

Nonlinear degradation of a visible-light communication link: A Volterra-series approach

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ABSTRACT

Visible light communications can be used to provide illumination and data communication at the same time. In this paper, a reverse-engineering approach is presented for assessing the impact of nonlinear signal distortion in visible light communication links. The approach is based on the Volterra series expansion and has the advantage of accurately accounting for memory effects in contrast to the static nonlinear models that are popular in the literature. Volterra kernels describe the end-to-end system response and can be inferred from measurements. Consequently, this approach does not rely on any particular physical models and assumptions regarding the individual link components. We provide the necessary framework for estimating the nonlinear distortion on the symbol estimates of a discrete multitone modulated link. Various design aspects such as waveform clipping and predistortion are also incorporated in the analysis. Using this framework, the nonlinear signal-to-interference is calculated for the system at hand. It is shown that at high signal amplitudes, the nonlinear signal-to-interference can be less than 25 dB.

1. Introduction

Light Emitting Diodes (LEDs) constitute a viable choice for energy efficient lighting applications. The potential synergy of illumination and data communication with LEDs is attracting worldwide attention reflected in recent research efforts and standardization activities [1,2]. Visible light communications (VLC) offers many advantages, including excellent coverage, worldwide available and unlicensed bandwidth, and zero interference with existing radio systems [2]. Combining a phosphorescent white LED and a low-cost pin photodiode receiver with a blue filter, Vucic et al. have successfully demonstrated 230 Mb/s gross data rate transmission [3]. Using a low noise avalanche photodiode (APD) at the receiver, this rate can be extended to 513 Mb/s [4]. Wavelength division multiplexing (WDM) can also increase the capacity of a VLC link reaching nearly gigabit-per-second data rates [5]. Recently the possibility of multi-Gigabit/s has been demonstrated on RGB LEDs [6]. Multiple subcarrier modulation schemes including discrete multitone (DMT) modulation [7], have been applied as an efficient means to compensate the small signal frequency response of the LED transmitter.

Fig. 1 shows a typical configuration of a VLC link including the digital and the analog parts of the system. The transmitter encompasses various components, including the data source, the DMT modulator and a digital-to-analog converter (DAC). A transconductance amplifier (TCA) is used to amplify the AC voltage waveform and produce the

AC part of the LED driving current. A DC current is added using an appropriate three port network. At the receiver, the modulated light passes through a blue filter which removes the (slowly modulated) phosphorescent components of the light. It is then concentrated at the receiving photodiode (PD) by an optical lens. The received signal is amplified by a transimpedance amplifier (TIA), passes through a bandpass (BP) filter and is sent to the digital part of the receiver. This part consists of an analog-to-digital (ADC) converter and a DMT demodulator, which estimates the received symbols. Nonlinearity can be a major source of signal degradation in optical communication systems in both single carrier [8] and multiple carrier modulation [9] formats. In the case of DMT modulation, nonlinearity can cause interference between the subcarrier channels and hence signal distortion [10]. Fig. 1, illustrates the link components that can act as a potential source of nonlinearity. At the transmitter, nonlinearity is mainly due to the LED and the TCA, while at the receiver the PD and the TIA constitute the primary potential sources of nonlinearity. Coming up with a suitable model to describe the end to-end nonlinearity is not an easy task, altogether. The static approach is based on the DC input/output characteristic [9–11]. For the VLC system at hand, this corresponds to measuring $v_O - v_I$ DC-characteristic where $v_I(t)$ is the voltage at the input of the TCA and $v_O(t)$ is the voltage of the output of the BP filter. Applying a polynomial fitting on the $v_O - v_I$ characteristic, one can calculate the nonlinear-induced distortion on the DMT symbol estimates and evaluate the performance

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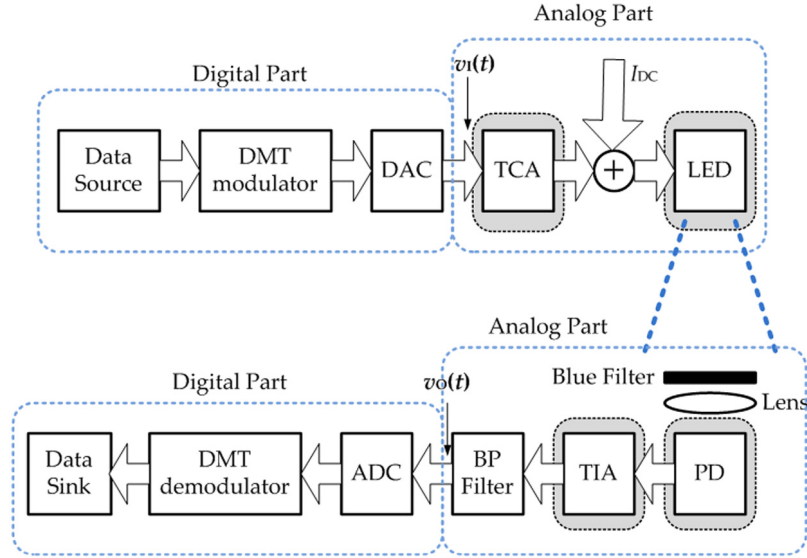


Fig. 1. Schematic representation of a VLC link showing both the digital and the analog parts. Potential sources of nonlinearity are marked with a gray color.

of the system [11]. Unfortunately this approach neglects memory effects that manifest as frequency-dependent linear and nonlinear response. The identification of suitable models to incorporate these effects is far from trivial, even at a component level. For example, LED nonlinearity is a direct consequence of carrier recombination dynamics [12] and simple rate equation models have been proposed to describe the LED transient large signal response [13]. However, in our work [14], we have shown that both the static approach and the rate equations model do not accurately describe the high frequency response of commercial visible and infrared LEDs. Instead, we proposed an empirical approach that is based on measurements of frequency domain Volterra kernels [15]. We experimentally verified that a second order Volterra series expansion can adequately describe the LED light current dynamics. In principle, this approach can be applied to any type of optical component and can even be used to describe the entire end-to-end VLC system. In this paper, we extend the approach of [14] to describe the end-to-end nonlinearity including all the sources of nonlinear degradation shown in Fig. 1. The VLC system in question is the demonstrator of the ICT-OMEGA project [16]. Our work in [14] is extended to include third order Volterra kernels in the expansion. In particular, we discuss how the second and third order Kernel can be measured using a suitable two and three-dimensional grid of frequencies respectively that minimize the nonlinearity order interference in the measurements. We discuss how the measured kernels can be applied to calculate the signal to interference ratio (SIR) in the case of a DMT system. Our empirical approach has the merit of being realistic and independent of any particular physical assumptions for the behavior of the link components. It can also be used as a basis for non-linearity mitigation [17]. The model is used to highlight the influence of various design aspects such as the clipping level and predistortion techniques. It is shown that for a clipped DMT signal, nonlinearity can set an SIR limit of the order of 25 dB even at a small quadrature amplitude modulation (QAM) level.

2. System model

2.1. Volterra series formulation

The Volterra series expansion relating the voltages v_O and v_I can be formally written as [15]:

$$v_O(t) = v_O^{(0)} + \sum_{n=1}^{\infty} v_O^{(n)}(t) + n(t) \quad (1)$$

where $n(t)$ is an additive noise component and the n th order contributions for $n > 0$ are given by:

$$v_O^n(t) = \frac{1}{n!} \int_{-\infty}^{+\infty} d\tau_1 \cdots \int_{-\infty}^{+\infty} d\tau_n h_n(\tau_1, \dots, \tau_n) v_I(t - \tau_1) \cdots v_I(t - \tau_n) \quad (2)$$

and $v_O^{(0)}$ is a constant. In (2), h_n are the n th order Volterra kernels of the system in the time domain. The first order term $v_O^{(1)}$ is the small signal (linear) response of the system. Eqs. (1)–(2) apply under very general assumptions and can be used to incorporate both memory and nonlinear effects in the VLC system model. The frequency domain kernels H_n are related to h_n through the Fourier transform [18],

$$H_n = (f_1 \cdots f_n) = \int_{-\infty}^{+\infty} d\tau_1 \cdots \int_{-\infty}^{+\infty} d\tau_n h_n(\tau_1, \dots, \tau_n) \times \exp\left(-j2\pi \sum_{k=1}^n f_k \tau_k\right). \quad (3)$$

2.2. Symbol estimates

Assuming that the input signal v_I is a DMT waveform, one obtains [11]:

$$v_I(t) = u_0 \sum_{m=1}^M w_m s_m e^{j2\pi f_m t} + u_0 \sum_{m=-1}^{-M} w_m s_m^* e^{j2\pi f_m t} \quad (4)$$

where M is the number of subcarriers, s_m is the quadrature amplitude modulation (QAM) symbol at subcarrier m , $f_m = m/T$ are the subcarrier frequencies, T is the DMT symbol duration and the asterisk (*) denotes complex conjugation. The second sum ensures that the DMT waveform is real. In (4), u_0 is the amplitude of the AC voltage waveform. For the system under investigation, the symbols s_m are chosen from a QAM constellation $C_Q = \{s | s = d(2p - Q^{1/2} - 1) + jd(2q - Q^{1/2} - 1)\}$ where the integers p and q lie inside $1 \leq p, q \leq Q^{1/2}$, d is the minimum symbol distance and the QAM level Q is assumed to be an even power of 2 [9,11]. The coefficients w_m are predistortion coefficients which may be used to ensure that all subcarrier channels have the same linear signal-to-noise ratio (SNR). For the undistorted signal one sets $w_m = 1$. Predistortion is discussed in Section 2.3. It is interesting to note that $|v_I(t)| \leq V_0$, where $V_0 = 2^{3/2} d(Q^{1/2} - 1) u_0 \sum_m w_m$. Given the maximum amplitude V_0 , the latter equation can be used to determine u_0 . The symbol estimates \hat{s}_r at the receiver are given by,

$$\hat{s}_r = \frac{1}{T u_0 H_1(f_r) w_r} \int_0^T dt v_O(t) e^{j2\pi f_r t} \quad (5)$$

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