue filter at the receiver in this work and select an 8 MHz system bandwidth. Using this setup in conjunction with an LMS equalizer, we find...
it is possible to support a link performance up to a transmission speed of 120 Mb/s. The net bit rate gain (15 times) is considerably lower than in [2, 3]; however a transmission speed suitable for fast Ethernet can be sustained with a simple technique.

II. VISIBLE LIGHT COMMUNICATIONS TEST SETUP

The schematic block diagram of the experimental test setup is shown in Fig. 1. A $2^{31}-1$ pseudorandom binary sequence (PRBS-10) is generated in MATLAB and passed through a unit height rectangular pulse shaping filter. The PRBS-10 signal is sent to the Tektronix AFG3252 arbitrary function generator by LabVIEW and mixed using a bias tee (cut-on frequency 7 kHz) to intensity modulate the WPLED.

The light-current and current-voltage (L-I-V) relationships are illustrated in Fig. 2 which also shows the selected bias point (dashed line) of 500 mA. The optimal AC voltage characteristics were selected empirically based on the real-time Q-factor measurement at low transmission speeds using the Agilent DSO9254A oscilloscope. The optical spectra of the WPLED and transmission of the blue filter used are shown in Fig. 3, showing characteristic peaks at 445 nm and ~550 nm. The blue filter removes the vast majority of the power introduced by the yellowish phosphor. The WPLED is a Lambertian emitter as given by [6]:

$$I(\theta) = \frac{(m + 1)}{2\pi} \cos(\theta)^m$$

where \(\theta\) is the angle of deviation from the normal and \(m\) is the Lambertian order. In this experiment, we consider a line of sight configuration and hence \(\theta = 0^\circ\) for maximum power transfer. The VLC channel gain \(H(0)\) for the LOS link is given as [6]:

$$H(0) = \frac{A}{d^2} I(\theta) \cos(\phi)$$

where \(d\) is the distance between transmitter and receiver. In this work \(d = 0.05\) m, which is kept very short in order to meet the typical office lighting illuminance level of 500 lux [7], but \(d\) can be increased simply by scaling up the number of WPLEDs. \(A\) is the photoactive area of the PD and \(\phi\) is the angle of incidence at the PD in degrees (also \(0^\circ\)). Clearly the LOS channel is not time varying thus resulting in a linear attenuation of the signal, which is proportional to \(d^2\).

The receiver is a ThorLabs PDA-10A-EC which consists of a packed silicon photodetector and transimpedance amplifier, offering 150 MHz bandwidth, 0.8 mm\(^2\) active area, $10^4$ V/A gain and 0.225 A/W responsivity @ 445 nm (noise power density $5.5 \times 10^{11}$ W/Hz\(^{1/2}\)). There are several sources of noise present in the system including shot, thermal and ambient, which are all additive white Gaussian noise (AWGN) sources [6]. The experiment was conducted in a controlled dark laboratory in order to minimize noise as a precaution. Nevertheless, the thermal and shot noise introduced by the receiver electronics is the dominant noise source [6].

After acquisition by the DSO9254A, the signal is by:
where $\mathcal{R}$ is the photodiode responsivity, $G$ is the $10^4$ V/A transimpedance gain, $\{h_j\}_{j=-\infty}^{\infty}$ is the sampled channel impulse response, $i$ is the current sampling instance, $j$ represents the contributions of the inter-symbol interference (ISI) and $n_i$ is a zero mean Gaussian random variable with variance $\sigma^2$. The equalizer selected in this work is a linear adaptive equalizer implemented as an FIR filter (shown with 5 taps in Fig. 1. Equalizers require training; i.e. the comparison of a known symbol pattern with the received samples at the start of any given transmission sequence. This comparison is necessary because it allows the equalizer to calculate the system transfer function and compensate for it by appropriately scaling its associated tapped weight coefficients. While there are a variety of training methods to achieve this calculation, LMS training is selected because it not computationally complex and hence lends itself well to future hardware implementation. The recursive least squares (RLS) algorithm is another popular option for training, offering a faster convergence to the target dataset. RLS requires a division in calculation of the correlation matrices (refer to [8]) that increases the complexity beyond that of the LMS algorithm. The weights $w$ are updated as follows [8]:

$$w_{t+1} = w_t + \mu e X$$  \hspace{1cm} (4)

where $X$ is the observable vector of input samples to the filter, $\mu$ is the step size parameter and $e$ is the error, given by [8]:

$$e = d_t - W^T X$$  \hspace{1cm} (5)

The unequalized threshold detector results are shown in Fig. 4 alongside the Q-factor measurements. At 10 Mb/s the link exhibits a Q-factor of ~23 dB and decreases approximately exponentially (fit not shown for clarity) with increasing data rate. Eye diagrams are shown inset at data rates of 10 Mb/s, 50 Mb/s and 100 Mb/s that illustrate gradual eye closure. An error free transmission speed can be supported up to 80 Mb/s using a symbol-by-symbol BERT. The adaptive linear equalizer BER performance is shown with varying $\mu$ in Fig. 5 alongside the threshold detector (raw) performance for an at-a-glance comparison. It was found that the equalized BER performance was largely independent of $N$. As a result the average BER response for each $\mu$ is shown. The error bars for every $\mu$ profile indicate the standard deviation from the average BER in each case. For $\mu = 0.0015$, the available transmission speed available at a BER of $10^{-6}$ is 90 Mb/s. The link fails for data rates of 100 Mb/s or higher. The reason for this is due to insufficient

$$y_i = \mathcal{R} \left[ y_i h_0 + \sum_{j=\infty}^{\infty} y_j h_{i-j} + n_i \right]$$  \hspace{1cm} (3)

where $d$ is the desired sample value and $W^T$ is the transpose of the complete weight vector. The training sequence lasts for 10,000 symbols in order to allow sufficient convergence on the target data set. Once the training sequence is complete, the weights are stored and they are no longer updated. Finally, the symbols at the output of the filter are compared with a mid-level threshold for bit error rate (BER) testing. It should be noted that the selection of $\mu$ is of critical importance in this work, along with the number of taps. As can be inferred from (4), if $\mu$ is set excessively, the weights will never converge on the system response. On the other hand, if $\mu$ is set insufficiently, the convergence may take too long and not be optimized by the conclusion of the training sequence. Therefore in this work we test $\mu = \{0.0015, 0.005, 0.01, 0.05\}$. The number of taps $N$ selected is important because increasing the $N$ allows for compensation of a higher ISI span; however if $N$ is excessive then resources are wasted. As such in this work we test $N = \{5, 10, 15, 20\}$. III. RESULTS

The unequalized threshold detector results are shown in Fig. 4 alongside the Q-factor measurements. At 10 Mb/s the link exhibits a Q-factor of ~23 dB and decreases approximately exponentially (fit not shown for clarity) with increasing data rate. Eye diagrams are shown inset at data rates of 10 Mb/s, 50 Mb/s and 100 Mb/s that illustrate gradual eye closure. An error free transmission speed can be supported up to 80 Mb/s using a symbol-by-symbol BERT.
selection of $\mu$. The equalizer does not converge to an acceptable mean square error level before the end of the training sequence. This is highlighted in Fig. 6 which shows the error convergence over the entire training sequence at a transmission speed of 100 Mb/s. The difference in mean square error between $\mu = 0.0015$ and $\mu = 0.05$ is around one order of magnitude.

For $\mu = 0.005$, the link can support a data rate of 110 Mb/s at a BER of $10^{-6}$. Once more for transmission speeds of 120 Mb/s or greater, the equalizer does not converge on the error floor and the equalizer fails, inducing errors into the system. For $\mu = 0.01$ and 0.05, transmission speeds of 120 Mb/s can be recovered at a BER of $10^{-6}$. As opposed to the previous two cases, there is no improvement by further increasing $\mu$, if $\mu = 0.1$; the link begins to suffer and a performance similar to $\mu = 0.005$ is observed. The reason for this is due to the step size parameter being excessively set; thus not converging on the error floor. Therefore the best performance obtainable from this link is 120 Mb/s; or a bit rate gain of 15 times in comparison to the bandwidth.

**Fig. 5 Equalized BER performance; transmission speeds of 90, 110 and 120 Mb/s can be achieved for $\mu = 0.0015$, 0.005, 0.01 and 0.05, respectively**

**Fig. 6 Training convergence to the error floor at 100 Mb/s**

**IV. CONCLUSION**

In this paper we have shown a VLC system operating at transmission speeds of ~100 Mb/s using linear adaptive equalizers for the first time. The WPLED used as the transmitter in this work is highly bandlimited due to the slow temporal response of the yellowish phosphor (~4 MHz). Thus, a blue filter is used in order to isolate the faster blue response and improve the bandwidth to ~8 MHz. Due to out-of-band transmission at high data rates, ISI is a critical factor and thus the requirement for a linear equalizer. Without the linear equalizer, the achievable data rate is 80 Mb/s, which can be increased up to 120 Mb/s when the optimal LMS filter is employed.

**REFERENCES**


