Real-Time OFDM Receiver with Robust Frequency Synchronization for Visible Light Communication

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Abstract: To evaluate the OFDM transmission performance and signal reconstruction error with the digital interpolation-based sampling frequency offset compensation for visible light communication, a real-time OFDM receiver with synchronization is experimentally investigated.
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1. Introduction

Orthogonal frequency division multiplexing (OFDM) can be applied to improve spectral efficiency limited by bandwidth of practical light emitting diodes (LEDs) for visible light communication (VLC) systems [1]. In a practical OFDM-VLC system, sampling frequency offset (SFO) occurs due to mismatch of sampling frequencies between the transmitter and receiver oscillators, which results in phase rotation and severe interference between adjacent OFDM subcarriers (inter-carrier interference, ICI) [2], [3]. Moreover, the LED nonlinearity causes extra spectral components within and beyond the OFDM signal spectrum, which may affect the synchronization performance. Therefore, precise synchronization is required for high level modulation formats in the high-speed OFDM-VLC systems with a high spectral efficiency. In the previous publications, there is rare study about real-time investigation of OFDM synchronization for VLC applications. Most investigations in a real-time system are relevant to digital predistortion waveform shaping [4], [5], equalization [6] and reduction of peak-to-average-power ratio (PAPR) [7]. We proposed a piecewise polynomial interpolator using Farrow structure to digitally compensate SFO between the transmitter and receiver oscillators for VLC systems [8]. Experiment results with offline signal processing show that the proposed scheme can be used to effectively compensate a local oscillator frequency offset up to ±1000 ppm at a minimum oversampling rate of 1.3 in an OFDM-based VLC system. However, the precision and complexity of digital signal processing (DSP) was not considered.

To further investigate the feasibility of the proposed synchronization scheme for practical VLC systems, in this paper, a field-programming-gate-array (FPGA)-based OFDM-VLC receiver incorporating the synchronization function is developed, based on which real-time OFDM transmission is demonstrated over a 6 m VLC link. In the OFDM-VLC receiver, the imperfectly sampled signal is reconstructed in real-time with the piecewise polynomial interpolator for the SFO compensation. The transmission performance with the 2nd/3rd/4th-order interpolator-based synchronization schemes are compared.

2. OFDM-VLC receiver incorporating sampling frequency offset compensation

In a practical OFDM-VLC system, the sampling frequency of the digital-to-analog converter (DAC) at the transmitter, $f_t = 1/T_t$, may not be equal to that of the analog-to-digital converter (ADC) at the receiver, $f_s = 1/T_s = \lambda f_t(1+\eta)$. λ is oversampling rate and η is SFO. To design a practical VLC receiver that mitigates the SFO effect, a block diagram of the real-time OFDM-VLC receiver with the OFDM synchronization is shown in Fig. 1(a). After the ADC, the digitized signal is recovered by DSP including SFO synchronization, fast Fourier transform (FFT) and equalization. The spectral aliasing effect resulted from the LED nonlinearity and SFO can be mitigated by digitally reconstructing the received signal. The theory on the OFDM synchronization with the digital interpolation-based SFO compensation for VLC applications is described in [8]. The digitalized signal from the ADC was reconstructed by a piecewise-polynomial interpolator. The resampled signal $y(nT_i)$ was given below [9]

$$y(nT_i) = \sum_{i=I_1}^{I_2} x[(m_n - i)T_s] \sum_{q=0}^{Q} c_q(i)\mu_n^q = \sum_{q=0}^{Q} \mu_n^q v(q) \tag{1}$$

$$v(q) = \sum_{i=I_1}^{I_2} c_q(i) x[(m_n - i)T_s] \tag{2}$$

where $m_n = int[nT_i/T_s]$, $\mu_n = nT_i/T_s - m_n$. The operator int[x] means the largest integer not exceeding x. $c_q(i)$ is coefficient of the interpolation filter. Here, a fourth-order piecewise polynomial interpolator (Q = 4) using Farrow structure was applied to improve the transmission performance. Therefore, Eq. (1) for Q = 4 can be expressed as

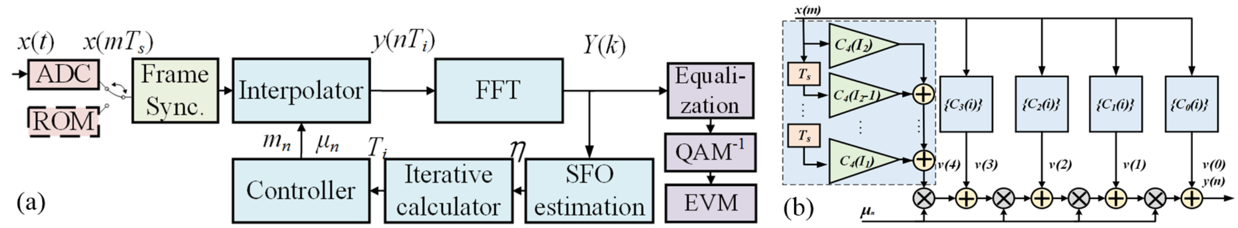

Fig. 1. (a) Block diagram of the designed real-time OFDM-VLC receiver with digital SFO compensation, (b) A fourth-order piecewise polynomial interpolator with Farrow structure

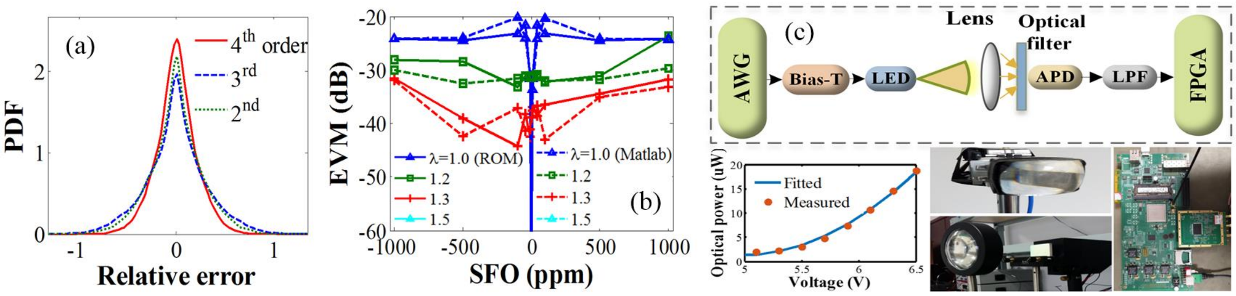

Fig. 2. (a) Experimental setup of the OFDM-VLC system. (b) Comparison in PDF of reconstructed signal errors, (c) EVM comparison between simulation and experiment (ROM). Q = 4, SFO=100ppm.

$$y(nT_i) = \left\{\left[\left(v(4)\mu_n + v(3)\right)\mu_n + v(2)\right]\mu_n + v(1)\right\}\mu_n + v(0) \quad (3)$$

A polynomial interpolator based on the Farrow structure from Eq. (3) is shown in Fig. 1(b). This Farrow structure consists of Q+1 columns of finite impulse response (FIR) transversal filters. Each FIR column has (I_2-I_1+1) taps. As the Farrow structure requires only one variable μ_n for each interpolation, it is suitable for the high-speed interpolation.

3. Experiment results and discussions

With a DSP tool (System Generator from Xilinx) to transform the synchronization algorithm to a hardware design, experimental evaluation of the synchronization performance was first conducted on a single FPGA board. The data of the simulated OFDM signal with an arbitrary SFO was stored in the ROM as the input of the FPGA receiver. Figure 2(a) shows the probability density functions (PDFs) of the relative error of reconstructed signal measured with 14,000 samples when SFO =100 ppm. The relative error is defined as a ratio of difference between the interpolated signal and ideal signal to the root mean square of the ideal signal. The variance of 0.042 for the 4th order interpolator was smaller than that of the 2nd (0.071) and 3rd (0.095) order interpolators. To investigate the impact of SFO on the transmission performance, Fig. 2(b) shows error vector magnitude (EVM) as a function of SFO in simulation and experiment. The EVM performance with the input signal from the ROM in the experiment was almost identical to the numerical result in the simulation (Matlab). This indicates the validity of the DSP design for the OFDM synchronization. For the perfect sampling case when SFO=0 and λ=1, the calculated EVM was less than -50 dB. As the oversampling rate increased beyond 1.3, the EVM was improved to around -40 dB.

After the evaluation of the synchronization in a single FPGA board, a VLC system with the developed real-time receiver was established for experimental investigation of the 16QAM-OFDM transmission performance with the synchronization in Fig. 2(c). Since the motivation of this study was to experimentally investigate the performance of SFO compensation at the OFDM-VLC receiver, an arbitrary waveform generator (AWG) was used as a transmitter for signal generation. The experimental setup of a 6-m VLC system was almost the same as that in [8] except the developed FPGA-based VLC receiver.

For the OFDM synchronization, every 40 OFDM symbols formed a data block for SFO estimation, which was realized with 4 pilot subcarriers in these symbols. A pilot block consisted of 50 OFDM symbols for channel estimation. At the beginning of each frame, a synchronization header of on-off keying (OOK) signal consisting of 128 bits was added for the frame synchronization. The OFDM signal generated offline in Matlab was loaded into the AWG (Tektronix 5014C, 14-bit DAC). The SFO between the transmitter and receiver was introduced by varying the sampling rate of the AWG, whilst the sampling rate of the ADC was fixed at 25 MS/s and 50 MS/s for $\lambda \leqslant 2$ and λ=2,

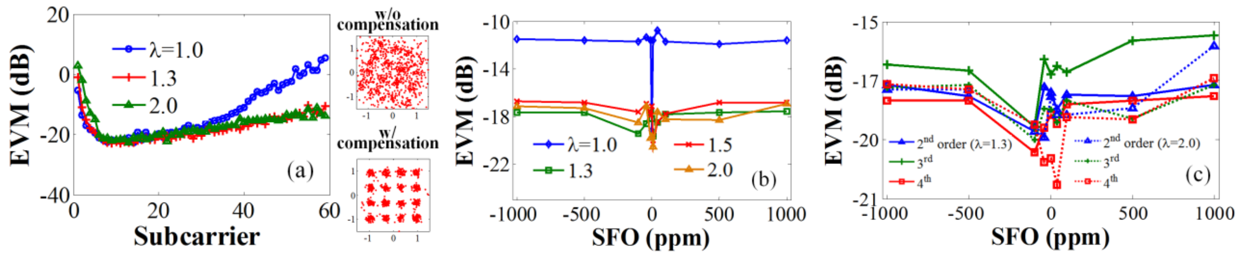

Fig. 3. (a) EVM performance with the 4th order interpolator (SFO=100 ppm), (b) Measured EVM versus SFO (the 4th order interpolator), (c) EVM performance with the 2nd, 3rd and 4th order interpolators.

respectively [8]. Because of discrete values of sampling rates at the transmitter and receiver, the bit rates of the OFDM signal varied from 25.7 to 43.8 Mb/s. The electrical OFDM signal from the AWG was used to drive the LED with a Bias-Tee. According to the measured transfer function ($P-U$ curve) in Fig. 2(c), the bias voltage of the LED was 5.75 V, and the peak-to-peak (PTP) voltage of the driving signal was 0.4 V [10]. At the receiver, a lens with a diameter of 10 cm was placed in front of the avalanche photodiode (APD) to collect light for a high optical gain. The light passing through a blue filter was then detected by the APD. After an electrical LPF, the received signal was sampled by an ADC (14-bit) following by the FPGA for real-time signal recovery.

Figure 3(a) shows EVM performance on each subcarrier using the 4th order interpolator when SFO=100 ppm. The EVM on the low frequency subcarriers (1-6) was relatively high due to the low frequency cut-off effect of the ADC board in the VLC link. These low frequency subcarriers were not used for the data transmission or EVM calculation. After the digital SFO compensation using the 4th order interpolator, the constellation was clear, which proved the effectiveness of the SFO compensation scheme. Figure 3(b) shows the measured EVM at different oversampling rates with the 4th order interpolator. All the EVM values for $\lambda \geqslant 1.3$ were below -16.6 dB, which corresponds to a bit error rate (BER) of 10^{-3} for 16-QAM. The EVM comparison between the 2nd, 3rd and 4th order polynomial interpolators is shown in Fig. 3(c). The EVM with the 4th order interpolator was improved by up to 1 dB compared with the low order interpolator when λ =1.3. As the oversampling rates increases, the EVM difference between the 2nd, 3rd and 4th order interpolators becomes small, which agrees with the theoretical prediction in [8].

4. Conclusion

A real-time OFDM-VLC receiver with a designed digital interpolation-based SFO compensation has been successfully demonstrated in experiment. It has shown that the real-time OFDM transmission performance with the digital synchronization based on a 2nd/3rd/4th-order interpolator is robust to SFO up to ±1000 ppm. A relatively low oversampling rate with a high order interpolator has been observed for the best EVM performance.

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