An IEEE 802.11 Compliant SDR-based System for Vehicular Visible Light Communications

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***Abstract*—We present a complete Visible Light Communication (VLC) system for experimental Vehicular VLC (V-VLC) research activities. Visible light is becoming an important technology complementing existing Radio Frequency (RF) technologies such as Cellular V2X (C-V2X) and Dedicated Short Range Communication (DSRC). In this scope, first works helped introducing new simulation models to explore V-VLC capabilities, technologies, and algorithms. Yet, experimental prototypes are still in an early phase. We aim bridging this gap with our system, which integrates a custom-made driver hardware, commercial vehicle light modules, and an Open Source signal processing implementation in GNU Radio, which explicitly offers rapid prototyping. Our system supports OFDM with a variety of Modulation and Coding Schemes (MCS) and is compliant to IEEE 802.11; this is in line with the upcoming IEEE 802.11 LC standard as well. In an extensive series of experiments, we assessed the communication performance by looking at realistic inter vehicle distances. Our results clearly show that our system supports even higher order MCS with very low error rates over long distances.**

I. Introduction

The surge of white Light Emitting Diodes (LEDs) as the primary source of illumination for different setups has paved the way for a range of new applications. The superior lighting and environmental properties of the LEDs compared to traditional lighting sources, such as incandescent and fluorescent bulbs, has resulted in a wide adaptation of LED-based luminaries for indoor and outdoor illumination [1]. Although illumination remains the predominant application domain for LEDs, their fast switching behavior enables a new networking technology: Visible Light Communication (VLC) [2].

As VLC utilizes the visible light portion of the electromagnetic spectrum, it differs significantly from RF-based communication technologies. For instance, the high directionality of light beams results in a small collision domain, and allows high spatial reuse of the modulation bandwidth for devices in close proximity. Moreover, VLC requires a Line Of Sight (LOS) link, hence improved security, as the interception of the relatively short LOS link by adversaries cannot go unnoticed. Such intrinsic characteristics of VLC make it a viable communication technology for different application scenarios, including Vehicular VLC (V-VLC) [3]. Meanwhile, V-VLC has gained substantial attention from both industry and the research community.

Nowadays, large-scale deployment of commercial VLC front-ends is possible in homes and industry buildings.[1] In parallel, multiple working units within the scope of IEEE 802 standards family[2] work towards the standardization of optical wireless communication based on the visible light medium [4].

Stimulated by the rapid adoption of LED-based lighting modules in the automotive industry, VLC can be considered as an access technology for Intelligent Transportation Systems (ITS). However, establishing a reliable V-VLC link in an outdoor environment, where most of the Vehicle-to-Anything (V2X) communication takes place, remains a major challenge. Many studies have demonstrated the feasibility of VLC for vehicular networking applications [5]–[7]. Nevertheless, application requirements, especially those dealing with safety, require careful design decisions regarding the Physical Layer (PHY) aspects of the system, e.g., linear front-end design [8], efficient and robust Modulation and Coding Schemes (MCS) [9], [10], and the choice of adequate lighting modules.

In this paper, we present a complete V-VLC transceiver system consisting of Commercial Off-The-Shelf (COTS) components, i.e., LED-based headlights and Photo-Detectors (PDs), a highly linear custom-built front-end board that converts the voltage signal to current signal to drive the lighting module, and Software Defined Radios (SDR)-based implementation using the GNU Radio[3] framework for signal processing. By means of our SDR implementation, we are able to study a range of MCS for Orthogonal Frequency-Division Multiplexing (OFDM) in V-VLC. Based on extensive measurements, we show that our prototype can support several V-VLC applications with high reliability. Our system currently achieves a data rate of 0.9 Mbit/s (16-QAM) over a distance of 50 m. If we trade data rate for distance, we can even achieve ranges of 70 m using lower order MCS.

Our main contributions can be summarized as follows:

- We present a flexible GNU Radio-based implementation for V-VLC on Open Hardware, which can be used with advanced modulation and coding schemes.

[1] www.purelifi.com/case-studies/
[2] e.g., Light Communications (LC) study group within IEEE 802.11.
[3] www.gnuradio.org

- We confirm that bandwidth and linearity characteristics of COTS devices are the main source of performance bottleneck in V-VLC systems, and highlight that minor system adjustments (i.e., introduction of simple optics on the receiving side) can largely improve the system performance.
- We demonstrate a good performance trade-off in terms of communication distance and data rate vs. the ability to use COTS hardware. We see our system as a first step towards the design of more sophisticated hardware and physical layer solutions for V-VLC.

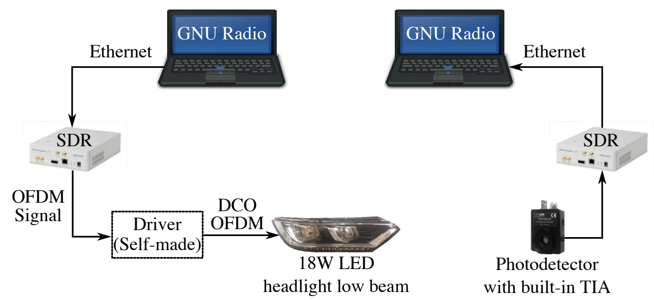

Figure 1. A high-level description of our VLC transmitter-receiver system.

II. Related Work

VLC has been investigated in substantial depth, and meanwhile even successfully applied, for many indoor use cases [2]. There are, however, many open challenges for outdoor operation. We focus on Vehicular VLC, for which research primarily focuses on physical layer aspects of this technology [10]–[12].

Gavrincea et al. [12] introduced a VLC prototype based on the IEEE 802.15.7 standard [4] for VLC. Their setup consists of COTS devices including GNU Radio-based SDR implementations for signal processing. Although, the IEEE 802.15.7 standard specifies three PHYs and modulation schemes, the presented prototype only implements PHY 1, which uses On-Off Keying (OOK) and Variable Pulse Position Modulation (VPPM). The third modulation scheme considered in the IEEE 802.15.7 standard is Color Shift Keying (CSK), where data transmission is realized by modulating the signal to instantaneous color of the RGB LEDs.

Kumar et al. [13] presented an FPGA-based VLC prototype for infrastructure-to-vehicle communication. A VLC-capable LED array is retrofitted into a traffic light case. The system uses Direct-Sequence Spread Spectrum (DSSS) to modulate the transmitted signal. Simulation results show that DSSS has better error performance compared to OOK and Pulse Position Modulation (PPM). Experiments confirmed that the system can perform reliably up to 40 m distance.

Multi-carrier modulation schemes, OFDM in particular, have also been considered to further improve the spectral efficiency of VLC systems. For instance, Shen and Tsai [7] use OFDM with BPSK modulated subcarriers. There, the number of subcarriers are limited to 16 to obtain a better Signal-to-Noise Ratio (SNR) for each subcarrier in real-world driving experiments. Due to the low pass behavior of the LEDs, bandwidth efficient MCS are required to achieve appropriate data rates. OFDM is established as a highly bandwidth-efficient modulation scheme, which additionally not only allows efficient ways to implement Frequency Division Multiple Access (FDMA), but through single tap equalizer, it is highly adaptive to changing channels and offers good robustness to narrow band noise, typically caused by interfering light sources.

To realize data transmissions, VLC uses Intensity Modulation (IM) to modulate a certain waveform onto the instantaneous optical power of the transmitting LED, and Direct Detection (DD) is used to recover the original signal on the receiving end, where photo-sensitive devices are used. Since the light intensity cannot be negative, the transmitted OFDM signals have to be non-negative unipolar with real values [14].

The most common techniques to realize optical OFDM are Asymmetrically Clipped Optical OFDM (ACO-OFDM) and Direct Current-Biased Optical OFDM (DCO-OFDM) [10]. In ACO-OFDM, the negative part of the original bipolar signal is clipped, which causes distortion and creates additional noise on every second subcarrier. Even though, ACO-OFDM does provide higher amplitudes, the noise-carrying subcarrier can no longer be used for transmitting data, which makes it bandwidth inefficient. In contrast, DCO-OFDM introduces a current bias to the signal which shifts it to the positive range. With current biasing, the full span of the bipolar signal has to be mapped onto the positive range which leads to a smaller amplitude and, therefore, makes DCO-OFDM less efficient in terms of average optical power [15].

In previous work, we presented a highly linear VLC front-end circuit with a 3 dB bandwidth of 20 MHz, which can be used to realize DCO-OFDM [8] as well as a simple SDR-based V-VLC implementation [9]. In this paper, we make use of these tools to investigate in detail the performance of different OFDM modulations for V-VLC. Our novel GNU Radio-based V-VLC implementation offers a flexible platform for future rapid prototyping. Moreover, it can provide interoperability with IEEE 802.11 devices, and it is in line with the goals of upcoming IEEE 802.11 Light Communication (LC) standard.

III. V-VLC System Design & Implementation

Our VLC prototype design for vehicular communication is depicted in Figure 1. The proposed VLC design comprises of two parts: the digital signal processing part, which requires laptop PCs running GNU Radio as well as SDRs (we use two N210 USRP from Ettus Research), and the VLC enabling front-ends that includes a VLC driver circuit, a headlight, and a photo-detector.

A. Baseband Signal Processing

In our VLC system, the baseband signal processing is done in the GNU Radio framework. While the Field-Programmable Gate Arrays (FPGA)-based SDRs such as the WARP Mango board do offer deterministic timing, and low latency, they are rather inflexible, and it is often challenging to implement complex signal processing algorithms. In contrast, GNU Radio framework is General Purpose Processor (GPP)-based, it is

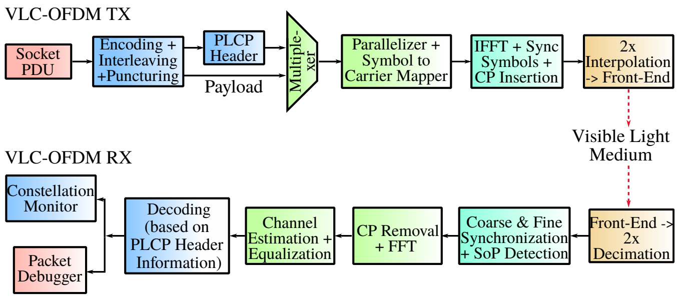

Figure 2. Detailed baseband level block diagram of the OFDM implementation in GNU Radio.

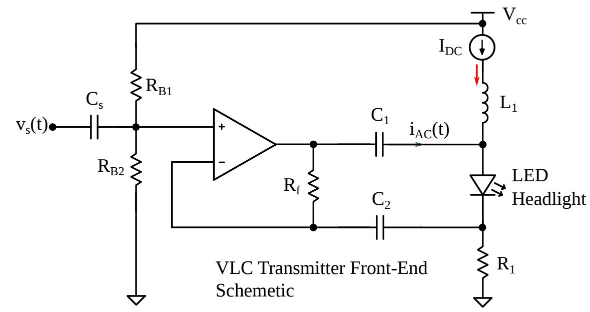

Figure 3. Schematic of the headlight driver circuitry from [8].

easily accessible and most importantly, the signal processing is done in software, with high-level programming languages C++ and Python, thus, making it particularly easy to use, modify, and debug.

For the baseband transmitter/receiver implementation, we have modified the available GNU Radio-based open source stack for IEEE 802.11p developed by Bloessl et al. [16]. The core of this framework is a modular OFDM transceiver that is fully inter-operable with commercially available Vehicular Ad Hoc Network (VANET) prototypes, and has been thoroughly evaluated in [17]. One of the key reason of building upon this implementation is to later test and possibly evaluate the performance of our V-VLC system with commercial prototypes.

Figure 2 illustrates detailed block diagram of the GNU Radio-based IEEE 802.11 compliant OFDM transmitter and receiver modules. Compared to the receiver, the transmitter implementation is rather straightforward as the signal is fully specified in the IEEE 802.11 standard, and has to be produced accordingly. Additionally, a 2x interpolation filter is employed on the raw OFDM samples to improve the spectral image and shape of the transmitted signal. The transmitter supports all packet sizes, and IEEE 802.11 compliant MCS as listed in Table I.

In contrast, the receiver implementation is a design decision and it is generally a trade-off between complexity and performance. The most crucial stages in the receiver design include frame detection/synchronization and channel estimation/equalization. The receiver implementation of our VLC system supports the four channel estimation techniques listed in Table I. In our previous work [9], we have already evaluated their performances and found Least Square (LS) being the best estimator in terms of both performance and complexity.

We used N210 USRP SDRs equipped with a LFTX daughterboard for our experiments. These special daughterboards provide operational bandwidth ranging from 0 MHz–30 MHz, which is well suited for VLC. The OFDM samples from GNU Radio are forwarded to the transmitting SDR via Ethernet. The SDR converts these samples into an analog signal, and up-converts the resulting baseband signal to the carrier frequency. The reason for this up-conversion is to overcome the ambient noise that exists in the low frequencies, which can then be easily filtered at the receiver through a high-pass filter.

Table I
KEY PHYSICAL LAYER PARAMETERS OF THE GNU RADIO OFDM IMPLEMENTATION.

Modulations	BPSK, QPSK, 16-QAM & 64-QAM
Code rates	1/2, 3/4, 2/3
Channel equalization	LS, LMS, STA, Linear Combiner
Interpolation factor	2x
FFT/IFFT size	64 points
PLCP (preamble + header)	(12 + 1) OFDM symbols

B. *VLC Front-Ends*

VLC front-ends typically modulate the signal onto the instantaneous optical power of the transmitting LED and detect the intensity modulated signal at the receiver through photosensitive devices such as photo-diodes or camera image sensors. Current LED-based car headlights are designed to solely illuminate the street. Since communication is not the intended goal, naturally, the switching speed of the LEDs, which basically defines the bandwidth of a VLC system, has never been a major concern. As a result, available headlights have a low operational bandwidth. This bottleneck can be compensated to some extent through efficient spectral usage, i.e, improved bit/s/Hz, which our OFDM implementation inherently provides by supporting 8 different MCS based on the received SNR. Additionally, by further employing Adaptive Modulation and Coding (AMC), each OFDM subcarrier can adopt an MCS dynamically based on its received SNR. With this, the optimal data rate per subcarrier may potentially be achieved, which can indeed lead to an overall improved link capacity because of effective bandwidth utilization.

1) Headlight Driver Circuit: Since the SDR generates voltage signals, and the luminous flux of the LEDs are almost linear to the current only in a certain region, a linear transconductance amplifier is used to drive the LEDs. The LED driver needs to be linear for a wide input signal range to support higher order MCS, especially in OFDM, which suffers greatly due to its inherently high Peak-to-Average Power Ratios (PAPRs). Additionally, for optimal functionality of the LEDs a proper biasing is crucial. Otherwise, parts of the signal may experience clipping, which can cause distortions and performance losses. Therefore, a driver circuit capable to combine an AC signal current-path with an adjustable DC current source for the biasing is required. In previous work, we

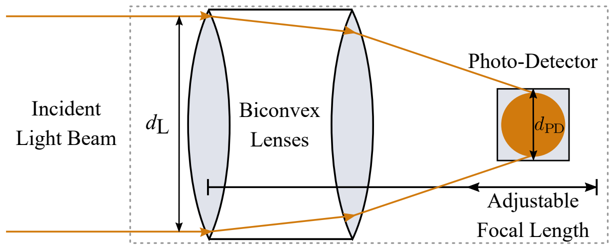

Figure 4. Schematic explaining the receiver optics.

Figure 5. Measurement facility and the transmitter and receiver setup.

proposed a highly linear amplifier, which is suitable to drive a COTS headlight [8]. As can be seen in Figure 3, the driver circuit includes an internal bias tee, which provides a DC bias and AC signal current within the linear region of the LEDs.

2) Photo-Detector: For the detection of intensity modulated light signal (through headlight), we used a Thorlabs photo-detector PDA100A-EC with built-in variable gain amplifier, and connected it directly to the receiving SDR. The photo-diode inside PD translates the incident light to photo-current, which is then converted into voltage signal by means of a built-in linear Transimpedance Amplifier (TIA). The resulting voltage signal is forwarded to SDR for baseband signal processing through GNU Radio in order to retrieve the transmitted payload.

3) Receiver Optics: The large active area of the used PD already leads to a better sensitivity. We have further utilized simple optics to converge the light intensity at the PD's aperture. As shown in Figure 4, the employed optic consists of two biconvex lenses with adjustable distance to fine tune the focal length. The optics is placed to focus the incident light onto the active area of the PD. In this setup, the achievable gain through the optics G_{optic}, can be calculated as

$$G_{optic} = \frac{\Phi_{\mathrm{L}}}{\Phi_{\mathrm{PD}}} = \frac{A_{\mathrm{L}}}{A_{\mathrm{PD}}} = \frac{\pi\frac{d_{\mathrm{L}}^2}{4}}{d_{\mathrm{PD}}^2}, \tag{1}$$

where Φ_{L} and Φ_{PD} are the radiant fluxes incident at the first lens and at the PD (without any optics), respectively, A_{L} and A_{PD} are the areas of the first lens and PD, and d_{L} and d_{PD} are the diameters of the lens and the PD, respectively. With $100\,\mathrm{mm}^2$ area of our PD and $1452\,\mathrm{mm}^2$ area of our first lens, the achieved optical gain is around 11.6 dB. Note that the described optics setup is suitable for this experiment only. For on the road applications, the field-of-view has to be increased by a smaller focal length.

IV. Performance Evaluation

A. Measurement Setup

To evaluate the performance of our V-VLC system, we performed measurements in the ground floor of a parking lot. Figure 5 shows the measurement facility, where fluorescent lamps are installed in the ceiling. We chose this location for our measurements as it offers sufficient space for relatively long transmitter-to-receiver distance. Moreover, the considered indoor facility suppresses the adverse time-varying effects of the sun, which is hard to reproduce. We observed that the effect of the fluorescent lamps is negligible as they operate in a frequency range different to our signal.

For the performance evaluation of our V-VLC design prototype, we recorded detailed measurements in our experimental facility. In the measurement campaign, we set the headlight and other related hardware in the transmission chain at one end of the parking lot. We placed the PD and corresponding devices in the reception chain on a mobile cart and incrementally increase the distance between transmitter and receiver in a straight line. Fortunately, there were equidistant marks (2.7 m apart) on the ground of the parking lot, which aided us in cart placement at incremental distances for the measurements. For each measurement point, we transmitted 1000 OFDM packets of size 250 B (2 million bits per transmission) with each MCS, and obtained Packet Delivery Ratio (PDR), received signal strength and Bit Error Ratio (BER) values at the receiver. During the whole measurement campaign, the gain of TIA (within the PD) is set to 0 dB, and the only receiver gain of roughly 11.6 dB is obtained exclusively through simple optics. Due to space constraints our maximum measurement distance was limited to about 75 m.

Table II lists the most important parameters for our measurements. We have used a center frequency of 2.3 MHz for the up-conversion of our baseband signal. While the translation to center frequency attenuates our baseband signal by a reasonably small factor due to the low pass behavior of the LEDs, this makes our system robust to flickering and ambient noise. Our system can achieve a maximum data rate of 1.35 Mbit/s with 1 MHz sampling frequency and 2x interpolation, which can be considered relatively low as compared to the ones reported in the VLC literature [18]. However, this is only due to the

Table II
Hardware specific parameters for the measurements.

Headlight	VW Passat 18 W LED-based low beam
Headlight's 3 dB bandwidth	1.3 MHz
PD	Thorlabs PDA100A
PD's 3 dB bandwidth	2.4 MHz
PD gain	750 V/A at 0 dB
Optics gain (G_{optic})	11.6 dB
Distance between RX/TX	2.4 m–75 m
Relative height RX/TX	40 cm
Center frequency	2.3 MHz
Sampling frequency	1 MHz
Data rates	0.15 Mbit/s–1.35 Mbit/s

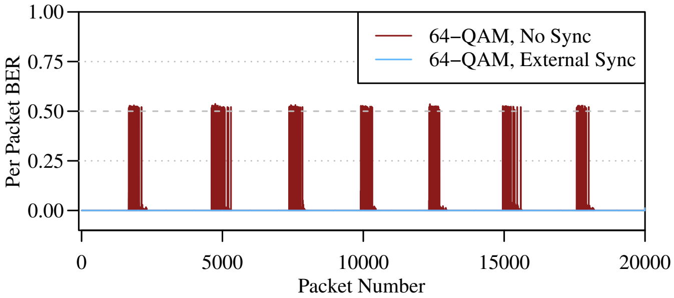

Figure 6. Impact of unsynchronized and externally synchronized clocks of the used SDRs on the BER of VLC receiver in controlled lab setup.

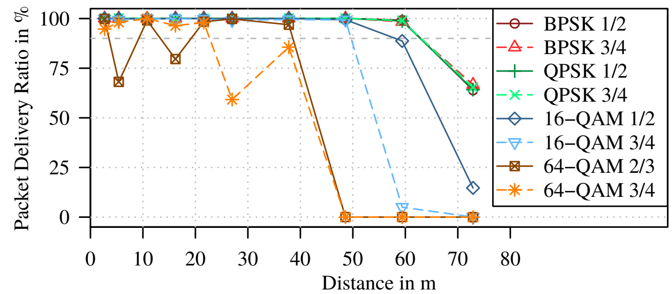

Figure 7. Experimentally measured PDR performance for every MCS, with 1000 packets sent per transmission.

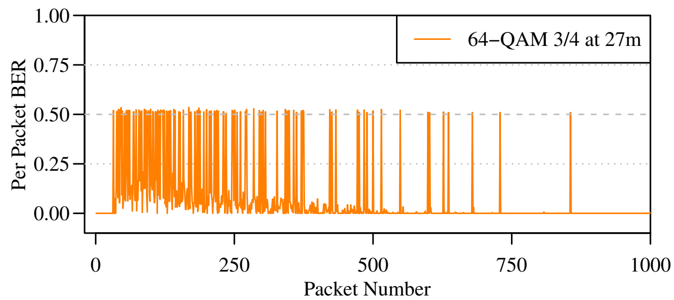

Figure 8. Experimental per packet BER performance with $64-$QAM $3/4$ at a distance of 27 m.

low switching frequency of the high brightness LEDs used in a typical design of automotive lighting modules, which restricted us to use lower sampling frequency, i.e., 1 MHz.

B. Impact of Clock Offset on Receiver Performance

During the initial trial sessions of our measurement setup in a controlled lab environment, we observed a periodic distortive behavior in the received constellation. This behavior appeared to be more severe in higher order MCS, where the euclidean distance between constellation points is smaller, which makes symbol decoding decisions more error-prone. The reason for this periodic distortion is intuitive, and it typically exists due to the drift between transmitter and receiver SDRs clocks, that causes a periodic sampling frequency offset. To further study the phenomenon, we computed the BER of our VLC system, first with the SDRs internal clocks, and then through a common external clock source. In both experiments, we placed the transmitter and receiver 2 m apart. For every MCS, we transmitted 20 000 packets, each containing 250 B payload, and computed the BER of each packet at the receiver.

Figure 6 shows the per packet BER performance of 64-QAM in both experimental scenarios. For lower order MCS up-to $16-$QAM, there were no bits in error at 2 m separation distance with both internal and external clocks. Therefore, the BER results for these MCS are not shown here. However, for $64-$QAM, a per packet BER of around 50 % was measured over periodic intervals with unsynchronized internal clocks of the SDRs. The most interesting fact in Figure 6 is the repetitive burst error behavior with $64-$QAM.

For such higher order MCS, these experiments provided us some very useful insights. First of all, we observed that, if the clocks of both transmitter and receiver SDRs are completely synchronized, these periodic error burst can be eliminated completely. Secondly, the repetitive burst error behavior with internal clocks, occurs approx. after every 2000 packets, specifically for $64-$QAM. Given the conditions of our actual experimental facility, where a common external clock source is not possible, these results forewarned us about what to expect in our measurements for performance evaluation. Nevertheless, in the future, with a complete vehicular-VLC system, this problem of clock synchronization can potentially be addressed through in-car GPS systems.

C. Packet Delivery Ratio over Distance

Figure 7 shows the PDR plot for each MCS with increasing distance between our VLC transmitter and receiver. In the plot, a PDR of 100 % means that all packets have been correctly detected and decoded, and the horizontal dashed line marks 90 % PDR. As can be seen, we measured over 90 % PDR at a distance of 60 m with lower order MCS (BPSK and QPSK). Compared to the experimental results presented in the V-VLC literature, such a high PDR performance over 60 m distance is remarkable [13]. Even, the $16-$QAM $3/4$ MCS is offering a smooth – close to 90 % – PDR performance at a distance of approx. 50 meters. These results are obtained without any external clock synchronization.

Nevertheless, with $64-$QAM, we see some deep drops in PDR performance irrespective of the distance. This performance drop is due to the sampling frequency offset between transmitting and receiving SDRs, which we already discussed in Section IV-B. The per packet BER performance of $64-$QAM $3/4$ shown in Figure 8 further demonstrates the impact of clock drift in our measurement campaign for the evaluation of our VLC prototype. It can be seen that the granular burst error behavior, which starts appearing in the initial packets, gradually fades away in a similar manner as observed previously in controlled lab measurements (Figure 6).

Regardless of the erratic performance drops with $64-$QAM, the MCS seems to offer 90 % PDR at a distance close to 40 m. These very positive PDR results especially with lower order MCS, clearly underline the quite optimal receiver implementation, and further confirm the claimed linear performance of our headlight driving circuitry [8].

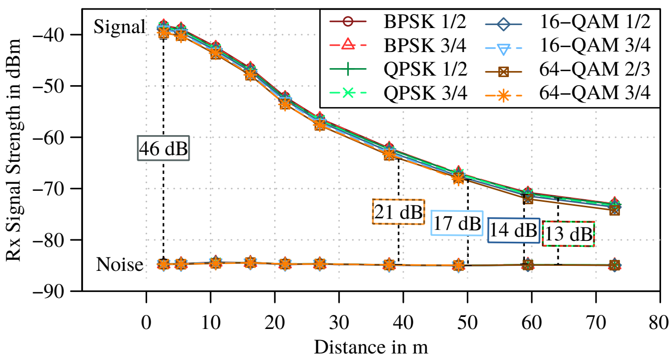

Figure 9. Experimentally measured received signal strength and noise floor with each MCS for increasing distances.

D. Received Signal Strength over Distance

In Figure 9, the averaged signal and noise powers are plotted with increasing distance. The major sources of noise in VLC systems are interference noise by ambient light, shot noise that is introduced by the pn-junctions of diodes, thermal noise produced by electrical components, and the quantization noise due to Analog-to-Digital Converters (ADCs). As can be seen in Figure 9, the measured noise power in our experimental scenario stays almost constant at around −85 dBm, regardless of the distance.

The received signal power on the other hand, degrades with increasing distance. In VLC, this signal degradation is essentially due to inverse square law, heterogeneous distribution of light which results in strong spatial dependency [3], and the propagation medium, e.g., the presence of particles in the air. As can be seen in Figure 9, a maximum SNR of 46 dB is measured with our V-VLC setup at the smallest distance of 2.7 m. Additionally, the figure also maps the distance onto the minimum required SNR to maintain 90 % PDR with all considered MCS. Take 64−QAM as an example, where an SNR of approx. 21 dB is required to maintain a PDR of 90 %.

V. Conclusion

In this paper, we presented a Vehicular VLC (V-VLC) prototype based on Software Defined Radios (SDR), which is capable of live communication over long distances using Commercial Off-The-Shelf (COTS) hardware. Our V-VLC prototype is based on the GNU Radio framework, which is rather flexible as all signal processing is done in software. From the Packet Delivery Ratio (PDR) results of our experimental measurements, we showed that our system provides reliable communication over 50 m range for different Modulation and Coding Schemes (MCS), including 16-QAM. We used simple optics for better reception throughout all our measurements. Furthermore, we experimentally confirmed that external synchronization helps compensating SDRs clocks drift, which substantiate that higher order MCS like 64-QAM can also be realized in a reliable way.

Our systematic and flexible approach allows rapid prototyping for different setups. Based on this, in future work, we plan to extend our study to a more challenging outdoor environment. We also plan to use more specialized solutions to address hardware limitations, e.g., better optics design, GPS for SDRs synchronization, and pre-equalization or mapping techniques to further improve the performance.

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