Implementation of Software-Defined Adaptive DCO-OFDM for Vehicular Visible Light Communication

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Abstract—**With its high data rates and electromagnetic interference-free operation capability, visible light communication (VLC), has emerged as a potential candidate for 6G and beyond networks. In this work, we present the preliminary experimental results of our rate-adaptive OFDM vehicular VLC implemented on software-defined platform. The physical layer of the system builds upon direct current biased optical OFDM (DCO-OFDM) and supports adaptive transmission with different modulation schemes/levels including BPSK, 4-QAM, 16-QAM and 64-QAM. For switching between different modulation schemes, a feedback link with on/off keying modulation is used to send channel state information (CSI) to the OFDM transmitter. Based on the CSI, the OFDM transmitter adapts its next transmission by selecting a modulation scheme/level which maximizes the spectral efficiency while satisfying a predefined error performance target of 3.8×10^{-3}.**

Index Terms—**Software Defined Radio, USRP, VLC, OFDM, 6G, Spectral Efficiency, Intelligent Transportation System**

I. INTRODUCTION

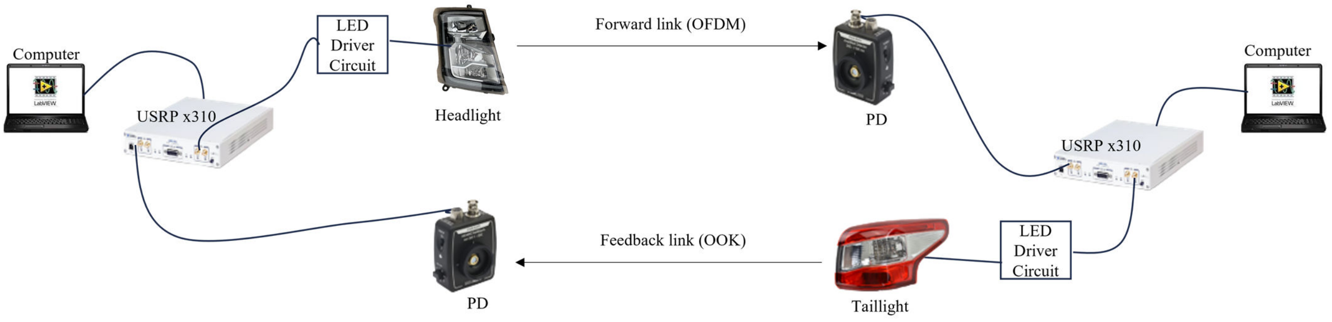
With its high data rates and electromagnetic interference-free operation capability, visible light communication (VLC) has emerged as a potential candidate for 6G and beyond networks. VLC leverages existing lighting infrastructure for both illumination and data transmission by modulating LEDs at a very high frequency unnoticeable to the human eye. One of the key challenges associated with VLC is the bandwidth limitation associated with commercial white LEDs, which behave as first order low-pass filters [1], [2]. Multicarrier modulation schemes such as orthogonal frequency division multiplexing (OFDM) are commonly employed to overcome the distortion imposed by bandwidth limitation. Furthermore, the optical wireless channel varies with time due to device or user mobility in addition to environmental conditions, and this can impair the performance of vehicular VLC systems which will operate in dynamic environment. Adaptive transmission allows the switching between different modulation sizes, code rates or transmit power as the channel varies and is critical to satisfy the system performance requirements in terms of bit error rate, spectral efficiency, and power efficiency.

In this work, we present for the first time in the literature a software-defined implementation of feedback link-enabled adaptive OFDM-based vehicular VLC system for future intelligent transportation systems (ITSs). Aided by a feedback link, the receiver updates the transmitter with channel state information based on which the spectral efficiency is maximized for a predefined BER performance target. For this implementation, we use modified Ettus USRP x310 platforms [3] where the RF daughterboards are replaced by LFTX/LFRX cards [4]. For VLC transmitter, we use actual LED headlight and taillights with photodetectors as receivers as shown in Fig. 1 and 2. The physical layer builds upon direct current biased optical OFDM (DCO-OFDM) and supports adaptive transmission with different modulation schemes/levels including BPSK, 4-QAM, 16-QAM and 64-QAM. The feeback link employs a low-rate on-off keying (OOK) transmission scheme to send channel state information (in terms of SNR) to the OFDM transmitter. Consequently, the transmitter selects a modulation scheme/level which maximizes the spectral efficiency for the current channel condition while satisfying a predetermined error performance requirement.

II. EXPERIMENTAL SYSTEM DESIGN

We consider that two vehicles moving in the same direction in the same lane communicates over VLC link. The vehicle at the back (follower) transmits OFDM packets to the leading vehicle (leader) via its headlight. The leader receives the optical signal with a photodetector located at its back, processes the signal, and decodes the packets. Next, the leader transmits a feedback message to the follower via its taillight using OOK scheme. The follower receives the feedback optical signal via a photodetector and decodes it. The decoded feedback message informs the follower about channel quality (SNR). With the availability of the SNR, next OFDM packets are transmitted with a modulation scheme/level that satisfies the performance requirements.

From the follower vehicle, LabVIEW software is used to generate the baseband transmit signal. The baseband signal is fed to USRP x310 via an ethernet cable. The baseband signal is processed by the DAC into an analog baseband signal and shifted to 1 MHz by the LFTX. By shifting the baseband signal from DC, we can reduce the impact of low frequency ambient light on the system performance. The output of the USRP x310 is fed to a bias tee which imposes the signal on a 26.5 V DC supply to ensure operation in the linear region of LED headlight. The output of the bias tee drives



(a) Follower Vehicle Set-up (b) Lead Vehicle Set-up

Fig. 1: Experimental system architecture (a) follower vehicle and (b) lead vehicle set-up

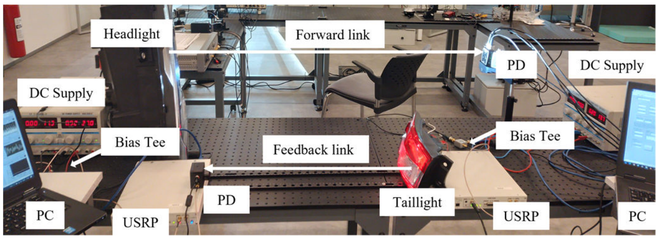


Fig. 2: Experimental system set-up in indoor lab environment

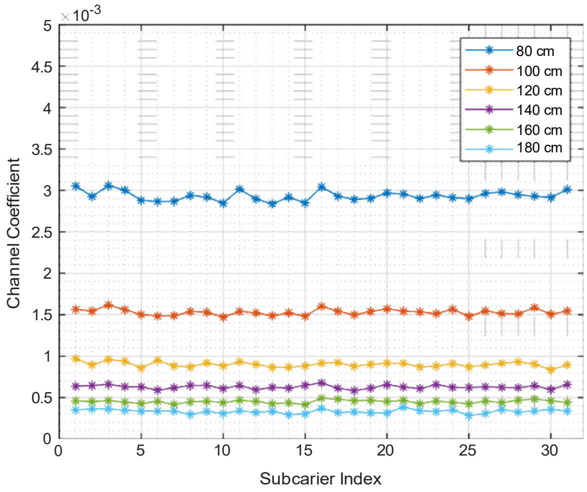


Fig. 3: Channel coefficient at varying distance

the LED to transmit over the forward link. On the receiver side of the leader vehicle, a photodetector is used to detect the optical signal, convert it to electrical signal and then fed to USRP x310. The USRP shifts the signal to DC and samples it. The sampled signal is fed to the computer for processing and decoding in LabVIEW. Similar operations occur on the feedback link using the LED taillight as wireless transmitter. For proper operation of the LED taillight, a DC bias of 14 V is supplied.

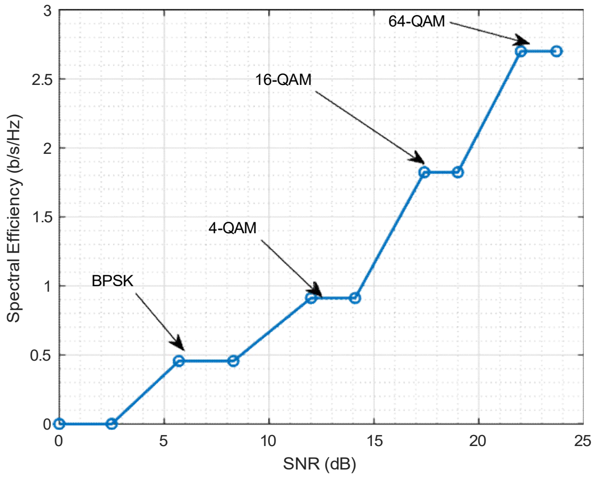


Fig. 4: Spectral efficiency of adaptive system

For link adaptation, the average SNR of the received OFDM frame is estimated and compared with a look-up-table (LUT) containing different modulation levels/schemes i.e., BPSK, 4-QAM, 16-QAM and 64-QAM. For each modulation level/scheme, a proper SNR range is defined for a targeted BER of 3.8×10^{-3} [5]. The SNR ranges are represented by distinct binary codewords in the LUT. The codeword corresponding to the estimated SNR is selected and modulated using OOK and transmitted on the feedback link. The received codeword indicating channel quality is compared with the LUT to select the appropriate modulation level/scheme for the next OFDM frame transmission.

III. MEASUREMENT RESULTS

The implemented OFDM transmission scheme is flexible, and its system parameters can be reconfigured to generate different baseband OFDM signals. Here, we employ a sampling rate of 2 MHz, 64 subcarriers, cyclic prefix length of 4 and upsampling factor of 4. The square root raised cosine (SRRC)

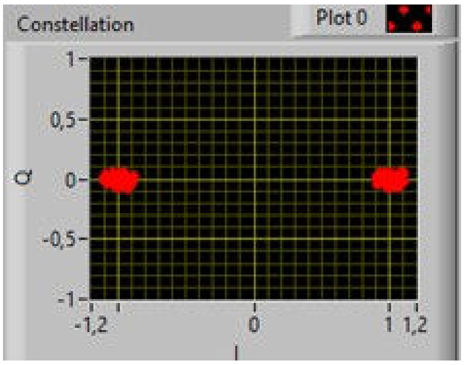


Fig. 5: Received constellation of BPSK-DCO-OFDM

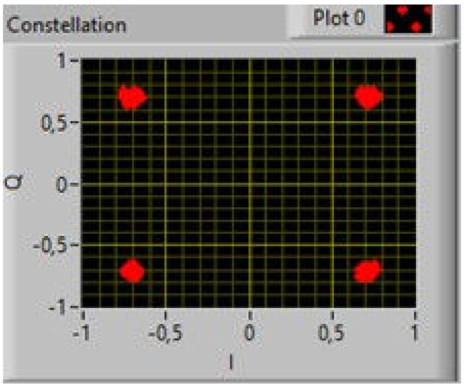


Fig. 6: Received constellation of 4QAM-DCO-OFDM

pulse shape filter with excess bandwidth of 0.8 is used for both forward and feedback links.

In Fig. 3, we show the channel coefficients per subcarrier of packets received at varying transmission distances. It is observed that as distance increases, the channel coefficient decreases. Fig. 4 presents the spectral efficiency of the adaptive system. At a fixed 1 m transmission distance, the power of the OFDM frame is increased continuously to vary the received SNR. As SNR varies across SNR ranges in LUT, appropriate modulation scheme/level is selected at every range to maximize the spectral efficiency. Fig. 5-8 present received constellation diagrams of OFDM packets with different modulation schemes at estimated average SNR of 29 dB at line-of-sight transmission distance of 1.2 m. Table 1 shows SNR measurement for the forward link when headlight and PD are strictly aligned for indoor environment.

TABLE I: SNR vs. distance measurements

Distance (cm)	80	100	120	140	160	180
SNR (dB)	36	31.4	28.5	26.3	24.6	22.1

IV. CONCLUSION AND FUTURE WORK

We have presented an experimental implementation of adaptive OFDM-based vehicular VLC system on software-defined

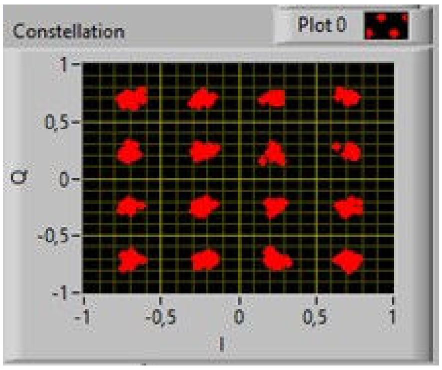


Fig. 7: Received constellation of 16QAM-DCO-OFDM

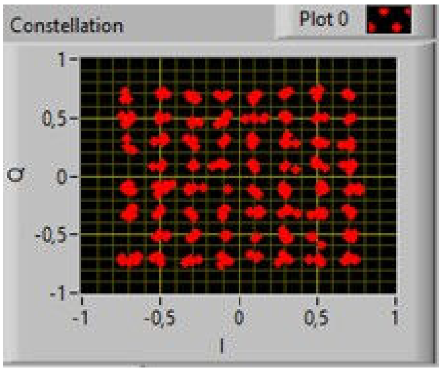


Fig. 8: Received constellation of 64QAM-DCO-OFDM

radio platform with real vehicle headlight and taillight as optical wireless transmitters. The adaptive system supports a maximum spectral efficiency of 2.7 bps/Hz using 64-QAM. As a future work, channel coding will be implemented to increase robustness of our system to the harsh outdoor vehicular environment. We will conduct different performance tests to ascertain the feasibility of the implemented adaptive system under different weather conditions in outdoor.

ACKNOWLEGMENT

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REFERENCES

[1] P. A. Haigh et al., "Visible Light Communications: 170 Mb/s Using an Artificial Neural Network Equalizer in a Low Bandwidth White Light Configuration," *J. Lightwave Tech.*, vol. 32, 2014, pp. 1807–13.
[2] H. Le Minh et al., "100-Mb/s NRZ Visible Light Communications Using a Post equalized White LED," *IEEE Photonics Tech. Lett.*, vol. 21, 2009, pp. 1063–65.
[3] https://www.ettus.com/all-products/x310-kit/ Accessed: 28/07/2023.
[4] https://kb.ettus.com/LFTX/LFRX. Accessed: 28/08/2023
[5] O. Narmanlioglu, R. C. Kizilirmak, T. Baykas and M. Uysal, "Link Adaptation for MIMO OFDM Visible Light Communication Systems," *in IEEE Access*, vol. 5, pp. 26006-26014, 2017, doi: 10.1109/ACCESS.2017.2771333.