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# Visible Light Communications: 170 Mb/s using an Artificial Neural Network Equalizer in a Low Bandwidth White Light Configuration

Paul Anthony Haigh, Zabih Ghassemlooy, Sujan Rajbhandari, Ioannis Papakonstantinou and Wasiu Popoola

**Abstract**—In this paper, we experimentally demonstrate for the first time an on off keying modulated visible light communications (VLC) system achieving 170 Mb/s using an artificial neural network (ANN) based equalizer. Adaptive decision feedback (DF) and linear equalizers are also implemented and the system performances are measured using both real time (TI TMS320C6713 digital signal processing board) and offline (MATLAB) implementation of the equalizers. The performance of each equalizer is analyzed in this paper using a low bandwidth (4.5 MHz) light emitting diode (LED) as the transmitter and a large bandwidth (150 MHz) PIN photodetector as the receiver. The achievable data rates using the white spectrum are 170, 90, 40 and 20 Mb/s for ANN, DF, linear and unequalized topologies, respectively. Using a blue filter (BF) to isolate the fast blue component of the LED (at the cost of the power contribution of the yellowish wavelengths) is a popular method of improving the data rate. We further demonstrate that it is possible to sustain higher data rates from the white light with ANN equalization than the blue component due to the high signal-to-noise ratio (SNR) that is obtained from retaining the yellowish wavelengths. Using the blue component we could achieve data rates of 150, 130, 90 and 70 Mb/s for the same equalizers, respectively.

**Index Terms**—Artificial neural network, adaptive equalizer, light emitting diodes, visible light communications

## I. INTRODUCTION

VISIBLE light communications is a growing field of research; interest has intensified in recent years with the development of high power gallium nitride (GaN) based white LEDs. The commercially available phosphorised white LEDs have bandwidth that is typically less than 5 MHz. The transient response of the blue GaN LED can be in the nanoseconds region and is slowed significantly by the cerium doped yttrium aluminum garnet (Ce:YAG) yellowish phosphor (colour converter) required to create white light [1]. To date, research in VLC has been mainly focused on increasing the data rate and the most popular way to do so has been to maximize the system bandwidth  $B_{sys}$  using a blue

filter (BF) and transmitting a spectrally efficient modulation scheme such as discrete multi-tone (DMT) modulation. With these techniques, a data rate of 1.5 Gb/s using the white spectrum from  $B_{sys}$  of 30 MHz has been reported [2]. While in principle this appears to be a promising method, there are some drawbacks such as a significant amount of signal processing at both the transmitter and receiver, and a feedback channel for the required adaptive bit and power loading. So far there is no agreement over an acceptable feedback channel and VLC remains mainly a unidirectional technology.

To further illustrate the case that DMT modulation is not ideal for VLC systems, demonstrations of real-time systems are only reporting data rates of 100 Mb/s or less, which is over 10 times less than offline speeds. This represents a significant difference that cannot be ignored [3].

Meanwhile, a data rate of 230 Mb/s reported in [4] with  $B_{sys}$  of 30 MHz and an avalanche photodetector (APD) and the less complex non return-to-zero, on-off keying (OOK) modulation technique [4]. The bit error rate (BER) target in [4] was set to  $2 \times 10^{-3}$ , the limit for forward error correction (FEC). It is well known that FEC codes are designed for error recovery in power limited systems where the noise is dominant as opposed to the band-limited system where FEC codes will offer limited improvement. Furthermore, the gross data rate reported in [4] also does not account for possible code puncturing that is required in order to implement the FEC codes. This will further reduce the useful data rate.

Band-limited systems employing symbol-by-symbol detection suffer significantly from inter-symbol interference (ISI), and hence there is the need to remove ISI to recover the transmitted data symbols. One would need to adapt basis functions to the particular channel to avoid ISI. Alternatively equalization could be used to both increase the data rate as well as remove any ISI [1, 5-8]. In particular, the decision feedback (DF) equalizer is often selected due to its reasonable performance and ease of hardware implementation [9]. Even though ANNs offer superior performance [10], they have largely been ignored for VLC systems, which is likely due to the difficulties in hardware implementation. However, ANNs are becoming increasingly popular due to advances in digital signal processing (DSP) technologies such as field programmable gate arrays (FPGAs) [11, 12].

In this paper we report for the first time, the implementation of linear, DF and ANN equalization schemes in VLC systems without and with a BF at the receiver. In this work OOK (the most widely used scheme in VLC) is adopted for reduced com-

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plexity [1, 4-6] and the targeted BER of  $10^{-6}$  in line with the ITU-T G.826 standard uncoded error floor [13]. The equalizers are performed in real time using the TI TMS320C6713 DSP hardware; a popular choice for signal processing applications [14, 15] due to the in-the-loop synchronicity with Simulink. Implementing the filters in the DSP board is a mediatory step between offline processing and real-time and provides a realistic assessment of the actual bit rates that could be achieved with real time processing in comparison to an offline analytical tool such as MATLAB.

The rest of the paper is organized as follows: in Section II we give an overview of the VLC test setup and the equalization theory is outlined in Section III. In Section IV the experimental results are demonstrated and discussed and finally in Section V conclusions are drawn.

## II. VISIBLE LIGHT COMMUNICATIONS TEST SETUP

The LEDs used in VLC have high optical power output, are low cost and have a low bandwidth  $B_{LED} < 5$  MHz. LEDs are Lambertian emitters with intensity  $I$  defined as [16]:

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

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, with a single Philips Luxeon Rebel DS64 white LED; a GaN LED with a Ce:YAG yellowish phosphor placed over the photoactive area in order to produce white light, see Fig. 1. The spectrum shown was measured with a Yokogawa AQ6373 optical spectrum analyzer (OSA). As mentioned, it is the yellowish component that slows the transient response of the LED and it is this component that introduces the bandwidth limitation into the system. It is possible to use a BF to isolate the blue wavelengths ( $\lambda_{peak} = 445$  nm) and improve the overall response time of the system.

The block diagram of the proposed VLC system under test is outlined in Fig. 2. The pseudo-random binary sequence (PRBS) data  $a_i$  is generated and shaped using a rectangular

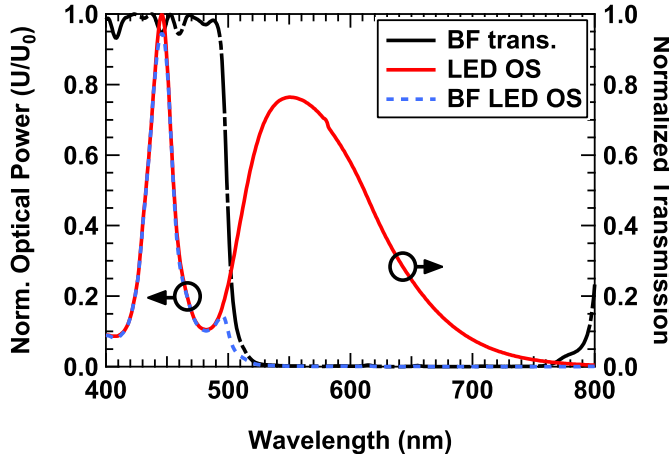


Fig. 1. BF optical transmission (trans.), LED optical spectrum (LED OS) and LED OS after BF (BF LED OS) as a function of wavelength. The blue GaN component has higher transient response than the phosphorised LED

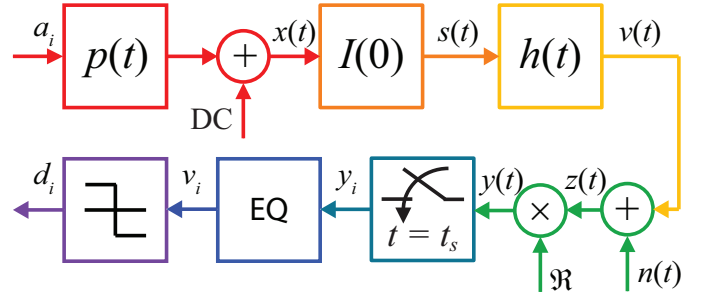


Fig. 2. VLC system block diagram

pulse filter  $p(t)$  in MATLAB then fed to a Tektronix 3252B arbitrary function generator (AFG) to produce the electrical signal. The data signal is mixed with a DC current to produce a non-negative signal  $x(t)$ , which is used for intensity modulation of the LED. The VLC channel gain  $H(0)$  for the LOS link is given as [16]:

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

where  $d$  (m) 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 [17], but  $d$  can be increased simply by scaling up the number of LEDs.  $A$  ( $\text{m}^2$ ) is the photoactive area of the PD,  $I(\theta)$  is the Lambertian intensity ( $\theta = 0^\circ$  in this case) 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  $d^2$ .

The system will be affected by a number of noise sources including the background ambient, thermal, shot, etc. that are assumed to be additive white Gaussian noise (AWGN) sources as stated in [16]. Here we have assumed that the dominant noise source is the electrical shot noise in the photodetector [16]. The PD used was a ThorLabs PDA10A-EC with bandwidth  $B_{PD}$  of 150 MHz,  $0.8 \text{ mm}^2$  active area and responsivity  $\mathcal{R}$  of  $0.225 \text{ A/W}$  @ 445 nm. Aside from the BF, no other optics such as focusing lenses were used in this work. The received optical signal is detected by a PD with an in-built transimpedance amplifier with  $10^4 \text{ V/A}$  gain at a noise power density of  $5.5 \times 10^{-11} \text{ W/Hz}^{-1/2}$ . The resulting voltage signal  $y(t)$  is given as:

$$y(t) = \mathcal{R}z(t) = \mathcal{R}[v(t) + n(t)] = \mathcal{R}[s(t) \otimes h(t) + n(t)] \quad (3)$$

where  $s(t)$  is the transmitted signal,  $v(t)$  is the received signal,  $h(t)$  is the channel impulse response, and  $n(t)$  is AWGN.

The output of the sampler matched filter is given by:

$$y_i = a_i \|u\|^2 + \sum_{i \neq j} a_i u \otimes \tilde{u}(jT_s - iT_s) + n_i \quad (4)$$

where  $T_s$  is the symbol period,  $n_i$  is a zero-mean Gaussian random variable with variance  $N_0 \|u\|^2 / 2$  and  $\tilde{u}(t) = v \otimes h(-t)$ . Since  $B_{PD}$  is large and  $h(t)$  is not band-limited for the majority of the frequencies considered, the system bottleneck is the LED with  $B_{LED}$  of  $\sim 4.5$  MHz, see Fig. 3 for the measured  $-3 \text{ dB}$  electrical bandwidth  $B_{ele}$  for the white

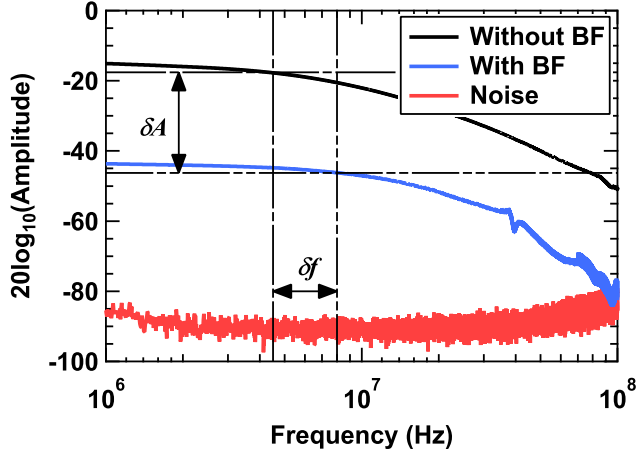


Fig. 3. System bandwidths of  $\sim 4.5$  MHz for the white component and  $\sim 8$  MHz for blue; each component is normalized to the peak power of the white configuration

LED without and with the BF. Filtering out the yellowish wavelengths allows  $B_{LED}$  to be extended by just under a factor of two to  $\sim 8$  MHz ( $\delta f = 3.5$  MHz) at a cost of a power penalty  $\delta A$  of  $\sim 29$  dB. The noise floor was also measured in order to calculate the signal-to-noise ratio (SNR) throughout the system by determining the difference between the signal amplitude and the noise floor. The noise floor was not time averaged to provide a smoother curve because this does not provide a realistic scenario as it would be impossible to time average the noise in a real system.

The system SNR without and with the BF is illustrated in Fig. 4. At the 3 dB frequencies the difference in power  $\delta A$  is  $\sim 29$  dB, which shows a significant power reduction in order to increase the bandwidth by two fold. The channel capacity  $C$  without equalization (i.e. the 3 dB bandwidth raw capacity) against SNR without and with the BF is depicted in Fig. 5. By examination of Fig. 4 the SNR is between 70 and 76 dB at the cut-off frequency without BF as indicated by the red coloured bar. The SNR of the system with BF at the cut-off frequency is between 41 and 48 dB as indicated by the blue coloured bar.

The link without the BF can theoretically sustain a link rate between 52–56 Mb/s while with the BF can theoretically sustain a link speed of 55 and 64 Mb/s without an equalizer as indicated by the red and blue bars respectively, which correspond to the relevant coloured bars in Fig. 4. The difference in capacities is very small when considering the significant cost of power penalty on the received amplitude by introducing the BF.

Later in the results section of this paper we demonstrate that a high performance equalizer such as an ANN can offer a further data rate extension in the high SNR environment offered by the link without BF than in the link with BF, in spite of the fact that the available bandwidth is reduced by half.

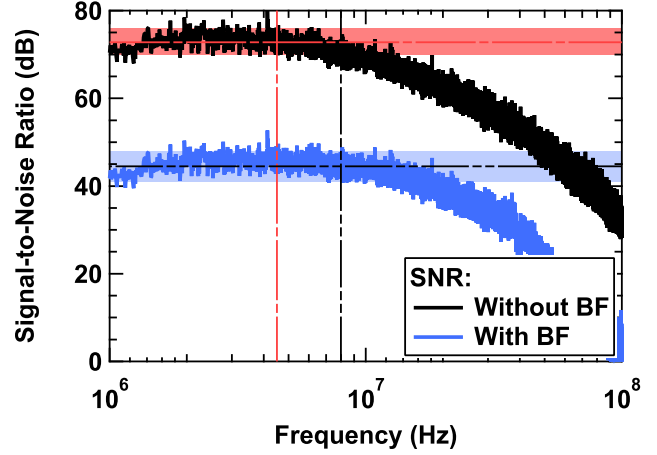


Fig. 4. The SNR experienced over the frequency response of the system. Note that the white configuration offers a significantly higher SNR than the blue

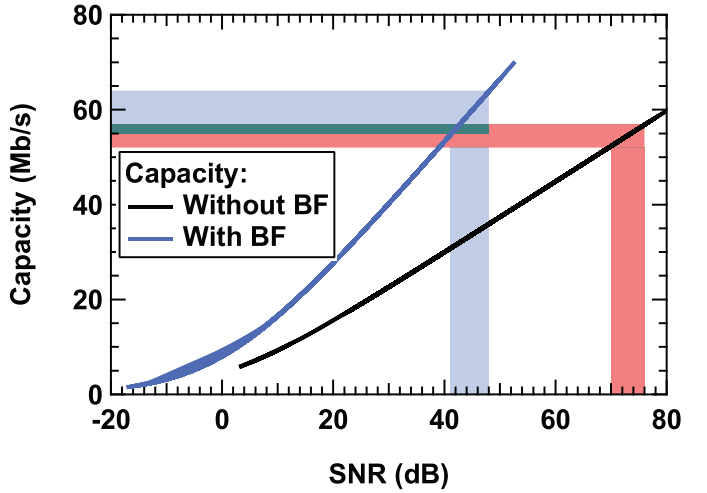


Fig. 5. The channel capacity of white and blue LEDs as a function of SNR

### III. EQUALIZERS AND ARTIFICIAL NEURAL NETWORK

At high data rates, the bandwidth limitation imposed by the white LED will smear the transmitted signal in time thus causing the effect of a symbol to spread to adjacent symbols, thus resulting in ISI that will degrade the error performance of the system. There are two major ways to mitigate the detrimental effect of ISI: (i) to design band-limited transmission pulses which minimize effect of ISI, and (ii) to use an equaliser, which is adopted in this work. By choosing to place the equaliser following the sampler the main advantage is that a digital filter is easy to build and is easy to alter for different equalization schemes, as well as to fit different channel conditions. There are two ways to view the problem of equalization: as an information theory or a classification problem. Treating equalization as an information theory problem involves finding the contribution of ISI to each successive symbol and nullifying it using appropriate filter tap coefficients. While using classification, the aim is to create a decision boundary that correctly classifies the incoming symbols based upon the received samples.

The theory of the equalizers are well known are not covered here, however the reader can refer to [18, 19] for the fundamental details. All the equalizers used in the experiments had same number of taps to ensure a fair comparison. For the linear equalizer,  $N = 10$  taps are selected, so in the DF case the feedforward filter is assigned  $N/2 = 5$  taps and the feedback is assigned  $N/2 = 5$  taps. The ANN based equalizer also has 10 taps and 10 neurons. Increasing the number of taps beyond this value offered negligible improvement at the cost of increased complexity.

Each tap behaves as a delay line and has an associated weight that is multiplied with the incoming sample. The weights must be updated over a training sequence that consists of transmitting a known sequence across the system and compared with the same sequence at the receiver. The equalizers adopted in this paper are transversal and trained with the recursive least squares (RLS) algorithm due to the faster convergence speed and superior performance at the cost of complexity in comparison to the least mean squares (LMS) algorithm [20, 21].

The RLS algorithm finds the filter coefficients for the linear equalizer and the individual feedforward and feedback filters that make up the DF equalizer. It aims to minimize an error cost function  $E$  between the  $i^{th}$  transmitted and received data symbol using a training sequence of 1000 symbols to ensure the impact on the useful information was minimized. The algorithm is trained to a predefined target by minimizing the sum of error squares as can be understood mathematically from the literature [18]. The forgetting factor is set to  $\eta = 0.995$  in this work.

Mitigating ISI using a classifier rather than a typical equalizer can provide several advantages, including superior error rate performance, the ability to generalize when unknown transitions occur and also the fact that any non-linear function can be mapped between the input and output of the classifier. There are several types of ANN that can be used for equalization including the multilayer perceptron (MLP), radial basis function (RBF) or functional link ANN (FLANN) [10]. In [22] different classifiers are examined in terms of their performance in mitigating ISI in communications systems. It was found the MLP has similar performance to the RBF for a fixed amount of ISI and the same training lengths.

The MLP is the least complex ANN when consisting of a single input, hidden and output layer and is thus considered for this work because hardware implementation as a linear transversal filter is considered as it is here. Similar to the previous equalizers, the MLP must be trained (1000 symbols) using a known sequence at the receiver in the exact same way. However the RLS algorithm is not applied here. The most popular training method for the MLP is the Levenberg-Marquardt back propagation algorithm (LM) due to simplicity and ease of hardware implementation which also works on the reduction of an error cost function as follows [23]:

$$E_i = \|d_i - y_i\|^2 \quad (5)$$

The ANN input layer consists of  $N = 10$  tap delay lines as in the transversal equalizers previously. The number of neurons in the hidden layer is also set to  $N = 10$  and it is in this layer

where the processing takes place. The output layer sums the weighted neuron outputs such that [24]:

$$v = f \left( \sum_i w_i y_i \right) \quad (6)$$

where  $w_i$  and  $y_i$  are the coefficients of the  $i^{th}$  weight and input, respectively, and  $i = 0, \dots, N$  since a bias weight is not used. The weights are updated as follows:

$$w_{ij}(n+1) = w_{ij}(n) - \eta \frac{\partial E(n)}{\partial w_{ij}(n)} \quad (7)$$

where  $\eta$  is the learning rate parameter, which requires careful selection – setting an excessively high value will result in instability whilst an inadequate value will result in either a long convergence time or failure to converge [5, 10, 25]. Therefore an adaptive learning rate is adopted, which has the advantage of guaranteed convergence as outlined in [26]. The output of the MLP is sliced and compared to the transmitted data in order to perform BER measurements.

The equalizers are each first implemented in the MATLAB domain and then using the TMS320C6713 DSP board. The output of the DSP board is uploaded to MATLAB in order to find the exact performance comparison with the offline case. In addition, it should be noted that the data used for the offline and DSP equalizers is different in order to ensure that the equalizers are tested thoroughly and to make the test more realistic.

#### IV. RESULTS AND DISCUSSION

The results are presented in terms of their adopted equalization method from best performing to the worst. Both the unfiltered white and filtered blue link configurations are also compared for each equalization method. Further, the offline MATLAB and online hardware implementations are also compared for each equalizer.

##### A. Threshold Detection (No Equalization)

The system performance for the case with no equalizer is shown in Fig. 6. The link implemented with the BF significantly outperforms the white, unfiltered link where data rates of 70 and 20 Mb/s can be supported, respectively at a BER of  $10^{-6}$ . Notably the link with BF is performing as expected in comparison to the system capacity shown in Fig. 5 while the link with no BF is underperforming due to the high ISI environment. ISI is the critical factor without equalization despite the higher SNR in the white system, thus causing threshold detection to fail due to the long rise and fall times of the symbols.

##### B. Artificial Neural Network Equalization

The BER performance with the ANN type equalization is depicted in Fig. 7. At the same BER of  $10^{-6}$ , the system without and with the BF can offer 170 and 150 Mb/s, respectively. The most significant aspect of this result is that with no BF, the data rate is 20 Mb/s higher than with BF. This is attributed to the additional  $\sim 29$  dB of SNR experienced at the receiver and

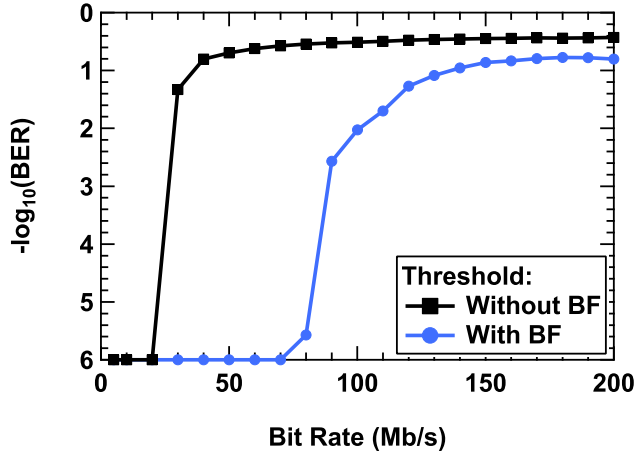


Fig. 6. BER performance of threshold detection without (20 Mb/s) and with (70 Mb/s) BF, respectively

the ability of the ANN to create arbitrary decision boundaries that classify signals based upon the incoming samples rather than attempting to calculate the contribution of the ISI and then remove it. Similar performance is observed with the same system implemented in DSP. Contrary to other reported demonstrations, this is the first experimental demonstration of a white LED without a BF delivering a higher data rate than the case with a BF. This is made possible by the use of ANN. Typically reports that have aimed to improve the transmission speed strive to improve the data rate by increasing the bandwidth, even at the cost of a higher power penalty far as in [1]. Here we show that an ANN equalizer is a more effective method for improving the data rate and mitigating ISI than using the BF at the receiver. Note that this conclusion may not hold true if the blue bandwidth is significantly higher than the white as presented in the theoretical study [27]. This is supported by the fact that links using the BF outperform the white channel rates for other equalizers tested, as discussed in the following section. Furthermore with respect to the raw bandwidth (4.5 and 8 MHz without and with BF, respectively), this represents the highest data rate reported for any real-time VLC system using pulse based modulation with digital equalization. A substantial data rate of  $\sim 40$  and  $\sim 20$  times the white LEDs bandwidth without and with a BF has been achieved. This implies that the link can offer sufficient transmission speed to support the 100Base-T Ethernet standards. It is also noticeable that the achieved data rates exceed those of the system capacity (refer to Fig. 5) and the reason for this is due to the bandwidth extension introduced by the equalizer.

For data rates in excess of 150 and 170 Mb/s with and without BF, respectively the BER is not lower than  $10^{-4}$  (see Fig. 7). The reason for this is that the ANN fails due to a combination of the extreme amount of ISI present in the system in conjunction with the declining SNR, which is close to the system noise floor. If the mitigating factor was exclusively ISI, it would be possible to increase the number of taps and neurons inside the ANN or increase the training length. In fact both of these suggestions offer no improvement,

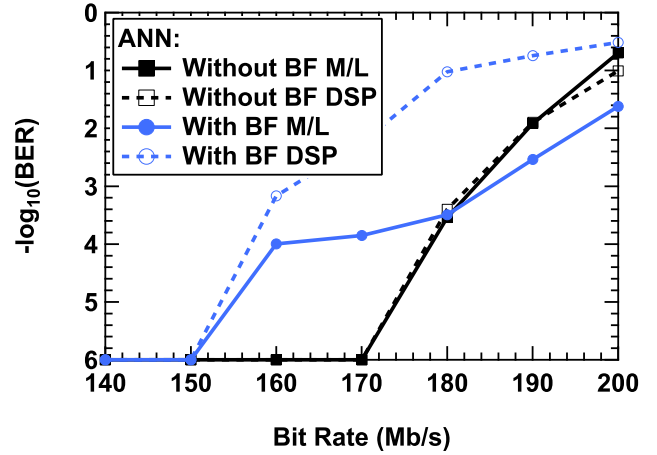


Fig. 7. BER performance of ANN equalizer for the MATLAB (M/L) and hardware implementation with and without BF with real time and offline processing, the data rates without and with BF are 170 Mb/s and 150 Mb/s, respectively

thus the maximum data rate we could achieve at a BER of  $10^{-6}$  was 170 and 150 Mb/s without and with a BF, respectively.

Though small, there is a noticeable difference in the performance of the ANN between the MATLAB and DSP domains. The DSP performance is inferior in comparison to MATLAB due to (i) limited resolution in DSP as the equalizer is implemented using the data type and (ii) the filter coefficients are optimized for MATLAB implementation. However, achievable data rates are identical for both cases.

### C. Decision Feedback Equalization

As shown in Fig. 8 the DF equalizer can offer 130 and 90 Mb/s for links with and without the BF, respectively in MATLAB. It should be noted that the configuration with the BF now outperforms the configuration without the BF. This is contrary to the previous results where the white outperformed the blue. We attribute this to the bandwidth of the devices and the amount of ISI that is contributed in each system. Despite the lower SNR level there is less ISI in the blue configuration and hence the DF equalizer can recover the data up to a higher transmission speed than in the white configuration.

The DF equalizer is incapable of forming arbitrary decision boundaries and also it is incapable of generalizing similar to the ANN. As a result, when transitions that have not occurred in training are present in the equalizer, they are impossible to recover because they are not expected. In terms of the DSP hardware implementation, the performance is similar but not identical as was seen with the ANN equalizer. Data rates of 120 and 90 Mb/s can be sustained for DF equalized links with and without the BF, respectively. There is a reduction in data rate of 10 Mb/s for the blue link compared to the offline processed DF equalizer. This seems like a relatively large difference. However samples were taken in 10 Mb/s intervals so it could be that the actual performance is closer to 130 Mb/s than Fig. 8 alludes to while not managing to successfully transmit 130 Mb/s. The link with BF can support



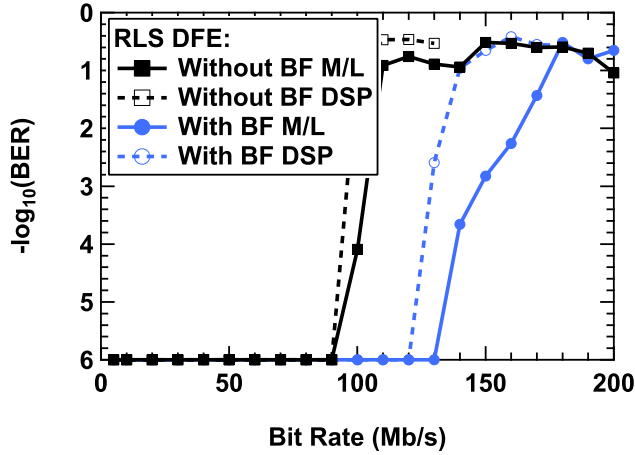


Fig. 8. BER performance of the DF in MATLAB and DSP hardware implementation for the blue and white configurations, which can sustain links of 130 (120) and 90 (90) Mb/s, respectively in the offline (online) case

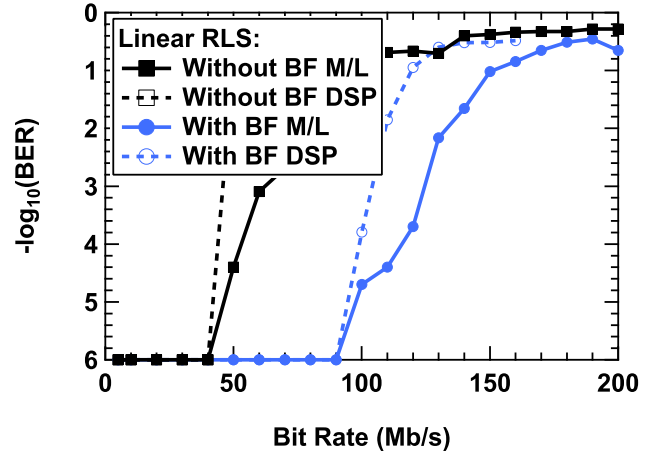


Fig. 9. BER performances of the linear equalizer with and without the BF; data rates of 90 and 40 Mb/s can be offered respectively in both MATLAB and DSP hardware implementation

100Base-T Ethernet (125 MHz bandwidth requirement) and is less complex than the ANN equalizer making this an extremely attractive result.

In comparison to the ANN, the DF equalizer offers 80 (80) and 20 (30) Mb/s less data rate in the offline (real-time) processing. This is a significant drop in available transmission speed and can be attributed to the aforementioned problems. Increasing the number of taps in each filter could help to improve this performance as it would increase the contribution of each previous symbol, however at such high data rates it could also be noise perturbing the signal that is introducing the errors.

#### D. Linear Equalization

The BER performance of the linear equalizer is presented in Fig. 9, which shows data rates of 90 and 40 Mb/s for link with and without the BF can be achieved, respectively. Significantly, the link with BF outperforms the link without BF by 50 Mb/s, which is a similar gap to the DF equalizer (40 Mb/s). The linear equalizer is significantly outperformed by its counterparts as expected due to the high level of ISI.

The linear equalizer is the least complex of all the equalizers under test in this paper and the performance drop in comparison to the DF is quite high. For links with and without the BF we observed a drop of 40 Mb/s and 50 Mb/s, respectively. In comparison to the ANN equalizer, the drop in performance is significant. For the case with no BF, the transmission speed must drop from 170 Mb/s to 40 Mb/s in order to support an error free transmission while for the case with the BF the drop is from 150 Mb/s to 90 Mb/s. As expected, the linear equalizer is the worst performing of the three equalizers and this is due to the inability to form arbitrary decision boundaries and generalize as previous. This is compounded with the fact that linear equalizers amplify the noise and struggle to form transfer functions for system responses that contain a large number of spectral nulls, as in this system. The DSP based linear equalizer can support the same transmission speeds as

the offline processing case and this is the last equalizer that is implemented in DSP.

#### V. CONCLUSION

In this paper we have experimentally demonstrated a high speed VLC system using adaptive equalizers at the receiver. The performance of linear, DF and ANN based equalizers were studied by means of offline signal processing in the MATLAB environment as well as real time implementation in a TI TMS320C6713 DSP board. The best performance is achieved using the ANN equalizer, followed by the DF and linear equalizers. The complexity however increases in the reverse order. The maximum error free data rates of 170 Mb/s and 150 Mb/s were achieved using white and blue bandwidth, respectively. With the most suitable equalizer (i.e. the ANN in this case), the white channel can offer higher data rate than the blue channel. This is largely due to the high power penalty imposed by the blue filter and the effectiveness of ANN equalizer to remove ISI. However, the blue channel outperformed the white channel in all other cases. The linear equalizer is suboptimal even for a high SNR environment as less than two times data rate improvements were achieved with both blue and white channels in comparison to the system with no equalizer. However, ANN and DF offered  $\sim 9$  and 7 times increment in data rates, respectively. This clearly indicates the superiority of ANN equalizers in mitigating ISI. Furthermore, this is the first document of the use of an ANN equalizer in VLC systems to achieve high data rates. The next step in this work is to implement a fully real time system using an FPGA.

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