Technical Report: Approaches for shared use of base-band hardware in OFDM-based hybrid VLC-RF Systems with multicolored LEDs

Pravallika Dhulipala*, Minju Kang*, Taejin Kim†, Siddhartan Govindasamy*

1 Introduction

Visible-light communication (VLC) has emerged as a viable approach to help mitigate the spectral shortage that is predicted to occur in the very near future. VLC systems use Light-Emitting-Diodes (LEDs) originally intended for illumination to transmit data by rapidly modulating light levels. Hence lighting systems can double up as network access points (AP) and use VLC for dowlink transmissions to user devices. However, given the bright light levels and high transmit power required for high-rate VLC, it is not very practical for uplink communications from user devices to the AP to use VLC. Hybrid VLC and radio frequency (RF) systems have been proposed to mitigate this problem as VLC can be used on the downlink and RF on the uplink. Additionally, VLC-RF systems can also be useful when Line-of-Sight (LOS) between the AP and user terminal is not available, as LOS is typically required for high-rate VLC systems. As such, RF could be used when LOS is unavailable. Hence, there is significant interest in designing hybrid RF-VLC systems.

Since RF systems have been deployed for a very long time, economies of scale have made hardware designs for systems such as 802.11 WiFi inexpensive. Moreover, there are many more research and development systems for RF than for VLC. Hence, designing hybrid RF-VLC systems that require minimal changes between RF and VLC processing is attractive from a cost perspective (for RF-VLC products), and an availability perspective for researchers who may wish to use devices originally designed for RF such as the MANGO Communications WARP system, for VLC.

In this document, we describe three approaches which enable the use of algorithms, and hence base-band processing hardware originally designed for 802.11 WiFi on VLC channels, with minor modifications. These approaches include:

*Olin College of Engineering

†Carnegie Mellon University. T. Kim's contributions were when he was a student at Olin College of Engineering. Supported in part by the National Science Foundation under grant CNS 1618646.

1) efficient use of the complex Fast Fourier Transform (FFT) and Inverse FFT (IFFT) originally intended for band-pass channels typical of RF systems, in base-band VLC channels, 2) channel frequency response pre-compensation to compensate for the sharper frequency response decay in VLC channels compared to RF channels and 3) impulse response shortening to enable the use of orthogonal frequency-division multiplexing (OFDM) systems designed for RF, which tend to have shorter impulse responses, in the VLC channel.

2 Efficient FFT Processing

2.1 Description of IFFT-FFT system

Since the VLC signal is typically base-band, most implementations of OFDM-based VLC systems rely on imposing conjugate symmetry on the transmit signal. As a result, with N subcarriers, only $N/2$ bear unique data. Given that the IFFT/FFT processing is typically the most computationally intensive part of an OFDM system [], this results in wasted computational resources. In our proposed system, we adapt well-known ideas on real FFT computation (see e.g. Chapter 2 of [**?**]) to use a single N-point IFFT/FFT to compute two independent data streams which are communicated through different colored LEDs.

2.1.1 Transmit-side processing

In the transmit side of our proposed system, we split N data symbols $X_0, \cdots, X_{N-1}$ into two parts. Symbols $X_0, \cdots, X_{N/2-1}$ are converted into N symbols $X_0^R, \cdots X_{N-1}^R$ as follows

$$X_k^R = \begin{cases} X_k & \text{if } k < \frac{N}{2} \\ X_{N-k-1}^* & \text{if } \frac{N}{2} \leq k < N \end{cases} \tag{1}$$

Symbols $X_{N/2}, \cdots, X_{N-1}$ are converted into N symbols $X_0^G, \cdots X_{N-1}^G$ as follows

$$X_k^G = \begin{cases} X_{k+N/2} & \text{if } k < \frac{N}{2} \\ X_{3N/2-k-1}^* & \text{if } \frac{N}{2} \leq k < N \end{cases} \tag{2}$$

A block of N samples $\hat{X}_k$ for $k = 0, \cdots \frac{N}{2} - 1$ is then generated as follows.

$$\hat{X}_k = X_k^R + jX_k^G \tag{3}$$

And N point IFFT is then taken of the block of N samples $\hat{X}_k$ and the cyclic prefix is added according as is done in RF systems. The real-part of the resulting time domain waveform (called the I-channel in RF systems) is then transmitted through the red LED, and the imaginary part (called the Q channel in RF systems), is transmitted through the blue LED. Note that the only additional computations beyond a standard RF OFDM system is in the generation of X_k^R and X_k^G which require N additions.

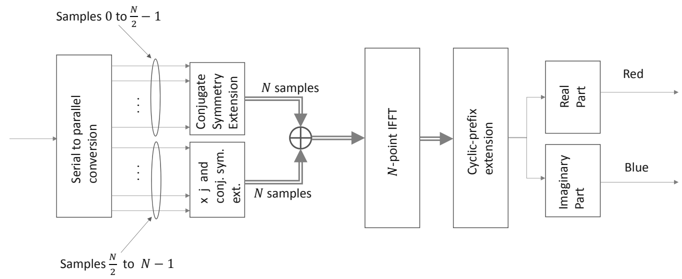

Figure 1: Transmit-side with improved IFFT processing.

2.1.2 Receive-side processing

On the receiver side, let w_k^R and w_k^B respectively represent the $k-th$ received samples from the red-filtered and blue-filtered photodiodes. Construct a new sequence $z_k = w_k^R + jw_k^B$ which is then synchronized, parallelized and followed by cyclic-prefix removal. An N-point FFT is applied to a block of N samples of z_k, generating N frequency-domain samples Z_k. From these, two additional $N/2$ point sequences are generated for $k = 0, 1, \cdots, \frac{N}{2} - 1$ as follows

$$Z_k^R = \frac{1}{2}(Z_k + Z_{N-k}^*) \tag{4}$$

$$Z_k^B = \frac{1}{2}(-jZ_k + jZ_{N-k}^*) \tag{5}$$

with $Z_N = Z_0$. A new set of frequency domain samples is then constructed for $k = 0, 1, \cdots, N$ as follows:

$$Y_k = \begin{cases} Z_k^R & \text{if } 0 \leq k \leq \frac{N}{2} - 1\,, \\ Z_{k-\frac{N}{2}}^B & \text{if } \frac{N}{2} \leq k \leq N-1\,, \end{cases} \tag{6}$$

Figure 2 illustrates the receive-side processing required to implement this system. Note that the receive-side processing requires N additions beyond the standard FFT processing since division by two, and multiplication by j can be done trivially in hardware.

2.2 Analysis IFFT-FFT system

Using this approach and a direct application of DFT properties, it can be shown that symbols $Y_0 \cdots Y_{\frac{N}{2}-1}$ are the received versions of symbols $X_0 \cdots X_{\frac{N}{2}-1}$ when transmitted through the red LED. Similarly, symbols $Y_{\frac{N}{2}} \cdots Y_{N-1}$ are the received versions of symbols $X_{\frac{N}{2}} \cdots Y_{N-1}$ when transmitted through the blue LED. This results in an input-output relationship (assuming timing synchronization and a linear system) as follows

$$Y_k = H_k X_k + V_k \tag{7}$$

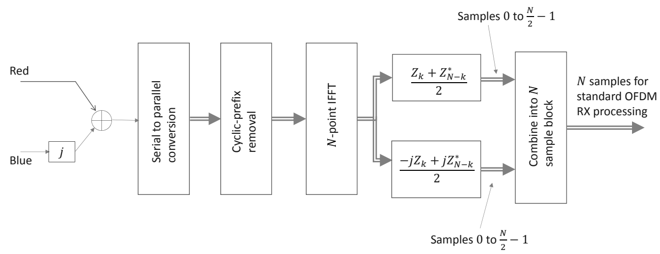

Figure 2: Receive-side with improved FFT processing.

where V_k represents noise and H_k is a channel coefficient representing either the Tx-Rx chain associated with the red or blue LEDs. Hence, standard OFDM channel estimation and equalization procedures can be utilized on Y_k.

In terms of computational complexity, the approach above requires N and $2N$ complex additions in addition to the N-point IFFT/FFTs. In contrast, a straight forward implementation would require 2 N-point FFT computational units. Therefore, this system can enable the use of FFT cores designed for complex RF signals with simple modifications.

3 Impulse Response Shortening

RF wireless channels typically have impulse responses that are shorter than VLC channels. The effective length of impulse responses can play a signficant role in OFDM systems where cyclic-prefixes (CP) which have to be longer than one sample less than the impulse response need to be used. For instance, in 802.11g WiFi systems, 16 samples are used for the CP, with an FFT size of 64. In order to utilize hardware designed for 64 point FFTs with 16 sample cyclic prefixes, in VLC channels which typically have longer impulse responses, we implemented impulse response shortening filters based on an approach designed for Discrete-Multi-Tone (DMT), Asymmetrical Digital Subscriber Line (ADSL) modems [**?**]. The basic idea behind this approach is to apply a channel-shortening filter to the received signal, which is designed to minimize the energy of the cascade of the channel impulse response and the channel-shortening filter outside a window of length equal to the cyclic prefix plus 1. Using this approach, and just a 3-tap filter, we have been able to shorten the channel impulse response of our system in both the red and blue LED channels as illustrated in Figures 3 and 4. In both cases, a greater than 10 dB reduction of the channel impulse response outside a 17 sample window (corresponding to a CP length of 16) was realized.

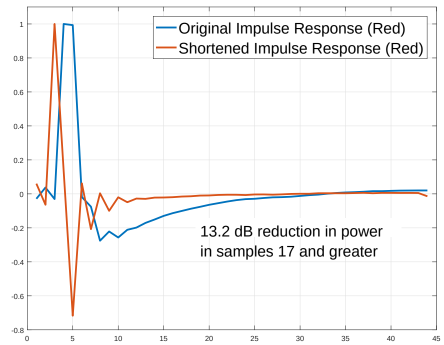

Figure 3: Shortened impulse response for Red Channel.

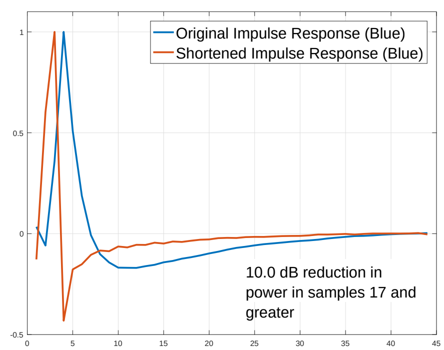

Figure 4: Shortened impulse response for Blue Channel.

4 Experimental Setup and results

Using these two approaches, we implemented a communications system using Universal Software Radio Peripheral (USRP) N200s with LFRX and LFTX daughterboards on the receiver and transmitter respectively. We generated transmit signals and processed received signals offline in MATLAB, which implemented the efficient IFFT/FFT processing, and the impulse response shortening, which we turned off for some experiments. Figure **??** illustrates this system, where we have used the transmitter USRP with power amplifiers and a bias-Ts connected to the red and blue LED array of the luminaire. The bias voltage for the red and blue channles was 21V and 26.75V respectively. On the receive side two avalanche photo-diode modules (APDs) are used with a red and a blue filter. The output of the modules was passed through a DC block to eliminate the DC voltages from the APDs, lowpass filters, and attenuators to reduce the levels of the received signals which are passed into the USRP N200 with the LFRX daughtercard. The specific part numbers for the transmitter and receiver subsystems are shown in Tables 1 and 2 respectively.

In order to match 802.11g implementations, we used a 20MHz sample rate for the system, resulting in a 10MHz bandwidth on each of the blue and red LED channels, effectively achieving 20MHz of useful bandwidth. We implemented a 20MHz sample rate system by utilizing a raw 25MHz sample rate on the hardware and using sample rate conversion in software to obtain an effective 20MHz sample rate. This was done since the USRP hardware does not support a sample rate of 20MHz without significant CIC roll-off due to implementation details of the hardware. The distance between the transmitter and receiver was 1 meter.

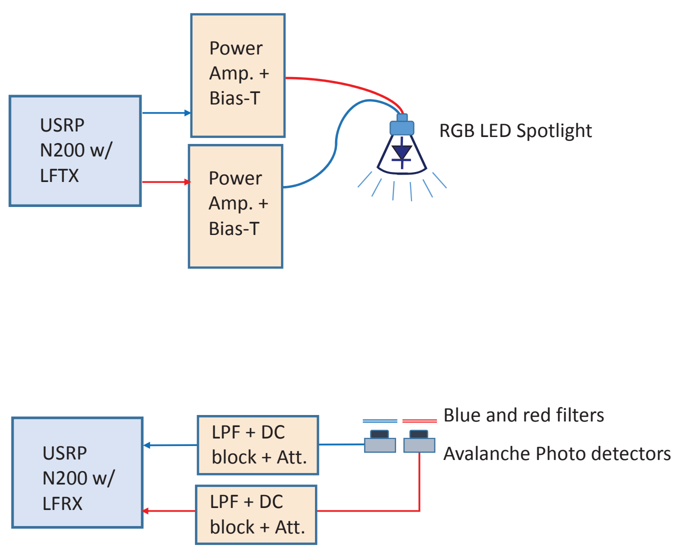

Figure 5: Block Diagram of Experimental System.

Using this approach, we implemented a 90Mbps OFDM system with 64 point IFFTs, and 16 sample cyclic prefixes with 64QAM modulation. The modula-

Base-band processing	USRP N200 with LFTX
DC-Blocks	Minicircuits BLK-89 S+
Power amplifiers	Minicircuits LZY-22+
Bias-Tees	Picosecond Pulse Labs 5575A
Luminaire	ELYSSA 50 Watt RGB LED Floodlight

Table 1: Transmit side hardware components

Base-band and processing	USRP N200 with LFRX
DC-Blocks	Minicircuits BLK-89 S+
Lowpass filters	Minicircuits SLP 10.7+
Attenuator 1 (red channel)	Minicircuits VAT-3+
Attenuator 2 (blue channel)	Minicircuits VAT-6+
APD (Blue channel)	Thorlabs APD130A2
APD (Red channel)	Thorlabs APD410A
Color Filters	Thorlabs FELH0600, FESH0500

Table 2: Receiver side hardware specifications

tion, cyclic-prefix length and the number of subcarriers were selected to match 802.11g OFDM symbol formats. We observed bit-error rate (without Forward Error Correction) of 0.0027. Note that without impulse response shortening, the BER was 0.0037. Thus, this work illustrates how one can reduce the computational complexity of the IFFT/FFT system, and how impulse response shortening can result in a reduction in the BER, using system parameters that are standard for 802.11 WiFi systems.

References

[1] Keith Jones. *The Regularized Fast Hartley Transform.* Springer, 2010.

[2] Peter JW Melsa, Richard C Younce, and Charles E Rohrs. Impulse response shortening for discrete multitone transceivers. *IEEE Transactions on Communications*, 44(12):1662–1672, 1996.