Proposal of a Pre-equalizer with Nyquist Filtering to Mitigate LED Nonlinearity in PAM-4 VLC Systems

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***Abstract*—Visible light communication (VLC) systems are widely considered for adoption in the upcoming sixth-generation (6G) systems. This is because they provide a power-efficient, non-complex, unlicensed frequency band, safe, and secure solution for data transmission. High data rates up to gigabit per second have been achieved in research over the past years using VLC. However, in order to achieve high data rates in such systems utilizing light emitting diodes (LEDs) already in the infrastructure, it is crucial to mitigate its impairments such as limited frequency response (tens of MHz bandwidth) and nonlinearity. In this paper, a novel transmitter system is proposed to compensate for the two main limitations in LED-based VLC systems. Different pulse shaping Nyquist filtering techniques are applied to minimize inter-symbol interference (ISI) caused by the LED's small modulation bandwidth. Additionally, a pre-equalizer is presented to alleviate LED nonlinearity. Results show an overall linear transmission and a significant enhancement in symbol-error rates (SER). Moreover, out-of-band side lobes are successfully suppressed, thus requiring smaller bandwidth for signal transmission without loss of information.**

***Index Terms*—Equalization, inter-symbol interference, light-emitting diodes, limited bandwidth, nonlinearity, Nyquist pulse shaping, pulse amplitude modulation.**

I. INTRODUCTION

A significant subset of optical wireless communication (OWC) is VLC that uses visible light as its carrier and operates in the wavelength region of (390–750) nm. Thanks to light emitting diodes (LEDs), we are able to have luminaires that are capable of data transmission without affecting the surrounding environment or their functionality. Commercial high power LEDs are therefore anticipated to be utilized heavily in communications since they provide a huge and unlicensed frequency spectrum that does not affect the surroundings unlike radio frequency (RF). Therefore, it is the subject of extensive research for applications in upcoming wireless communication systems [1]. It is also used with many technologies in hybrid applications such as indoor positioning systems (IPS), machine-to-machine (M2M) communications, augmented reality, smart cities and non-RF friendly environments [2]. Also, light fidelity (LiFi) is a well-known type of VLC that is bidirectional and high speed networked communication which is already deployed and provides high quality of service (QoS) [3].

Although VLC has been intensively studied through the past years, some challenges still limit high data transmission rates due to LEDs limitations such as phosphor long photoluminescence lifetime, small modulation bandwidth, and nonlinearity [2], [4]. The phosphor conversion method for white light generation is cheaper and less complex than the RGB one. However, it suffers from ISI due to the slow response of the yellow component of phosphorus that does not take advantage of the switching speed of the blue LED [5]. That low phosphor conversion efficiency limits transmission rates. Optical filters are used at the receiver side to reject the slow yellow component and hence only the blue part is detected.

Another bottleneck in high-speed VLC systems is the low modulation bandwidth of commercial white LEDs, which is due to the physical mechanism in the LED quantum well [6]. The limited bandwidth (few MHz) dramatically decreases transmission rates despite the available vast optical bandwidth. Modeling and equalization of LED response are a key issue for utilizing the optical bandwidth [7], [8]. Most of the models describe the LED response as a first-order or Gaussian low pass filter. To make use of the offered high bandwidth, an equalizing stage is needed to achieve an almost flat frequency response over the bandwidth [7]. Another method to tackle the limited bandwidth is using spectral efficiency enhancing schemes such as using high order modulation, multiple access (MA) and multiple-input multiple-output (MIMO) techniques or a combination of them [9]. The first is widely used and deployed in systems such as orthogonal frequency division multiplexing (OFDM), quadrature amplitude modulation (QAM), carrierless amplitude and phase modulation (CAP) and pulse-amplitude modulation (PAM) [10]. In which cases, information is modulated in multilevel formats to increase symbol rate beyond bandwidth limitation. In the second approach, multiple access techniques which support multiple users simultaneously and assign them resources such as frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA) and space division multiple access (SDMA) are used [11]. In addition, applying MIMO to the aforementioned techniques further enhances system performance and adds higher spectral efficiency and throughput.

Increasing symbol rates using high-order modulation, however, introduces ISI and results in closed eye-diagrams. As a result, transmitting high data rate signals through a band-limited channel is usually accompanied by equalization and filtering stages [7], [12]. Designing the filter is key to reducing the transmitted signal bandwidth in the frequency domain so

978-1-6654-6463-5/22/$31.00

that at sampling times the response of the previous pulse is zero [13]. Nyquist-based pulse shaping technique achieves the optimum solution for zero ISI at the minimum transmission bandwidth possible in a noise-free environment. It has advantages in terms of increasing both the spectral efficiency and the symbol rate when transmitting signals through band-limited devices i.e., LEDs. The frequency response of such filters decays gradually depending on a roll off factor α ranging from 0 to 1 to suppress out-of-band emission within the limited bandwidth of the LED [14].

LEDs emit light based on the input forward current and hence intensity modulation (IM) is done where the transmitted signal is modulated into optical power produced by the LED. Practically, however, the LED current-power curve is recorded to be nonlinear [4]. In an LED, there is a nonlinear relationship between the voltage and current as well as the current and light intensity. The input signals must be greater than the LED turn-on voltage in order for the LED to operate. Thus signals lower than the turn-on voltage are clipped, likewise signals higher than the maximum allowable voltage or the saturation point are also clipped to avoid overloading [15]. A VLC system's nonlinearity can therefore be thought of as a collection of dynamic-range-limited nonlinearities. In some cases like high-order modulation, the input signal has a value beyond the quasi-linear region, consequently, electrical to optical conversion is nonlinear [16]. This makes LED nonlinearity the major source of nonlinearity in a VLC link. Since increasing the driving current, increases the heat and non-radiative recombinations become dominant [17], [18]. Indeed, it severely distorts the signals in systems with high modulation order, e.g., OFDM, CAP, and PAM, and accordingly, it limits the transmission rates.

Nonlinearity can be analyzed by the external quantum efficiency (EQE) that suffers from efficiency droop due to non-radiative recombinations in the p-n junctions, such as Shockley Read Hall (SRH) and Auger recombinations [19]. That is why nonlinearity is another major obstacle for high-capacity VLC systems, which is being tackled by several equalization techniques. First, the nonlinear power-current curve of the LED is to be estimated, then used to compensate for the LED nonlinearity. Otherwise, straightforward techniques are employed simply to avoid nonlinearity effects by using one or two levels modulation schemes such as on-off keying (OOK) and pulse position modulation (PPM) but they offer low bandwidth utilization efficiency [4]. Different LED models are categorized and studied in literature such as memoryless polynomial, Volterra series, Wiener Model, Hammerstein Model, memory polynomial and the ABC Mode [4], [17].

An effective technique for reducing ISI and LED nonlinearity has been presented in this paper. Given that the constrained LED bandwidth considerably affects the transmitted signal, which introduces ISI and loss of information, the traditional PAM signal bandwidth is first compared with the Nyquist modulated signals with different roll-off factors. Next, the contributed pre-equalizer, which decreases the effects of LED nonlinearity, is comprehensively examined against the conventional system output performance, which lacks a nonlinearity mitigation stage. The novel nonlinearity pre-distortion and pulse shaping proposed system is incorporated to minimize SER and expand the LED modulation bandwidth with reduced complexity compared with most literature, as shown from the results [4], [16]–[18].

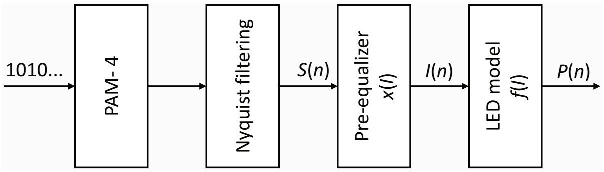

Fig. 1: Schematic diagram of proposed nonlinear pre-equalizer Nyquist PAM-4 system.

II. SYSTEM MODEL

The proposed system in this study is schematically illustrated in Fig. 1. A novel transmitter system is introduced to compensate for the two main limitations in LED-based VLC systems; low modulation bandwidth and nonlinearity. To overcome the small modulation bandwidth of LEDs, high-order modulation schemes are candidates. However, this results in a higher bit-error rate (BER) which needs to be reduced to an acceptable range. PAM is much simpler to implement than OFDM without IFFT, FFT, or complex-to-real conversion. It also has better resistance to the nonlinear behavior due to the absence of peak-to-average power ratio (PAPR). In addition, in comparison to CAP, no I/Q separation is required [12]. However, the spectral efficiency of rectangular PAM signals is relatively lower, as the frequency response of a rectangular pulse signal is a sinc function needing unlimited bandwidth and causing ISI due to the low-pass filtering effect of the LED [14]. The proposed system takes the PAM modulated signal then subjects it to different pulse shaping Nyquist filters to reduce ISI within a small bandwidth. The result is the convolution in time between the PAM mapped signal and the Nyquist filter. The resulting bandwidth in the frequency domain is limited unlike traditional PAM signal bandwidth. Then the pulse shaped signal is passed through the pre-equalizer $x(n)$ that takes the discrete input signal $S(n)$ and generates a discrete output current $I(n)$ which is the LED input current.

A. Pulse Shaping

When the energy of one symbol collides with the energy of a consecutive symbol, the receiver will not be able to reconstruct the transmitted signal successfully causing distortion and interference in the result that is called inter-symbol interference (ISI) [20]. It happens due to multi-path propagation and non-ideal channels. One other main cause of inter-symbol interference is transmitting an infinite signal through a band-limited channel. Such channels ideally have a zero frequency response for signals with frequencies exceeding the cutoff frequency. When a PAM signal is transmitted

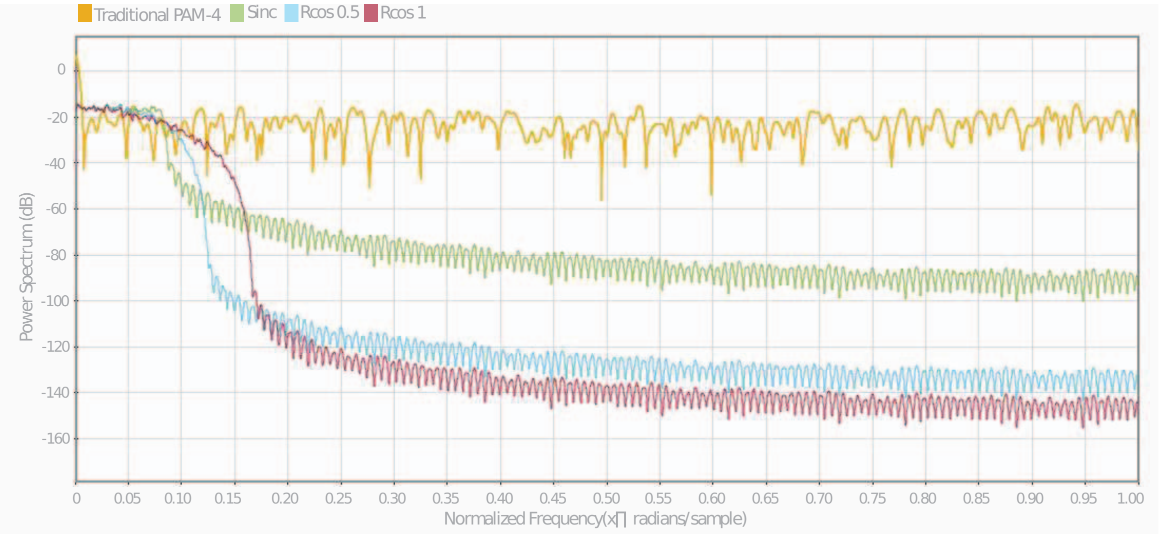

Fig. 2: Normalized frequency responses of a PAM-4 system without filtering and with either a Sinc filter ($\alpha = 0$) or a raised cosine filter with $\alpha \in (0.5, 1)$.

through a band-limited channel i.e., LED, signal frequency components above this cutoff frequency are removed, thus losing part of the signal and causing ISI [12]. Pulse shaping yields better spectral efficiency and less side lobes gain than traditional rectangular PAM based on α, the roll-off factor, where there is a trade-off between smaller side lobes and slightly larger spectral width [21] as shown in Fig. 2. As each pulse now has less oscillations at the symbol interval, there is no inter-symbol interference between adjacent symbols at sampling time. Smaller α generates a smaller bandwidth signal, however, higher side lobes. The effect of changing α is studied on signal bandwidth and symbol-error rate.

B. *Proposed Nonlinear Pre-equalizer*

Since the optical front-end typically uses simple intensity modulation and direct detection (IM/DD) methods, the nonlinearities affect system performance significantly. Some equalization techniques get the inverse of the LED transfer function and cascade it to the system to have a linear overall performance. Pre-distortion techniques are simpler and done at the transmitter side and can be classified into static or dynamic models based on the model assumptions and availability of calculated parameters. On the other hand, post-distortion techniques are done at the receiver side but are more complex as the channel effect on the distorted transmitted signal by LED nonlinearity needs to be known [4]. Also in OFDM, some PAPR reduction techniques can be used to reduce the nonlinearity effect on high-level signals [21]. If the parameters to be estimated in the model and their inverse are not generic and not depending on either time or temperature, static models are easy to be acquired. When LED dynamics are taken into consideration, adaptive techniques can be used. However, these techniques are complex because the goal is to minimize the difference between the LED output and the desired one. So it is difficult to obtain feedback from the light intensity and the driving current given nonlinearity in both LEDs and photodetectors (PD) [22].

Some models whose LED parameters defined from the rate equation such as carrier recombination rates and doping level are difficult to be estimated. Despite the fact that the Volterra series and its reduced versions such as Wiener and Hammerstein models successfully address the nonlinearity problem taking into consideration the memory effect, they fail to be feasibly employed in a simulation system. Since based on the memory size the number of coefficients to be determined increases aggressively, and hence more computational resources are needed [23]. In this paper, the LED model in [24] is adopted where the nonlinear relationship between the output light power and the driving forward current is represented by a second-order polynomial. It was obtained from a model-driven deep learning (DL) scheme. The LED model demonstrates a well structured mathematical approach and further does not disregard the memory effect of the LED model unlike the model in [25]. In [24], the LED transfer function and its coefficients (b_0, b_1, b_2) are built upon measurements of a commercial LED that exhibits nonlinear behavior with memory effects. Consequently, a pre-equalizer $x(n)$ is introduced to inverse the effect of the LED transfer function as follows. The pre-equalizer $x(n)$ takes the discrete Nyquist filter output signal $S(n)$ and generates a discrete output current $I(n)$ which is the LED input current as:

$$I(n) = \sqrt{\frac{b_1^2}{4b_2^2} - \frac{b_0 - S(n)}{b_2}} - \frac{b_1}{2b_2}, \qquad (1)$$

where $b_0 = -0.0628$, $b_1 = 1.9472$, and $b_2 = -0.8940$ are the DC term, linear gain, and second-order nonlinear coefficient respectively.

Fig. 3 shows the normalized outputs as functions of LED current: the nonlinear LED model $f(I)$ (dashed black) without using equalization, the pre-equalizer alone which is the inverse of LED model $x(I)$ (dashed red) and the resultant output power $P(I)$ (solid blue) if using a pre-equalizer in the LED transmitter. It turns out that the resultant discrete output signal $P(n)$ is a linear function of the input signal $S(n)$. The entire system of the pre-equalizer along with the LED model outperforms conventional nonlinear LED that distorts some values in the transmitting signal affecting system performance and SER.

III. Results and Discussion

In this section, we simulate the PAM-4 system in Fig. 1 with and without the proposed pre-equalizer in the presence of additive white Gaussian noise (AWGN) channel for different Nyquist filtering. The bit rate used in our simulation is 40 Mbps. Fig. 4 shows the SER versus SNR [in dB] for signals (a)-(f) of different Nyquist filtering at $\alpha = 0$ (Sinc), $\alpha = 0.5$ (Rcos 0.5), and $\alpha = 1$ (Rcos1) without (w/o) and with (w) the pre-equalizer. The performance of the conventional LED is evaluated against the contributed pre-equalizer in terms of SER. Nonlinearity mitigation has a remarkable influence on SER for different Nyquist modulated signals. The SER deteriorates rapidly for signals (a)-(c) without using the pre-equalizer. At 16 dB SNR, for $\alpha = 1$ (Rcos1), the SER with the pre-distorter is 1.4×10^{-4} which is about 480 times less than that without using the pre-equalizer. For $\alpha = 0$ (Sinc), the SER is 18.6×10^{-4}, inferring that as α increases better SER is achieved. It is clear from Fig. 4 that SER is degraded severely due to LED nonlinearity. However, our proposed pre-equalizer significantly improves it. Also, increasing α gives better SER but on the other hand smaller bandwidth utilization as illustrated in Fig. 2.

In conclusion, the proposed system is novel and advantageous to both overcoming LED bandwidth limitations and the nonlinearity mitigation problem from the aforementioned simulations and discussions.

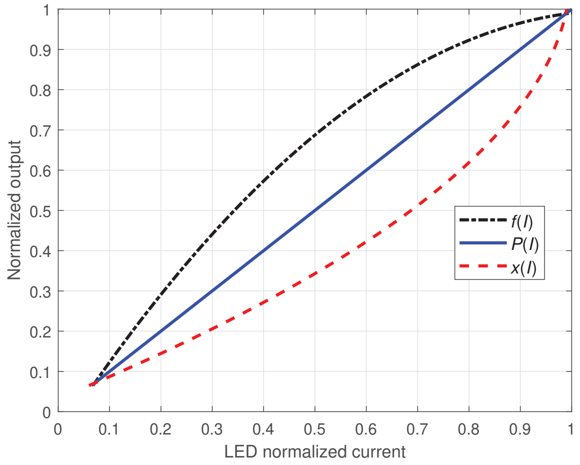

Fig. 3: Normalized outputs of LED model $f(I)$, pre-equalizer $x(I)$, and resultant output power $P(I)$ as functions of LED current.

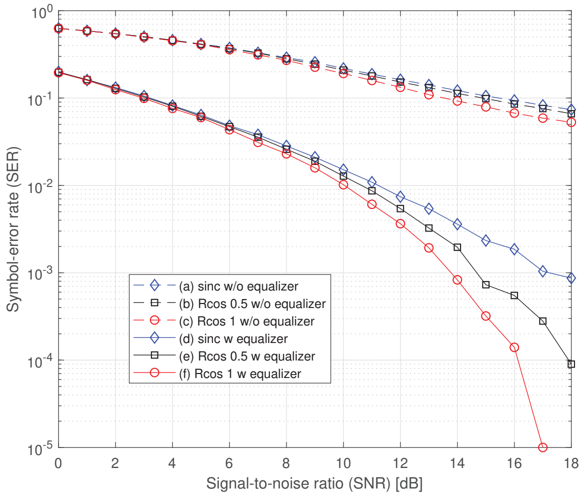

Fig. 4: SER for PAM-4 systems with and without pre-equalizer versus SNR [in dB] for different Nyquist filtering.

IV. Conclusion

Very high-speed VLC systems are accompanied with equalization techniques, this is due to they are more subject to LED impairments such as limited bandwidth and nonlinearity. Choosing the most suitable modulation technique and LED model is key to alleviating impairments. A pre-distortion technique is used in this work because it is regarded as one of the best and easiest ways to reduce the effects of distortion in LED transmission. Hence, the received signal levels are redistributed properly. The proposed model consists of a novel pre-equalizer to compensate for distortion in high-order modulation using PAM-4 along with different Nyquist pulse-shaping filters to study the effects on bandwidth performance. An improvement in SER of up to 480 times was achieved with the proposed pre-equalization using (Rcos1) filtering at 16 dB SNR than the conventional transmission. Moreover, we are able to suppress out-of-band side lobes thus requiring smaller bandwidth for signal transmission without loss of information.

Future work would analyze the equalizer performance on eye-diagrams and higher modulations schemes and also improving system parameters in Eq. 1 for advanced SER performance.

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