Raised Cosine Pulse Shaping for Pre-equalized Optical Wireless Links

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***Abstract* – Their programmability means that digital pre-equalization techniques are more flexible than analog circuit equalizers. However, their performance depends on the number of samples per data symbol needed to accurately represent the pre-equalized time domain pulse. This requirement limits the maximum data rate that can be generated by a digital-to-analog converter (DAC). Another challenge when pre-equalizing the signal applied to a transmitter is the need to restrict the maximum voltage applied to the transmitter. Given these challenges, this paper demonstrates the benefits of constructing digitally pre-equalized On-Off Keying (OOK) symbols with raised cosine pulses. In addition, results are presented which show that each symbol can be represented with as few as 5 samples per bit. The performance of the proposed equalization method is investigated using an off-the-shelf LED-based optical wireless communication (OWC) link. Using equalization, the bandwidth of the link is increased by a factor of 10 to 100 MHz. Consequently, the data rate achievable with a 2 GSa/s DAC is 400 Mb/s.**

Keywords* – *Digital pre-equalization, optical wireless communications, raised cosine pulses.

I. INTRODUCTION

With rising deployment of mobile devices over the recent years, there has been an increase in the demand for wireless internet access. The additional capacity created by using Optical wireless communication (OWC) to complement to the existing radio frequency links is one possible way to support this increased demand [1-3]. An important aspect to consider when implementing an OWC link is its -3dB bandwidth.

Channel equalization techniques can be used to reduce the impact of a channels limited bandwidth. Use of pre-equalization in OWC links gained momentum [4-5] because it does not enhance noise in the received signal. On-Off-Keying (OOK) is an attractive modulation scheme to combine with pre-equalization, as it allows simple receivers that do not require digital signal processing to be implemented, thus limiting receiver complexity and potential cost, and focusing complexity at the transmitter.

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Zero-pole-based pre-equalizers have previously been implemented using analog circuits and these have been shown to improve the link bandwidth from a few MHz up to tens of MHz and achieve on-off-keyed data rates of 200-600Mb/s [6-8]. However, the variety of pre-equalizers that can be created using analogue circuits is limited by the frequency responses of analogue circuits. In contrast, their programmability means that digital methods can be used to create a wide range of pre-equalizers, including equalizers that would be difficult to fabricate over cascading analog circuits for links whose response isn't a product of a few single poles [9-10].

The pre-equalization of OOK pulses results in overshoots at the bit transition edges. It has been shown that in a digital implementation, these overshoots need to be appropriately represented by the number of samples (or points) per bit N_{ppb} [10]. This is because a more precise construction results in a better representation of the overshoot and therefore compensation for the low-pass response of the link. However, there are two main challenges when digitally pre-equalizing a signal.

The first challenge is that the requirement to have N_{ppb} points per bit limits the maximum data rate (R_b). In particular, if the DAC has a maximum sampling rate (F_s) then

$$N_{ppb} \times R_b \leq F_s. \tag{1}$$

Secondly, pre-equalizing an OOK data stream creates overshoots which must remain below the maximum that can be applied to transmitter.

The starting point for equalization of an OOK data stream is shape of the pulses used to represent a bit. One pulse shape that can be used is a rectangular (rect) pulse. The alternative pulse shape which can be used is a raised cosine (RC) pulse. This pulse shape is used to reduce the impact inter-symbol interference (ISI) caused by the limited bandwidth of the link [11].

In this paper, RC pulses are shown to reduce the overshoot introduced by pre-equalization. By allowing the number of points per bit to be reduced, this pulse shape also allows higher data rates to be supported. These two benefits are confirmed by experiments with a link that uses the blue component of the output from a white-LED as the transmitter. With digitally pre-equalized RC pulses, the bandwidth of the link is increased by a factor of 10 to 100 MHz using as few as 5 points per bit. Consequently, when the equalized data is sampled at 2GSa/s, data rates as high as 400 Mb/s are

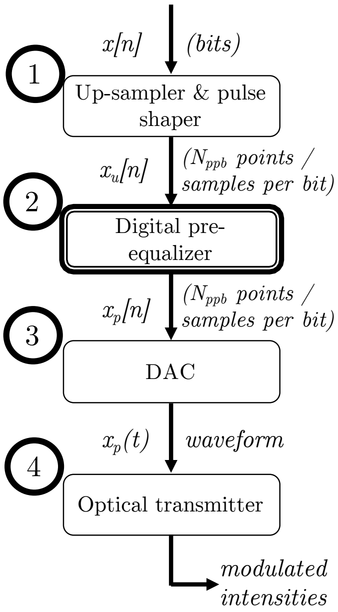

Fig.1. The transmitter-side block diagram.

achievable within the forward error correction bit error rate (FEC BER) limit. To the best of authors' knowledge, this is the first time that these benefits of using RC and pre-equalization have been highlighted.

The paper is organized as follows. The benefits of using RC pulse shaping are described in Section II. These benefits are then demonstrated with an example system. Concluding remarks are then presented in Section IV.

II. System Model and the Pulse Shaping

The steps required to perform digital pre-equalization are shown in Fig.1. Firstly, the OOK modulated data symbols *x[n]* are up sampled and pulse shaped into $x_u[n]$ with N_{ppb} points per bit. The pulses are then pre-equalized into $x_p[n]$ through a digital pre-equalizer and then converted to a continuous-time waveform $x_p(t)$ by a DAC. These waveforms are then transmitted using an optical transmitter.

In this process, the up-sampling N_{ppb} should be an odd number so that there is a mid-point within each bit. In order to also have points at the edges of each bit this means N_{ppb} should be greater than or equal to three. However, more points may be required per bit to achieve a better representation of the pre-equalized signal and hence link performance.

For a certain data rate R_b, the impulse response of a rectangular pulse shaping filter is given as rect$(R_b t)$. Whereas the impulse response of an RC pulse shaper is given as

$$\frac{\sin(\pi R_b t)}{\pi R_b t} \times \frac{\cos(\pi \beta R_b t)}{1-(2\beta R_b t)^2}, \qquad (2)$$

where β is the roll-off factor of the resultant pulse. Typically, β=1 is preferred because it makes the waveform robust to synchronization errors in the receiver [12-13].

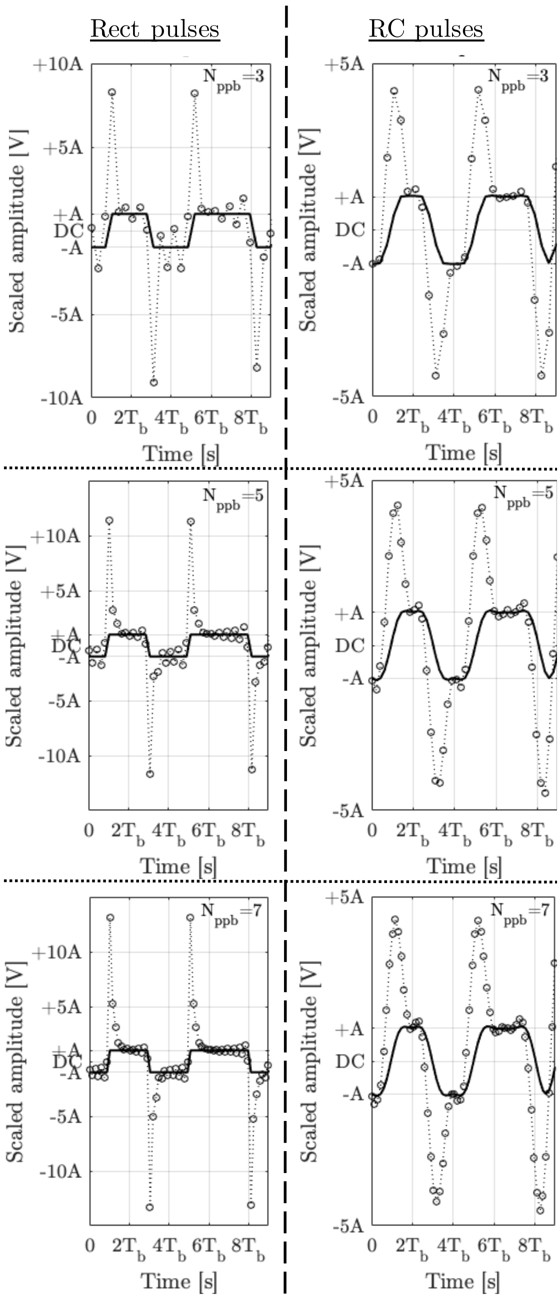

Fig.2. Rect and RC-OOK bit streams **0110 01110** over N_{ppb} values of 3, 5 and 7 with pre-equalizer at k_a=10, f_{3dB}=1MHz, R_b=k_a xf_{3dB}. In each graph, the un-pre-equalized and the pre-equalized pulses are respectively shown as solid lines and marker-based lines. In this figure T_b is the duration of a single bit.

For links with a dominant single pole, a zero-pole (ZP) pre-equalizer has been used to increase the bandwidth of the link. If f_{3dB} is the 3dB bandwidth of a single pole OWC link, then a zero-pole equalizer with the response

$$H_{zp}(s) = \frac{1+\frac{s}{f_{3dB}}}{1+\frac{s}{k_a f_{3dB}}}. \qquad (3)$$

increases the bandwidth by a factor k_a. This bandwidth enhancement is obtained by amplifying the higher frequencies and it therefore causes overshoot in the time-domain.

The benefits of using raised cosine pulses with pre-equalization can be demonstrated by considering the pre-equalization of an example single pole link with a 3 dB bandwidth of 1 MHz. In this case, the value of f_{3dB} in (3) is 1 MHz and to increase the bandwidth by a factor of 10, k_a=10. The impact of this equalizer on the OOK bit stream $x[n]$=**011001110** with voltage levels $+A$ and $-A$ and a bit duration $T_b=1/R_b$ is shown in Fig. 2.

For the rect-pulse-shaped OOK bits the accuracy of construction of the overshoots in the pre-equalized waveform improves as N_{ppb} increases from 3 to 7. However, increasing the number of points per bit also increases the amplitude of the overshoots from 8A to 13A. In some situations these overshoots would exceed the maximum voltage that can be applied to the transmitter.

In comparison, the rounded edges of the RC pulses significantly reduce the overshoot caused by a pre-equalizer. Consequently, for the same pre-equalizer the overshoot amplitude reduces to less than 5A for all 3 N_{ppb} values. Moreover, when RC pulses are used the shape of the sampled signal is almost independent of N_{ppb} when 5 points per bit or more are used. This suggests that when RC-pulses are used as few as 5 points per bit can be used without a significant impact on the links performance. This will increase the data rate that can be supported by a digital equalizer with a fixed output rate.

III. Experimental results

The experimental link is shown in Fig.3. In this link a 2GSa/s DAC within a Keysight AWG81150A was used to generate the transmitted signal. This signal was applied to an Osram Engin LZ400 cool white-LED, which has a specified maximum voltage of 4 V. The bandwidth of the link was increased by using an FGB25M blue filter with a centre wavelength of 450 nm, to remove the slow-yellow phosphor component of the light from the white-LED.

The receiver in the link was a Femto HSPR-XI-1G4-SI PIN photodiode with a bandwidth of 1.4GHz and a diameter of 0.4 mm. Similar to other links with such small receivers [9,14] a lens has been used to increase the input aperture of the receiver. In particular, an

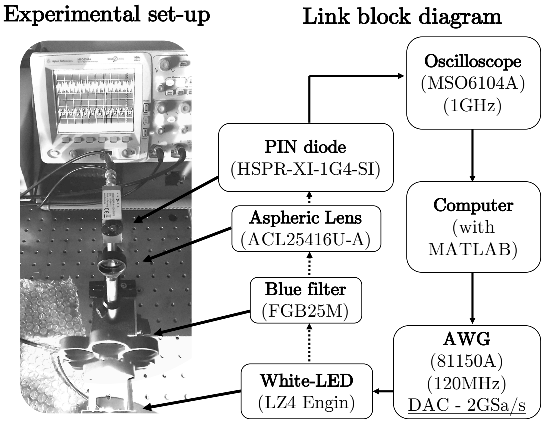

Fig.3.The experimental set-up over a link distance of 10cm.

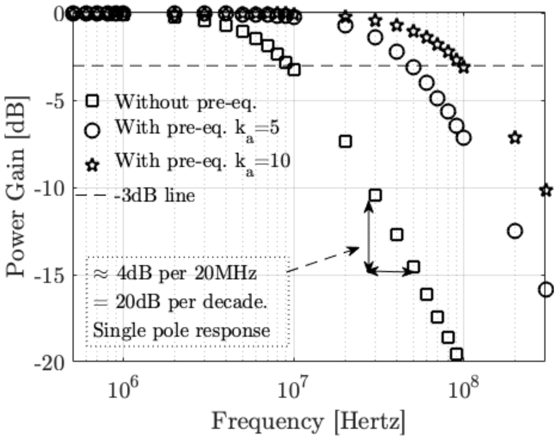

Fig.4. Measured channel response without and with pre-equalization.

ACL2520U, aspheric lens, was used to concentrate the light onto the photodiode. The output of the photodiode was digitized by a 1GHz MSO6104A oscilloscope which has a sampling rate of 4GSa/s. The captured data was then processed in MATLAB and the bit error rate was calculated.

With the blue filter in place the measured frequency response of the link, Fig. 4, has a bandwidth of 9.8 MHz. In addition, the response falls-off at approximately 20dB/decade in the stopband, which means it is a single pole response. Consequently, one ZP-equalizer would be sufficient to significantly increase the bandwidth of the link.

Experiments have been performed without an equalizer and with a ZP-equalizer with f_{3dB}=9.8 MHz. Then, to ensure that the maximum voltage generated by overshoot is less than the maximum voltage that can be applied to the white-LED, the maximum value of k_a that could be used was 10. Experiments were therefore performed for k_a values of 5 and 10. The measured pre-equalized responses for both the k_a values are shown in Fig.4. As expected, the 3dB bandwidth of the link increases by k_a to 49 MHz and 99.5 MHz respectively.

The BERs for rect-pulse and RC-pulse (amplitude normalized over the AWG's peak voltage for the un-equalized case) over various data rates are shown respectively in Fig.5 and 6. The BER values in these

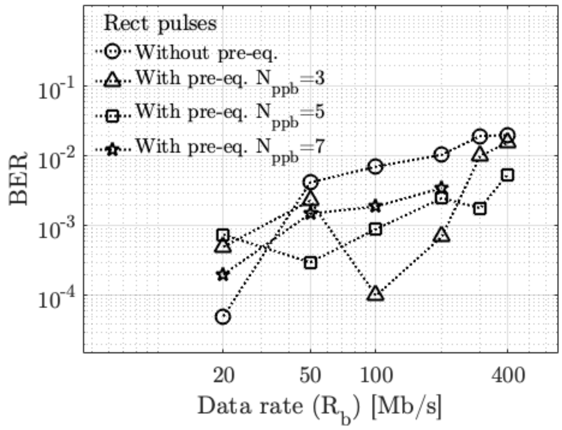

Fig.5. *(Rect-pulses):* BER vs. data rates over various N_{ppb} values at k_a=10.

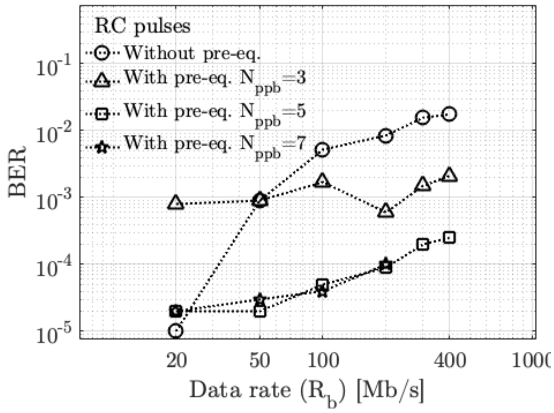

Fig.6. *(RC-pulses):* BER vs. data rates over various N_{ppb} values at k_a=10.

figures were obtained by transmitting 2^{12} randomly generated bits 20 times. The results in these figures were obtained both without equalization and with equalization using k_a=10 and 3, 5 or 7 points per bit. The lack of overshoot before equalization is applied means that the BER results obtained before equalization are the same for 3, 5 and 7 points per bit.

The first observation from Fig.5 is that before rect-pulses are equalized a BER of 10^{-3} can be achieved at data rates less than 35 Mb/s. Figure 6 shows that in contrast, when RC-pulses are used the same BER is achieved for data rates less than 50 Mb/s. This improvement of 42.8% is caused by the reduction in ISI arising from the use of RC pulses.

The results in Fig.5 show that the BER achieved when a ZP-pre-equalizer is used with rect-pulses and a small number of points per bit is unpredictable. This unpredictability is possibly caused by either inaccuracies in the representation of the signal or distortion of the large overshoots by the response of the white-LED or a combination of both of these effects. Any problems arising from using too few points per bit could be avoided by increasing the number of points per bit. However, this would reduce the maximum data rate that could be transmitted.

The results in Fig.6 show that when a ZP-pre-equalizer is used with RC-pulses the BER values are also unreliable when N_{ppb}=3. However, using N_{ppb}=5 and N_{ppb}=7 both result in relatively smooth and predictable increases in BER as the data rate increases. Moreover, the similarity of the results obtained for these two values of points per bit show that only 5 points per bit are required when RC-pulses are used with this ZP-equalizer. As shown in Fig.6, this means that a data rate of 400 Mb/s can be supported by an equalizer with a sampling rate of 2 GSa/s. Furthermore, at 400Mb/s the BER is only $2x10^{-4}$, which is well below the BER limit of $3.8x10^{-3}$ [15] needed to use FEC codes to generate an acceptable final BER. The trend in Fig.6 also suggests that by using a digital equalizer with a sampling rate of 5 GSa/s it would be possible to use this white-LED and receiver to create a link that can support 1 Gb/s with a BER that is still below this FEC limit.

IV. Conclusions

In this paper, the benefits of combining RC pulse shaping and zero-pole equalization have been highlighted and demonstrated using an OWC link that has a single pole response. The experimental results showed that using a zero-pole equalizer it is possible to increase the bandwidth of a single pole link. More importantly, the results showed that as few as 5 points per bit are required if RC-pulses are used. Consequently, for the particular link that was investigated it was possible to increase the data rate that could be supported from 35 Mb/s to 400 Mb/s whilst also significantly reducing the BER. In the future this approach to equalization can be applied to fluorescent concentrators [16]. More importantly, the versatility of digital equalization means that it can be adaptively applied over a wider range of frequency responses including those not arising from one or more poles.

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