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Demonstration of 2.97-Gb/s video signal transmissions in DML-based IM-DDO-OFDM systems

Ming Chen [a], Jing He [a,*], Rui Deng [a], Qinghui Chen [a], Jinlong Zhang [b], Lin Chen [a]

[a] Key Laboratory for Micro/Nano Optoelectronic Devices of Ministry of Education, School of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, China
[b] Program & Research Institute of GuangDong Power Grid Corporation, China

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ABSTRACT

To further investigate the feasibility of the digital signal processing (DSP) algorithms (e.g., symbol timing synchronization, channel estimation and equalization, and sampling clock frequency offset (SCFO) estimation and compensation) for real-time optical orthogonal frequency-division multiplexing (OFDM) system, 2.97-Gb/s real-time high-definition video signal parallel transmission is experimentally demonstrated in OFDM-based short-reach intensity-modulated direct-detection (IM-DD) systems. The experimental results show that, in the presence of ~12 ppm SCFO between transmitter and receiver, the adaptively modulated OFDM signal transmission over 20 km standard single-mode fiber with an error bit rate less than 1×10^{-9} can be achieved by using only DSP-based small SCFO estimation and compensation method without utilizing forward error correction technique. To the best of our knowledge, for the first time, we successfully demonstrate that the video signal at a bit rate in excess of 1-Gb/s transmission in a simple real-valued inverse fast Fourier transform and fast Fourier transform based IM-DD optical OFDM system employing a directly modulated laser.

1. Introduction

In the past few years, optical OFDM has been extensively studied by using offline [1–7] and real-time digital signal processing (DSP) approaches [8–13]. Compared with coherent optical OFDM (CO-OFDM), direct-detection optical OFDM (DDO-OFDM) has a low complexity. In [4], the OFDM signal is linearly directly encoded in an optical field by an external modulator, and a single optical sideband spaced from the carrier by a frequency gap is performed to avoid power fading caused by chromatic dispersion in long-haul links, and signal-to-signal beating interference (SSBI) due to the square-law photo-detection. Meanwhile, the directly modulated laser (DML)-based real-time intensity-modulated DDO-OFDM has also been investigated in short-reach application scenarios for cost-effective implementations [9]. Different from off-line DSP approaches, some important features such as computational precision and speed requirements for practical DSP hardware implementations should be considered for real-time optical OFDM.

Among the real-time works, the transmission performance is mainly studied by transmitting pseudo-random binary sequence (PRBS) at OFDM transmitters. In addition, real-time application data such as multimedia services can be used to further verify the feasibility of the designed systems. In [14], 1-Gb/s multimedia service upstream transmission based on complex-valued inverse fast Fourier transform/fast Fourier transform (IFFT/FFT) and digital domain up/down-conversion was experimentally demonstrated in real-time direct-detection OFDM-PON. The real-time system based on the digital domain up/down-conversion can cut off the cost of in-phase and quadrature (IQ) radio frequency mixers in the transceiver. Compared to most of real-valued IFFT/FFT DDO-OFDM transmission systems [8–11,15–17], it can also improve the spectral efficiency (SE) of system. However, it requires DACs/ADCs with higher sample rate, and has higher hardware implementation complexity due to digital domain up/down-conversion and digital carrier frequency offset. In contrast, the real-valued IFFT/FFT-based DDO-OFDM systems have a low hardware implementation and without carrier frequency offset problem. So it may be more suitable for the cost-effective optical access networks and some short-reach systems such as data centers.

In our previous works [15–17], we have reported several real-valued IFFT/FFT-based real-time DDO-OFDM systems, and experimentally investigated some key DSP algorithms in direct-detection systems. A pilot-aided SCFO estimation and compensation incorporating with sampling clock synchronization technique has been studied in our previous works [15,16]. Besides, only sampling clock synchronization enabled optical OFDM was also

* Corresponding author.
E-mail addresses: hnu_jhe@hotmail.com (J. He), liliuchen12@vip.163.com (L. Chen).

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experimentally demonstrated in short-reach passive optical network (PON) [17]. In these systems, the sampling clock for the receiver is synchronized with the transmitter clock according the estimated SCFOs in the initial stage of establishing a connection between transmitter and receiver. Usually, a voltage controller oscillator (VCO) may be required to achieve this synchronization. In this work, to reduce system cost and then achieve a more cost-effective PON system, only the DSP-based SCFO estimation and compensation method described in [15], but without sampling clock synchronization, is employed into the real-time OFDM systems under the presence of small SCFO. The power penalty and BER stability of the only SCFO estimation and compensation enabled real-time OFDM signals are experimentally investigated in a DML-based IM-DD system. Moreover, to further investigate the feasibility of the DSP-based algorithms for real-time optical OFDM, parallel transmission of 2.97 Gb/s high-definition (HD) video signal over such link without using FEC technique is also experimentally demonstrated by utilizing the effective symbol timing synchronization, channel equalization and only DSP-based small SCFO estimation and compensation techniques.

2. Experimental setup

The experimental setup of real-time end-to-end optical OFDM transmission systems is depicted in Fig. 1. Link performance of the physical layer is assessed by real-time measured BER values. In the real-time measurement, the input bit stream is a PRBS with a length of $2^{16}-1$. The PRBS is generated by Matlab program and stored in the read only memory (ROM) of field programmable gate array (FPGA). For high-definition video demonstration, the 1080p HD video signal is generated by a lap-top with a high-definition media interface (HDMI), and then the signal is converted to 2.97 Gb/s 3G-SDI non-return-zero (NRZ) encoded serial signal. A cable equalizer (CE) is used to equalize data transmitted over coaxial cable, and it outputs a differential signal for Xilinx GTX high-speed interface at the FPGA of the transmitter. The GTX is configured for receiving the 3G-SDI signal. Then it sends the recovered parallel data to Rx Data Buffer as shown in Fig. 1. In this case, the input data stream is provided by the Rx Data Buffer. The type of input data for the digital OFDM transmitter can be chosen by monitoring an external control signal.

In the digital OFDM transceiver, most of DSP algorithms can be found in our previous works [15–17]. The DSP algorithms for transmitter and receiver are implemented on Virtex-6 and Virtex-7 FPGA evaluation boards, respectively. Here, we only introduce some key parameters and DSP flow in the digital OFDM transceiver. Firstly, the 180-bit parallel data provided by Rx Data Buffer or PRBS pattern is mapped to 40 16QAM and 10 QPSK symbols. To combat power fading on the high-frequency sub-carriers (SCs), 40 16QAM symbols are modulated on 40 low-frequency sub-carriers; while the 10 high-frequency SCs are modulated with QPSK symbols. Then 4 pilot BPSK-encoded SCs (SC indices are 11, 22, 33, and 44) are used to realize sampling clock frequency offset estimation and compensation in the receiver. In addition, the DC SC (SC index is 0) and Nyquist SC (SC index is 64) are filled with zeros. Other 9 SCs at the edge of the spectrum (SC indices from 55 to 63) are set to zeros to relax the anti-aliasing filter requirements. In order to obtain a real-valued signal at the output of the 128-point IFFT module, all of the modulated data on the negative SCs (SC indices from −1 to −63) are the complex conjugates of the 63 corresponding positive-frequency SCs. After IFFT process, the real outputs are clipped at a digital clipping ratio of 12.5 dB, and then scaled to obtain the negligible clipping noise and quantization noise. A 16-sample long cyclic prefix (CP) is inserted at the beginning of every OFDM symbol. Subsequently, the signal is fed into a 14-bit resolution DAC operating at 2.5 GS/s.

An OFDM frame consists of one training sequence (TS) with a length of 144 samples and 256 data-carrying OFDM symbols. So the OFDM frame duration is $257 * 144 * 0.4\ \text{ns} \approx 14.8\ \mu\text{s}$, the net bit rate can be up to $180 * 256/(257 * 144 * 0.4)\ \text{Gb/s} \approx 3.11\ \text{Gb/s}$, and the bandwidth of the generated OFDM signal is only $54/64 * 1.25\ \text{GHz} \approx 1.05\ \text{GHz}$. Therefore, the real-time system can be implemented to transmit 2.97 Gb/s HD video using a narrow-band OFDM signal. With the help of the TS, both the symbol timing synchronization and channel estimation will be done in the receiver.

The DAC outputs analog signal with a peak-to-peak voltage (Vpp) of ∼700 mV is firstly amplified up to ∼1.7 Vpp by a variable electrical amplifier (VEA). Then the cost-efficient DFB-DML is driven by the amplified base-band OFDM signal, and outputs double-side-band optical OFDM signal. The center wavelength and optical power of the output signal are 1549.9 nm and −0.9 dBm, respectively. Without optical amplification, the optical signal is directly coupled into 20 km SSMF. The chromatic dispersion and attenuation of the SSMF are 17 ps/nm/km and 0.19 dB/km, respectively. At the receiver, in order to measure BER performance at different received optical powers (ROPs), the received signals are attenuated by a variable optical attenuator (VOA). A PIN photo-diode is utilized to recover the base-band OFDM signal, and then a 3 dB bandwidth of 1.1 GHz low-pass filter (LPF) is used to avoid aliasing. The high-speed serial samples are fed to the FPGA of the receiver by a 10-bit resolution ADC operating at 2.5 GS/s.

After the symbol timing synchronization, 16-sample CP is removed and 128-point FFT is performed. The next DSP flows consist of TS-based channel estimation, one-tap frequency-domain equalization and sampling clock frequency offset (SCFO) estimation and compensation. After SCFO compensation, 16/4

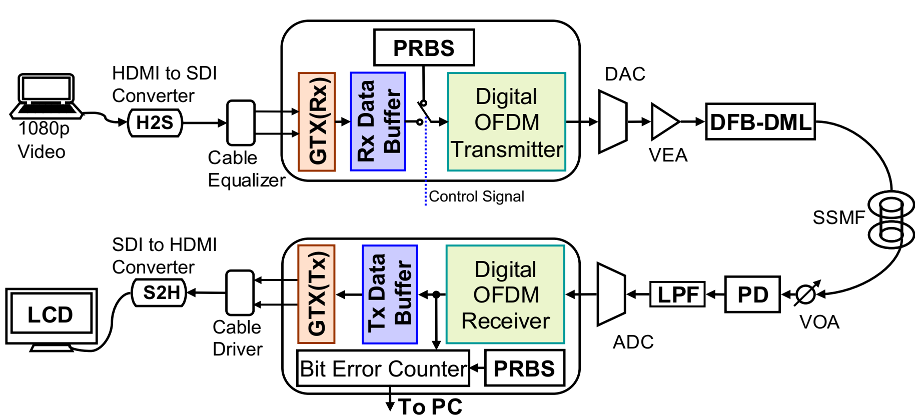

Fig. 1. Experimental setup of real-time end-to-end optical OFDM transmission systems.