Physical Layer Implementation of Standard Compliant Vehicular VLC

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***Abstract*—Visible light communication (VLC) has recently gained popularity as a complementary technology to radio frequency (RF) based alternatives for vehicular communications as a low-cost, secure and RF interference free technology. In this paper, we propose IEEE 802.15.7 standard-compliant physical layer (PHY) implementation and experimental evaluation, using commercial off-the-shelf (COTS) automotive light emitting diode (LED) fog light for the purpose of low-latency safety message dissemination. We first show that the standard is applicable to line of sight (LoS) vehicle-to-vehicle (V2V) VLC. We then demonstrate that the proper selection of modulation coding schemes (MCS) plays an important role in order to minimize bit-error-rate (BER) for the reliable transmission with varying inter-vehicle distances. We also addressed the angular limitations of COTS automotive LED light for viable vehicular VLC.**

***Index Terms*—Vehicular communication, visible light communication.**

I. Introduction

Visible Light Communication (VLC), a subset of Optical Wireless Communication (OWC), uses the visible light spectrum (400-790 THz) and provides low-cost, energy efficient wireless solutions to achieve high data rates. VLC uses modulated optical radiation of light emitting diode (LED)s [1] and laser diodes to convey digital information without any noticeable effect on human eye. Intensity modulation and direct detection (IM/DD) are typically preferred in the physical layer (PHY) of VLC. Therefore, initial works are based on simple modulation techniques such as on-off keying (OOK) and pulse position modulation pulse position modulation (PPM) [2]. OOK and PPM have been selected as modulation schemes in the IEEE 802.15.7 standard which was issued in 2011 [3]. Additionally, Color Shift Keying (CSK) is defined as the third modulation scheme.

Various vehicular communication architectures in Intelligent Transportation Systems (ITS) aim to provide relevant traffic and road information in a timely and reliable manner to decrease traffic accidents while constituting a milestone for autonomous driving. RF based communication schemes such as Dedicated Short Range Communication (DSRC) and Long Term Evolution (LTE) are believed to play a major role in vehicular connectivity as a result of their non-line-of-sight (NLoS) communication capabilities [4]–[6]. Recently, in addition to DSRC and LTE, the usage of vehicular VLC has been proposed [7]. LEDs offer energy efficient and brighter road illumination while their small sizes enable easier shape manipulation of vehicle lights. Many automotive companies have already started using LED lights in their product line. In the near future, all vehicles are expected to be equipped with LED lights. VLC based vehicular communications is believed to provide a secure alternative and complementary solution to the RF based wireless communications as it is robust to intentional jamming and spoofing [8].

It is envisioned that grouping vehicles into platoons will increase efficiency of road usage while reducing fuel consumption [9]. Platooning requires secure and interference free communication in order to exchange information and warning messages. VLC, operating on a line-of-sight (LoS) basis with its interference free nature, is a strong candidate for platoon based applications.

VLC for vehicular connectivity has been addressed for its channel characteristics [10], link budget [11], [12], hybrid usage with radio frequency (RF) wireless communications [13], modulation [14], and coding [15] schemes. On the other hand, several experimental performance evolution studies [16]–[18] of IEEE 802.15.7 standardization have been conducted. The first practical implementation of Software-Defined Radio (SDR)-based standard compliant VLC system is provided in [16]. [17] implements the standard compliant VLC system with fully integrated Complementary Metal Oxide Semiconductor (CMOS) circuits after investigating the optical wireless link budget. In [18], same layer requirements are implemented on Xilinx Virtex-5 Field Programmable Gate Array (FPGA) and demonstrate the bit-error-rate (BER) performance. [**?**] uses Universal Software Radio Peripheral (USRP) to implement the standard and obtain BER curves with respect to different illumination levels. However, implementations are mainly evaluated for their indoor performance at short distances. To date, none of the studies, addressed outdoor night time performance of IEEE 802.15.7 PHY-1 standard for practical platoon headway distances (6-10 meters) with varying angles. To best of our knowledge, this is the first experimental study, investigating outdoor performance of the standard compliant implementation for practical platoon headway distances.

The goal of this paper is to evaluate SDR based, standard-

Figure 1: Vehicular VLC experimental setup.

compliant implementation of vehicular VLC for practical applications. First, we implemented the IEEE 802.15.7 on a SDR, using automotive LED fog light. Then, we evaluated the performance of modulation coding schemes (MCS) with respect to varying inter-vehicular distances for platoon headway distances. We further provided the execution time for all transmission modes under consideration and angular communication limitations of an off-the-shelf automotive light.

The rest of the paper is organized as follows. In Section II, we briefly describe the IEEE 802.15.7 standardization. In Section III, we explain our system model including implementation details and experimental setup based on the standardization. We show the performance evaluation in Section IV. Finally, we conclude the paper in Section V.

II. IEEE 802.15.7 Standardization

IEEE 802.15.7 Task Group standardized the PHY and medium access control (MAC) layer specifications for VLC in 2011 [3]. The standard supports mainly three PHYs which are categorized according to their data rates and dimming support [19], [20]. PHY-I supports the data rates from 11.67 kbps to 266.6 kbps and PHY-II supports the data rates from 1.25 Mbps to 96 Mbps. Both PHY-I and II use OOK and variable pulse position modulation (VPPM) as modulation schemes. PHY-III supports the data rates from 12 Mbps to 96 Mbps and its modulation scheme is CSK, requiring multiple optical sources with different frequencies.

PHY-I is optimized for reliable long distance outdoor transmission with low data rates. The transmitter and receiver blocks for PHY-I are depicted in Fig. 2. For outdoor applications, stronger coding schemes such as Reed Solomon (RS) and Convolutional Code (CC) are used in order to handle path loss and interference sourced by background lighting. The input bit stream is first encoded by RS coding scheme in which n bits are encoded to k codewords, based on generator polynomial in Galois Field (GF). An interleaving, including zero padding and puncturing, between RS and CC exists in PHY-I to eliminate burst errors, providing additional performance improvement with the amount of 1 dB. Each mode has Run-Length Limited (RLL) line codes to guarantee DC balance and remove the effect of flickering while avoiding long runs of 1s and 0s. Manchester code, which expands 1-bit to 2-bit, for OOK and 4B6B code, expanding 4-bits to 6-bits, for VPPM are used as RLL line codes. The specifications of PHY-I are presented in Table I.

Table I: PHY-I operating modes

Mode	Data Rate	Modulation	Optical Clock Rate	FEC	
				Outer Code (RS)	Inner Code (CC)
PHY I.A	11.67 kbps	OOK	200 kHz	(15,7)	1/4
PHY I.B	24.44 kbps			(15,11)	1/3
PHY I.C	48.89 kbps			(15,11)	2/3
PHY I.D	73.3 kbps			(15,11)	None
PHY I.E	100 kbps			None	None
PHY I.F	35.56 kbps	VPPM	400 kHz	(15,2)	None
PHY I.G	71.11 kbps			(15,4)	None
PHY I.H	124.4 kbps			(15,7)	None
PHY I.I	266.6 kbps			None	None

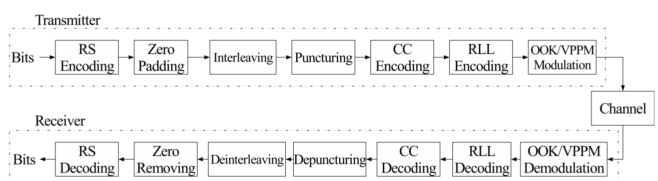

Figure 2: Block diagram of a PHY-I type VLC system.

Different dimming methods are defined for various modulation selections. OOK modulation, changing ”ON” and ”OFF” levels or varying average duty cycle of the signal waveform is employed. In order to adjust the average intensity for OOK, compensation symbols are inserted into data frame. Dimming for VPPM is applied via varying the ”ON” time pulse width. VPPM dimming resolution of 0.1% is delineated in the standard. It should be noted that, dimming under OOK modulation provides constant range and variable data rate, whereas dimming for PPM offers constant data rate but variable range.

III. System Model

A. Implementation Details

1) Transmitter Unit: Transmitter Unit (TU) consists of commercial off-the-shelf (COTS) automotive LED fog lights, bias-tee, DC power supply and USRP equipped with a LFTX daughter-board to generate baseband signals with the maximum bandwidth of 30 MHz. National Instruments LabVIEW software and Matlab scripts are used for the software implementation. Based on the dimming support of the standard as detailed in Section II, LED fog lights are selected as optical front-end. Dimmed LED fog lights can be regarded as day-time running lights.

According to IEEE 802.15.7 PHY standard, PHY data unit encompasses synchronization header (SHR), physical header (PHR) and physical service data unit (PSDU) fields. SHR handles optical clock synchronization for the incoming messages using one fast locking pattern (FLP), followed by the relevant topology dependent pattern (TDP). SHR is not involved in any channel coding or line coding. PHR frame contains selected wavelength and MCS information in addition to PSDU length. PSDU field carries the information to be transmitted. Both SHR and PHR are transmitted using only OOK modulation. Hence, at the transmitter side, PHR and PSDU frames are generated separately. The former is fed into an OOK modulator block, while the latter is modulated with either OOK or VPPM modulation in another modulator block. Forward Error Correction (FEC) scheme, zero padding, interleaving, puncturing and RLL coding implemented as the transmitter blocks according to Table I. Interleaving is implemented between RS and CC encoding blocks. Furthermore, puncturing minimizes zero padding overhead. In addition to aforementioned capabilities, RLL coding also aims to provide the clock recovery. Both modulator outputs are combined with TDPs and FLP is inserted into stream to be transmitted first with the USRP.

2) Receiver Unit: Receiver unit (RU) is composed of photodetector with switchable gain, aspheric lens to focus the optical transmission on photodetector and USRP for analog to digital conversion, signal conditioning and processing at the computer. At the RU, Matlab scripts are executed for RLL decoding process while rest of the implementation is carried out using LabVIEW.

Frame synchronization is executed with the exploitation of FLP at the RU and SHR bits are stripped from the input stream. Due to propagation delays and distortion resulting from the channel, it is crucial to determine the optimum sampling time. Thus, timing recovery is implemented by detecting maximum energy of oversampled sequence to decide optimum sampling instant. PHR and PSDU frames are parsed, demodulated, deinterleaved and decoded in separate demodulation blocks. Viterbi decoder with soft decision is utilized for convolutional decoding.

B. Experimental Setup

In the experimental setup, both TU LED fog lights and RU photodetector are mounted at 40 cm height. Received optical power decreases with the increasing distance and incidence angles of the transmitter and receiver. Thus, fog lights and photodetectors are positioned at the same sides of leading and following standstill vehicles and it provides 0° incidence angle to avoid received optical power degradation. Inter-vehicular distances are changed from 6 to 12 meters with the step size of 2 meters in order to evaluate IEEE 802.15.7 PHY-1 MCS performance. Night time measurements are conducted at the outdoor parking lot, illuminated with fluorescent street lights to conduct measurements under uniform background illumination levels and compensate shot noise from diurnal variations. The low beam headlights and taillights of both vehicles are also utilized to take into account their effects on BER.

Figure 3: Transmitter Unit

Figure 4: Receiver Unit

Fig. 3 shows the TU experimental setup. At the TU, DC power is inserted into baseband RF output of the USRP using Minicircuits ZFBT-4R2G+ bias-tee. Bias-tee output is fed into LED fog light for dual purpose of illumination and communication.

Fig. 4 depicts the RU components. Received signals are captured via Thorlabs PDA36A photodetector with aspheric condenser lens, using built-in transimpedance amplifier set to 20dB gain for all distance and angle variations. Photodetector output is connected to USRP for analog to digital conversion and further processing at the computer. Both TU and RU USRPs are connected to DELL Latitude E5440-4668 laptops for processing.

High mobility of vehicular ad-hoc networks creates challenge for gain characterization of automatic gain controller (AGC) at the RU. Despite the various studies in the literature [21] for AGC to compensate artificial lighting, it is still a debated topic of either using AGCs or adaptive optical lenses. In our experimental setup, in order to observe pure signal characteristics of the modulation schemes, AGC is not employed.

Two different experimental scenarios are considered, aiming to evaluate standard compatibility of COTS automotive LED light at practical inter-vehicular distances. In the first, both vehicles are positioned one after another in the same lane, emulating platoon of two vehicles with fixed headway distances. In the second, vehicles traveling towards each other on a two-lane road is emulated to inspect limitations of vehicular VLC, using single LED light and two photodetectors. Since the automotive fog lights provide flat and wide illumination pattern in the second scenario under investigation, data is transmitted from left fog light of the proceeding vehicle to the photodetectors located near the left and right fog lights of the upcoming vehicle on a two-lane road. Minimum angle for one-to-one reliable transmission from left fog light of the proceeding vehicle to the photodetector located near the left fog light of the upcoming vehicle is defined as measured limit angle (ϕ). On the other hand, minimum angle for reliable transmission between left fog light of the proceeding vehicle and the photodetector located near the right fog light of upcoming vehicle is defined as the required angle (φ).

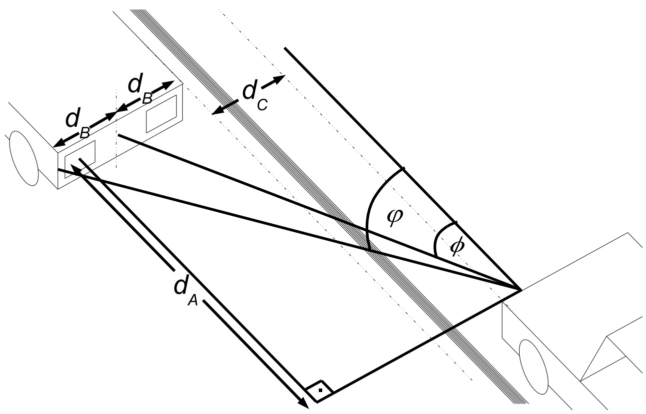

Figure 5: Critical Angles for Reliable Communication

IV. Performance Evaluation

In this section, we present the effect of distance and angle on the BER performance under the consideration of fixed transmit power that is set to 0.81 dBm. Performance evaluation is conducted based on measured BER. In order to measure BER, parsed PSDU frames are compared with the regenerated PSDU frames at the receiver.

Fig. 6 shows the dependence of the BER performance on the distance between LED and photodetector. The two vehicles are aligned and communicate with each other through LoS. We conduct our practical experiments with a data stream including 40k bits, composed of 1000 bit PSDUs. Therefore, we expect to see roughly 2.5x10^{-5} BER as minimum value and we are 95% sure that our decision is within the 10% of the true value at the target BER of 10^{-3} according to Central Limit Theorem (CLT). It is observed from Fig. 6 that PHY-I.A gives the best performance since it has the strongest coding scheme such as RS with (15,7) and CC with 1/4 code rate. Up to distances of 14 meters, results did not indicate any error. Similarly, transmission in the range of 0-12 m is robust with specification of PHY-I.B. Even though coding is not used in PHY-I.E, the bits are transmitted without any error until 6 meters. In the case of PPM, we increase the system bandwidth twice in order to get desired data rates in the standard. Therefore, noise power is enhanced by two. In addition to noise power, CC is not considered in PPM transmission. Our results show that the worst case of OOK, which is PHY-I.E, outperforms the best case of PPM, which is PHY-I.F, in terms of BER.

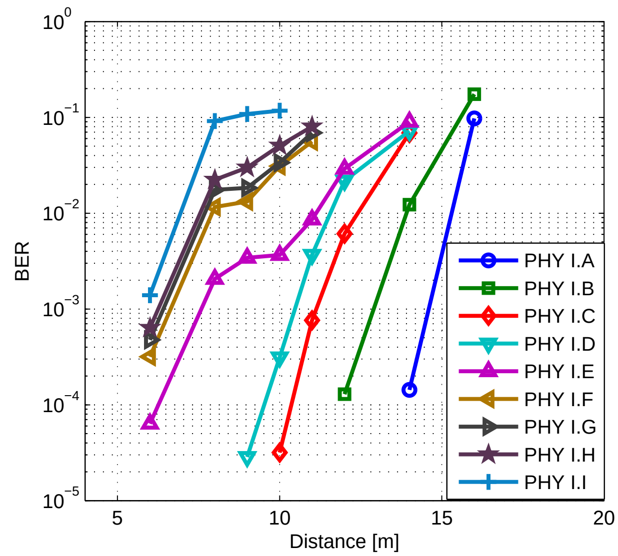

Figure 6: BER performance of PHY-I modes.

Fig. 7 shows the encoding and modulation processing durations for PHY-I operating modes at the TU. Vehicular communications are exposed to short link durations due to high mobility of vehicles. Additionally, blinking lights such as turn indicators are also expected to be utilized for vehicular VLC. Hence, latency plays an important role in the selection of MCS. Using non real-time operating system, encoding process for each MCS is iterated 10000 times and mean of the total encoding execution time is regarded as the encoding time. It is observed that, despite its robustness PHY-I.A encoding did not take as much time as PHY-I.F which employs PPM. Thus, it can be concluded that if constant data rate feature of PPM dimming is not concerned, OOK based modulation schemes are more favorable in terms of latency.

Table II: Angular Communication Limitations

Longitudinal Distance	Measured Limit Angle	Required Angle
6.15 m	16.74°	21.31°
8.16 m	11.22°	16.38°
10.51 m	8.01°	12.86°
12.1 m	5.71°	11.21°

Table II shows the angular limitations of a single LED fog light and required incidence angles for reliable transmission using PHY-I.A (see Fig. 5). Considering vehicle width of 2 meters (d_B=1m) and lane separation (d_C=40cm), it is concluded that COTS LED fog lights can not be utilized for transmitting data to the receiver fitted on the further side of vehicle on adjacent lane (d_A) for distances greater than

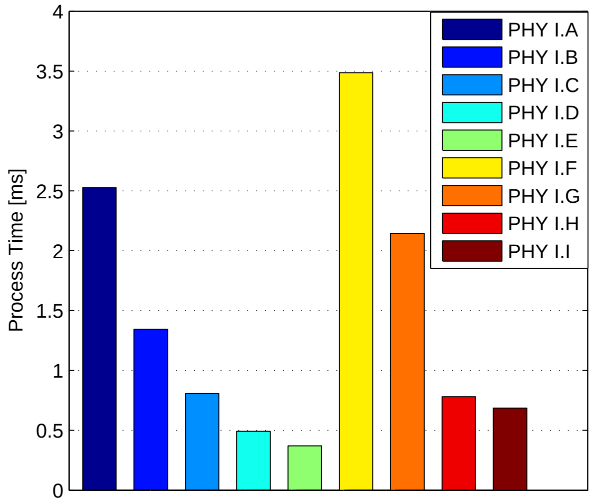

Figure 7: Process time of PHY-I modes

6 meters. According to measurement results, two vehicles proceeding in the opposite direction, can only communicate as long as the transmitter and receiver are located in minimum distance configuration. Hence, utilizing both photodetectors located at the left and right corners of the vehicle to capture two different data, transmitted from the LED fog lights of the vehicle on adjacent lane is not viable.

V. Conclusion

VLC is gaining popularity as it is free from legacy considerations such as spectrum scarcity, high-cost and security when compared to RF based wireless communications. In the near future, most vehicles are expected to be equipped with LEDs. Therefore, VLC is foreseen to serve as a reliable and secure communication solution. By implementing the IEEE 802.15.7 PHY-I standard on a SDR, we compared MCS available in the standard with COTS automotive LED fog light transmitter front-end. It is shown that proper selection of MCS is key in achieving reliable VLC at various inter-vehicle distances in highly dynamic vehicular networks. We explored possibilities of VLC usage with respect to varying angles, and demonstrated the limitations of COTS automotive LED fog lights for lane to lane vehicular VLC.

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