Design of an Automotive Visible Light Communications Link using an Off-The-Shelf LED Headlight

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Abstract

We present a transmitter circuit to drive a commercial Light Emitting Diode (LED)-based headlight for automotive Visible Light Communication (VLC). Based on the design of the presented transmitter (TX), we provide a design methodology for VLC TXs and make it available as Open Hardware. Furthermore, a complete wireless VLC link is built using the GNU Radio signal processing tool chain and demonstrated on an Universal Software Radio Peripheral (USRP). The Total Harmonic Distortion (THD) of the system is below 5% for a wide input voltage range and the 1 dB compression point (P1dB) is at 1.02V, which makes the circuit attractive for more advanced modulation formates like Orthogonal Frequency Division Multiplexing (OFDM) or Pulse-Amplitude Modulation (PAM).

1 Introduction

White Light Emitting Diodes (LEDs) are becoming more and more the primary source of illumination in different indoor and outdoor environments. Besides their illumination function, their ability for fast switching enables a new kind of application, namely Visible Light Communication (VLC). VLC uses the multi-THz wide, license-free visible light bands of the electromagnetic spectrum [1]. In comparison to Radio Frequency (RF)-based communication technologies, VLC has highly directional light beam, which makes for a small collision domain and allows high spatial reuse of the modulation bandwidth. This advantages make the system interesting for a lot of applications. In [2] a VLC link was used for a wearable patient monitoring device, and in [3] a Multiple-Input and Multiple-Output (MIMO) system for indoor applications is presented.

Recently, first studies have demonstrated the feasibility of VLC for vehicular networking applications [4, 5, 6]. Due to the strict requirements of such applications, careful design decisions are required for the implementation of efficient front-ends, and the choice of robust modulation and coding schemes.

In this paper, we present a highly linear transceiver system for a vehicular VLC link consisting of a commercial white LED headlight. Additionally, we describe in detail the design methodology for our linear VLC transmitter (TX) circuit and make it available as Open Hardware (Section 6).

Our main contributions can be summarized as follows:

- We present the hardware setup for advanced modulation schemes and a design methodology for VLC TX (Section 2).
- We performed initial experiments in a lab environment to explore the performance of our system (Section 3).

2 Hardware and Circuit Design

The hardware setup can be divided into two subsystems: the transmitter, which drives a commercial LED headlight from Volkswagen, and the receiver, namely a photodiode with a Transimpedance Amplifier (TIA). Each of the subsystems is operated by a Universal Software Radio Peripheral (USRP) (model N210 from Ettus Research). The two USRPs, are programmed using the GNU Radio open source signal processing framework. An overview of the transmission system is given in Figure 1.

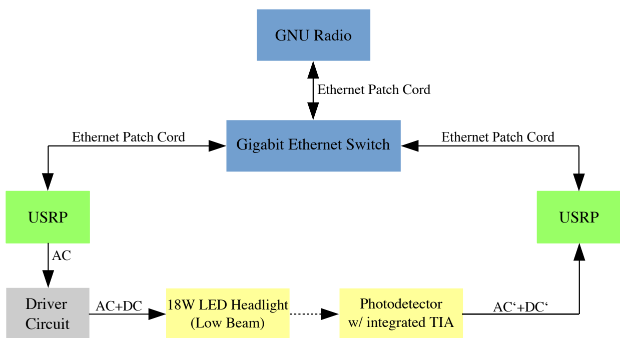
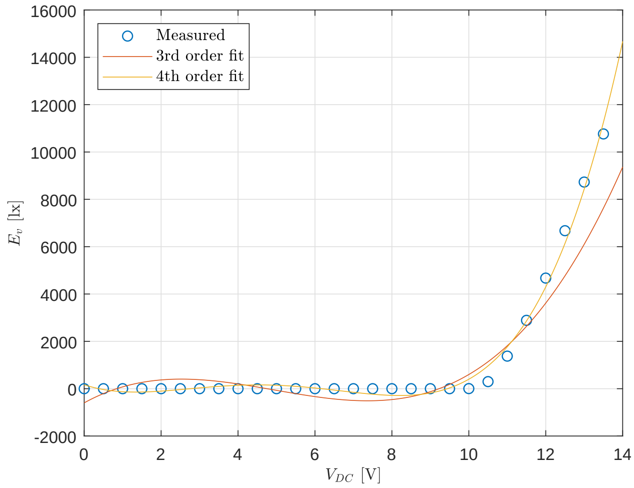
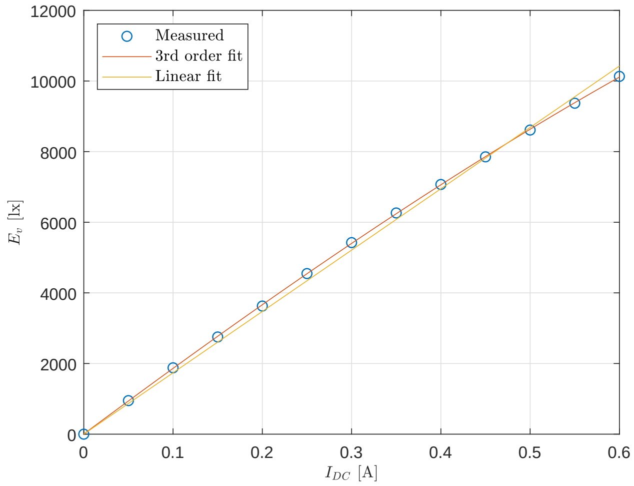


Figure 1 Block diagram of the VLC transmission system which consist of the digital part (in blue), A/D-D/A conversion part (in green), the presented TX circuit (in grey), and the optical components (in yellow).



(a) Illuminance vs. DC voltage. A 4th order fit is neccesary to cover the measured points.



(b) Illuminance vs. DC currrent. Linear fit is sufficient to cover the measured points.

Figure 2 Measured and fitted illuminance characteristic. Figure 2(a) shows the illuminance vs. voltage characteristics. The behavior is not linear. Figure 2(b) outlines the illuminance vs. current characteristics. The behavior is approximately linear

2.1 Transmitter

For the transmitter and the receiver each of the N210 USRPs are equipped with a LFTX daughter boards enabling a transmission bandwidth of up to 30 MHz. These daughter boards support the most promising frequency range for VLC based on Intensity Modulation and Direct Detection (IM/DD) [7].
Figure 2 shows the relationship between optical power E_v and voltage V and current I, respectively. The linear relationship between optical power and current, is caused by the physical process of stimulated emission of photons in the LED, and allows a linear transmitter.
Figure 3 shows a simplified schematic of the driver. Since the USRP can only generate voltage signals while the LEDs needs to be driven linearly by a current mode driver, an LT1206, a current feedback amplifier, is connected in a Transconductance Amplifier (TCA) configuration. The re-

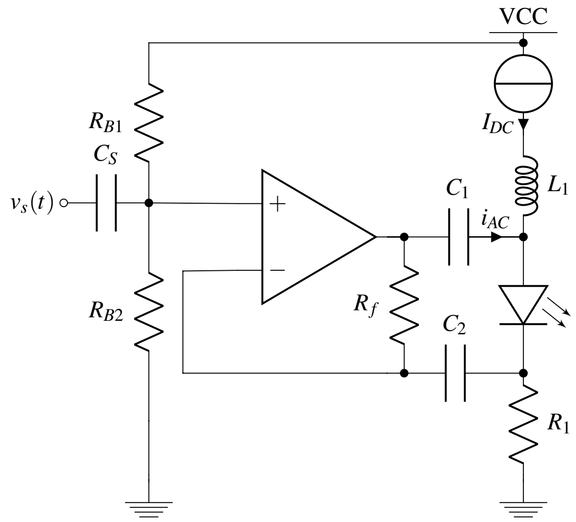


Figure 3 Simplified schematic of the transmitter circuit

sistors R_f, R_{B1}, and R_{B2} are necessary to provide the inputs with a DC bias voltage.
Correct biasing of the LED is also crucial for proper functionality. If the operating point of the LED is chosen too low, negative parts of the transmitted signal get clipped, which introduces additional distortion due to non-linearity. If the operating point of the LED is chosen too high, the LED is operating in the non-linear region or even gets harmed. The DC bias current source is implemented by using of an LT3080, an adjustable 1.1 A single resistor low dropout regulator, from Linear Technology, connected in the current source configuration.
DC and AC currents are summed up by means of an internal bias tee (C_1, L_1). The capacitors C_S and C_2 decouple the DC bias of the operational amplifier from the DC potential of the input and of the resistor R_1.
To design a VLC transmitter for commercially available light sources, the following design procedure was applied:

- Unsoldering of all unnecessary components from the light source
- Measurement of the optical power vs. current characteristic, and setting the bias point to the center of the linear region
- Measurement of the S-parameters of the LED at the optimal bias point
- Importing the S-parameters to a circuit design program, or generation of an equivalent circuit and importing this circuit into the design program
- Selection of a high current and high bandwidth amplifier and proper setting of input bias points
- Use of the optical power vs. current characteristic to determine the linear region of the light source and tune R_1 to stay in this region

Linearity of the system is crucial in order to support advanced modulation schemes, like multi-level Pulse-Amplitude Modulation (PAM) or Orthogonal Frequency

Division Multiplexing (OFDM). The linearity of the system can be characterized by means of total harmonic distortion (THD) as

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} A_n^2}}{A_1} , \tag{1}$$

with A_n being the amplitude of the n^{th} order harmonic considering a sinusoidal input signal with the fundamental amplitude A_1. It was shown that sufficient linearity is achieved when the third order harmonic, being the dominant harmonic in differential amplifiers, is -15dB lower than the fundamental frequency without using a pre-distorter [8]. Hence, a Total Harmonic Distortion (THD) of around 3–5 % can be assumed as a design goal.

Under the assumption that the driver Integrated Circuit (IC) has acceptable linearity, suppressing distortions and intermodulation, and C_1, C_2 and L_1 of the bias tee are chosen sufficiently high, the transmitted optical power P_{TX} can be given as

$$P_{TX}(t) \propto I_{DC} + \frac{v_s(t)}{R_1} , \tag{2}$$

with $v_s(t)$ the driver input voltage.

In order to achieve high data rates, the transmitter needs to drive the LED with high bandwidth. The major issue is the trade-off between high light intensity and effective capacitance of the LED. Since we have used a standard type LED headlight, the goal of the manufacturer was clearly to deliver certain illumination according to safety regulations. Since communication was not the intended goal when designing the headlight, the interconnect capacitance of the LED was not optimized. Also, additional capacitors and resistors are placed on the LED board, which are unsoldered to increase the bandwidth.

2.2 Receiver

As mentioned previously, also the receiver USRP was equipped with the LFRX daughterboard for low frequency transmission. A Thorlabs photodiode PDA100A-EC with built-in variable gain amplifier was used as receiver and directly connected to the USRP. The photodiode's amplifier was integrated without any high-pass filters, meaning that low frequency light needs to be digitally filtered in software, because 87.8 % of the ambient daylight power is below 1 kHz [5]. In the analog domain this includes unwanted ambient light.

For the received optical power P_{RX}, considering the optical channel response $H(f)$, P_{RX} can be given as

$$P_{RX}(f) = H(f) \cdot P_{TX}(f) . \tag{3}$$

In [9], it is mentioned that the optical path loss is nearly independent of the signal frequency in direct-line-of-sight links, and therefore $H(f) \approx c$ with the constant $c \in \mathbb{C}$. Using the transmit power from the previous section, we get

$$P_{RX}(f) \propto c \cdot \left[I_{DC}(f) + \frac{V_s(f)}{R_1} \right] . \tag{4}$$

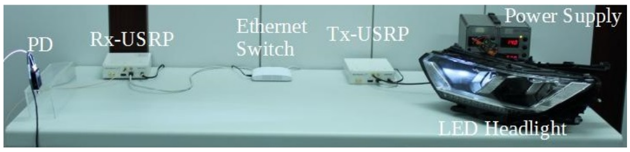


Figure 4 Image of the measurement setup.

The photocurrent can be written as product of the received optical power and the photodiode's responsivity [10] as

$$I_{PD}(t) = R \cdot P_{RX}(t) \propto R \cdot c \cdot \left[I_{DC}(f) + \frac{v_s(t)}{R_1} \right] . \tag{5}$$

If the following TIA is also linear, the receiver is well suited for all modulation schemes including OFDM, PAM and Direct Sequence Spread Spectrum (DSSS).

3 Measurement Results

All measurements were performed indoor and in the dark to minimize the effect of ambient light sources, and disturbances related to the outdoor channel: sun, rain, fog, etc. The distance between the LED and the photodiode is fixed to approximately 1.25 m. No optical gain or filters are used for the measurements. An image showing the measurement setup is given in Figure 4.

With a simple voltage source and a resistor model of the LED, in simulation the driver shows a 3 dB bandwidth of 20 MHz. This could be confirmed with measurements as well. However, after incorporating the LED headlight to this circuit, the 3 dB bandwidth reduces to 1.3 MHz. The same results could be replicated in simulation, if the equivalent circuit consist of a capacitor and a resistor. The measurement results for the THD at 130 kHz are depicted in Figure 5. If the input voltage is below 450 mV, the THD reaches the design goal of 5 %. By increasing the resistor R_1, the linear region can be extended to any desired input voltage.

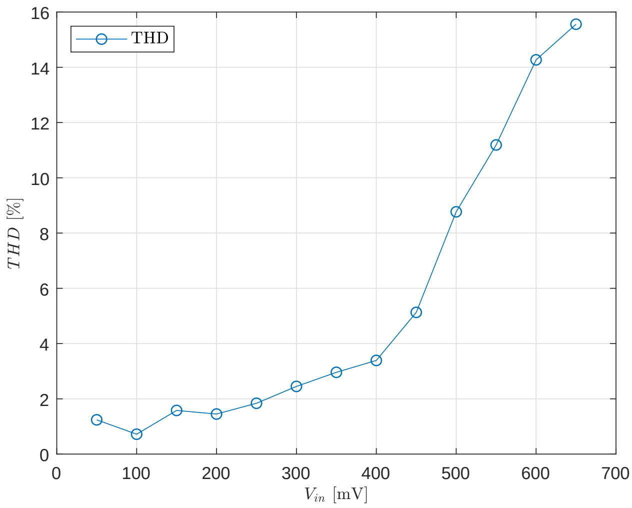


Figure 5 THD measurement results of the complete system (TX and receiver (RX)). If the input peak to peak voltage is below 450 mV, the THD is below 5 %

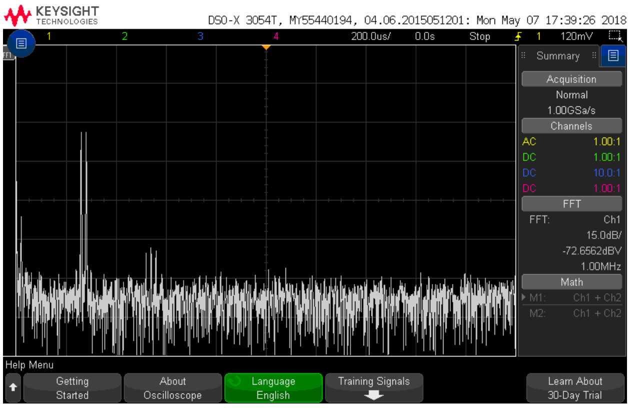
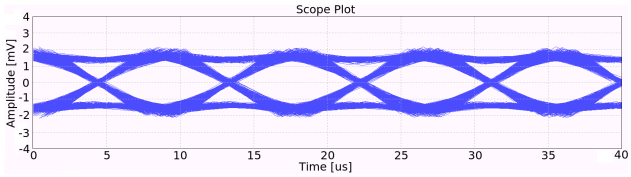


Figure 6 Measurement results of the two tone test at $f_1 = 130\,\text{kHz}$ and $f_2 = 140\,\text{kHz}$ and an input amplitude of 50 mV. The third order harmonic is 62.97 dB lower than the two fundamentals.

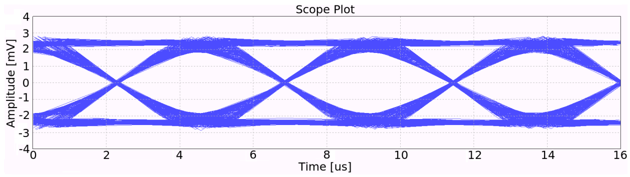
Another important factor in terms of linearity is the 1 dB compression point (P1dB). Using basic manipulation, the P1dB compression point can be calculated by two tone tests. The measurement result with $f_1 = 130\,\text{kHz}$ and $f_2 = 140\,\text{kHz}$ and an input amplitude of 50 mV is shown in Figure 6. The third order harmonic is 62.67 dB lower then the two fundamentals. Using two tone measurements a P1dB value of 1.02 V can be calculated. To give an impression about the quality of the VLC link eye diagram measurements of On-Off Keying (OOK) transmissions with different switching frequencies were carried out. Figure 7 shows the results of the eye diagram measurement at 128 kbit/s, 256 kbit/s, and 512 kbit/s, respectively. In Figures 7(a), 7(b), and 7(c) the eye is completely open. A Costas Loop is used to recover the phase and to compensate the inaccuracies in the USRPs. Beyond 512 kbit/s, the USRPs could not be synchronised any longer.

4 Conclusion

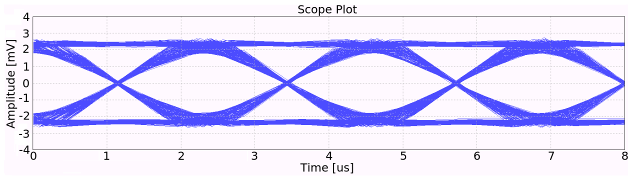
We proposed a linear TX circuit for automotive VLC in this paper, using standard ICs and a commercial off-the-shelf LED headlight. A comparatively low bandwidth of 1.3 MHz was achieved, due to the high capacitance of the standard automotive LED headlight. Since only the resistor for the DC bias current of the LED, and the resistor for the AC current through the LED have to be changed, the TX driver should be usable for most VLC systems. In this configuration, the input voltage can be varied from 0mV to 450 mV with a THD below 5%. Measurements show that the third order harmonic is 62.97 dB lower than the fundamental at an input voltage of 50 mV. The P1dB compression point is at an input voltage of 1.02 V. Eye diagram measurements in GNU-Radio show good eye opening for 128 kbit/s, 256 kbit/s and 512 kbit/s. Finally, to the best of our knowledge, for the first time a design methodology for designing a VLC TX is presented.
In 1 our design is compared with state of the art transmitter. The current generated by our transmitter has high linearity compared to state of the art transmitter circuits, whereas



(a) Eye diagram at 128 kbit/s. The eye is open



(b) Eye diagram at 256 kbit/s. The eye is open



(c) Eye diagram at 512 kbit/s. The eye is open

Figure 7 Eye diagram measurement results for different data rates and different USRPs synchronisation method.

the DC offset is generated internally. This reduces the cost of the system, because no additional bias tee is needed.
Future work will focus on more advanced modulation schemes like OFDM and DSSS for larger distances and in outdoor setup. Also techniques for bandwidth enhancement will be used in future work.

Ref.	P_{Tx} (W)	BW (MHz)	E_v contr. via	Lin. tech.
[11]		5	V	Ext. DC offset
[12]	8	0.25	V	Ext. DC offset
[13]	0.05		V	Ext. DC offset & predistortion
[14]	3	0.3	V	Ext. DC offset
This work	18	1.3	I	Int. DC offset

Table 1 Transmitter summary and comparison to literature. P_{Tx}: Transmit power; BW: Bandwidth; E_v contr. via: Illuminance control via voltage (V) or current (I);Lin. tech: Linearisation technique.

5 Acknowledgement

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6 Open Hardware

The schematic and layout of the presented TX can be downloaded from Heinz Nixdorf Institut web page `https://www.hni.uni-paderborn.de/sct/projekte/vlc-projekt/`.

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