Required Resolution of Digital-Analog-Converter for Optical OFDM

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Abstract: The required resolution of digital-analog-converter for optical OFDM was evaluated through simulation and experiment. Signal degradation caused by quantization was independent of subcarrier modulation, and the performance improvement saturates with increasing bit resolution.

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1. Introduction

In order to satisfy the demand for a further increase of data traffic in optical networks, a higher spectral efficiency is indispensable. Orthogonal frequency division multiplexing (OFDM) has attracted attention as a promising technology for high capacity wavelength-division-multiplexed (WDM) optical communication systems due to its inherently low linear crosstalk and higher dispersion tolerance utilizing many subcarriers with lower symbol rate [1-8]. Typically these subcarriers are generated by fast-Fourier transform (FFT) [1-4,6-8], in conjunction with digital-analog-converter (DAC) in order to convert the OFDM symbols to analog waveforms in time domain. A fine resolution of DAC is desirable to be able to closely match the ideal waveform. However, the effective bit resolution of practically available high-sampling-rate DACs is limited. Furthermore, the resolution is limited by the digital signal processing (DSP) capability of the transmitter. Therefore it is important to evaluate the resolution dependency of OFDM signal quality. To date, there are a few reports on a numerical simulation with QPSK and 16-QAM subcarrier modulation [6-7] and an experiment with QPSK [7]. In these studies, it was concluded that 3.4-bit and 5-bit effective resolutions were enough for QPSK and 16-QAM, respectively [6-7]. However, to the best knowledge of the authors, the dependence of required bit resolution on different subcarrier modulations was not evaluated experimentally.

In this paper, we numerically and experimentally evaluated the required DAC resolution for optical OFDM with various kinds of subcarrier modulations. It was confirmed that the signal degradation caused by a quantization is independent of the subcarrier modulation, and the performance improvement by using higher resolution is saturated.

2. Concept of resolution-dependent OFDM signal

Figure 1a shows the concept of waveform distortion of OFDM baseband signal when the resolution is limited. OFDM signal inherently has a higher peak-to-average power ratio, therefore an amplitude clipping is usually required [7]. After that, the analog waveform is rounded to the nearest resolution step of DAC-output during generation of OFDM signal, adding quantization error. Figure 1b shows an example of OFDM waveform distortion DAC resolutions of 3, 4 and 6 bits. The difference from the clipped signal becomes larger as the number of bits for

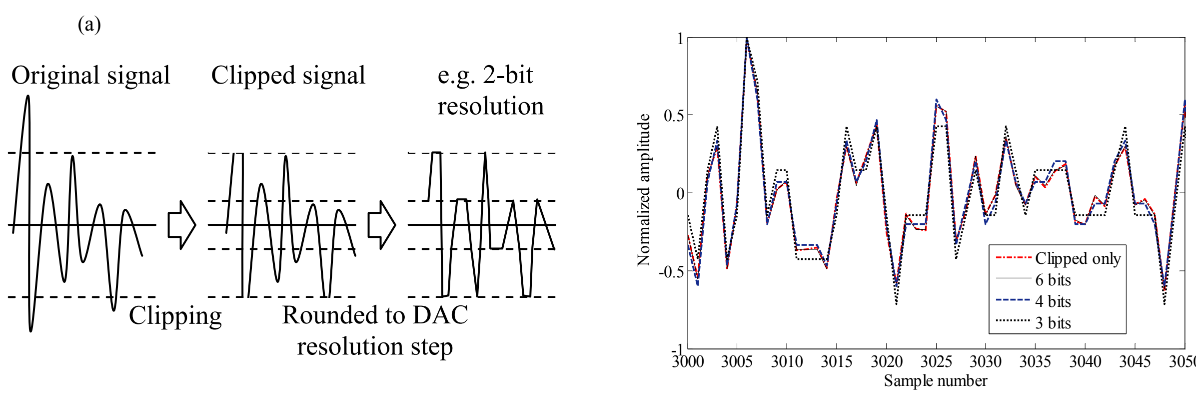

Figure 1: a) Concept of waveform generation regarding clipping and DAC resolution, b) Example of baseband OFDM waveform scaled to different values of DAC resolution.

DAC resolution decreases. The difference gives quantization noise which causes a degradation of the energy per symbol to noise power density ratio (Es/No). The Es/No is expressed by:

$$E_s / N_o = (P - N)/ N * (B / f_s) \quad (1)$$

where P is the total of signal and noise power, N is the total noise power, B is the bandwidth of the signal, and fs is the symbol rate. The Es/No and the constellation size of subcarrier modulation determine bit-error-rate (BER).

3. Experimental setup

We conducted simulation and experiment to evaluate the degradation of Es/No caused by quantization for different number of DAC resolution bits. The parameters for Tx and Rx of the simulation are same as the experimental setup as explained below. Figure 2a shows the experimental setup. In this experiment, an external cavity laser (ECL) with the linewidth of ~100 kHz is used for carrier lightwave at Tx. An optical IQ modulator is used to modulate the carrier lightwave with the in-phase (I) and quadrature (Q) components of the OFDM baseband signal. The OFDM baseband waveforms produced by an arbitrary waveform generators (AWG) with a sampling rate of 10GSample/s are calculated offline and outputted continuously. The DACs in the AWG have 10-bit resolution physically, therefore the resolution of less than 10 bits can be emulated by the offline calculation. Note that effective number of bits (ENOB) is estimated to be 7.0 bits. The clipping ratio is set to 8 dB. At the outputs of the AWGs, electrical low-pass filters (LPF) with a cut-off frequency of 5 GHz are used to suppress image-band products that are generated by the DACs in the AWG. The FFT size is 1024 from which 668 subcarriers carries data. The subcarriers are modulated with QPSK, 8-QAM, 16-QAM and 32-QAM. The cyclic prefix length is 20 samples (2.0 ns) per OFDM symbol, therefore a symbol rate becomes 9.57 MHz. Two consecutive training symbols are inserted every 47 OFDM symbols. The bit-rate before coding is 32.5 Gbit/s with 32-QAM subcarrier modulation. The spectra of optical OFDM signals with different resolutions are shown in Fig. 2b. The power of side-lobes increases with the lower number of bits for resolution. The optical signal-to-noise-ratio (OSNR) measured by an optical spectral analyzer is 34.5 dB/ 0.1nm.

At the receiver, the state of polarization of signal is adjusted by a polarization controller (PC). The signal is filtered with a 12.5-GHz FWHM optical bandpass filter (OBPF). After the OBPF, the signal is mixed with lightwave from a local oscillator (LO) in a 90 degrees optical hybrid. An ECL with ~100-kHz linewidth is used as a LO and two single-ended 20-GHz PIN/TIA PD modules are employed for a detection. A real-time digital storage oscilloscope with 16-GHz bandwidth and 50-GSample/s sampling speed is used to sample the two outputs from the optical hybrid. The sampled data is post-processed offline. We assume sufficiently large number of effective bits at the receiver, as the goal of the paper is to focus on the transmitter.

The signal is extracted electronically by a digital filter. RF-aided phase noise compensation is employed to compensate for the phase noise of the local oscillator [8]. For all reported BERs, over 1 Mbits of data are evaluated.

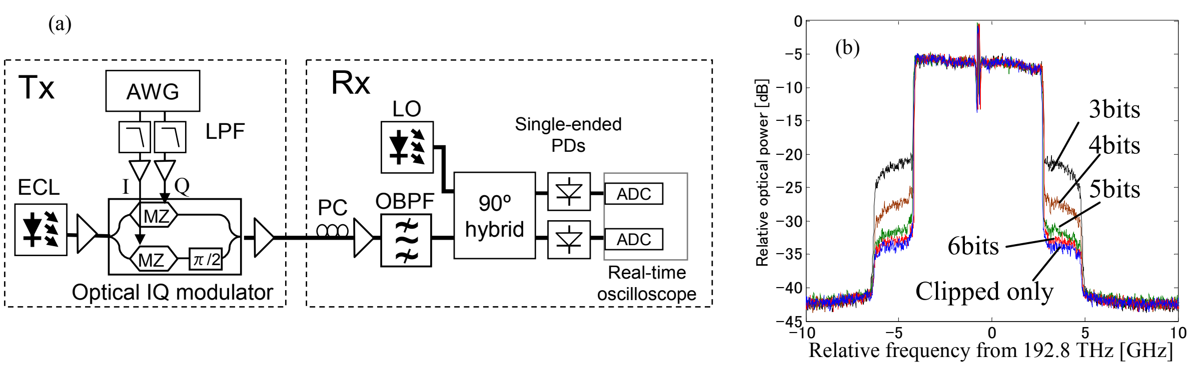

Figure 2: a) Experimental setup, b) Optical spectra of OFDM signal with different number of bits for DAC resolution.

4. Results in experiment and simulation

Figure 3a shows the experimental and simulated results of the relationships between the DAC resolution and Es/No for different subcarrier modulations. The symbol rate and the number of subcarriers are constant for all subcarrier modulations as 9.57 MHz and 668, respectively. The simulated and experimental results show that the performances of all subcarrier modulations are similar. It means that the performance degradation due to quantization noise is independent of the subcarrier modulation with OFDM parameters used. Some difference in the obtained Es/No is observed between the simulation and experiment, which seems to be caused by some noise factors ignored in the simulation.

Figure 3b shows the simulated and experimental results of Es/No as a function of DAC for 32-QAM. In this case, a bit rate before coding is 32.5Gbit/s. The open-marker and solid-marker show the simulated and experimental results. To emulate the additional noise in electrical/optical domain, the white Gaussian noise, N_{add}, for the N of Eq. (1) is included in the simulation. The ratio between the P in Eq. (1) and the added noise N_{add} is shown in Fig.3b expressed as P/N_{add} [dB]. The value of P/N_{add} is changed from 14 to 38 dB in 2dB step as a parameter. As lower value of the P/N_{add}, the value of Es/No degrades and become insensitive to the bits for resolution at around 7 bits. To determine the minimum required bits for resolution, a criterion is set for the Es/No which gives a bit-error-rate (BER) of $1\text{x}10^{-3}$. The line which corresponds to BER of $1\text{x}10^{-3}$ are also shown in Fig. 3b. For 32-QAM, approximately 20 dB of Es/No is required for BER of $1\text{x}10^{-3}$. With this criterion, 5 bits for resolution with over 24 dB of P/N_{add} is required. When the P/N_{add} decreases to 22 dB, the resolution must be higher than 6 bits. The experimental result shows that BER of less than$1\text{x}10^{-3}$ is practically achievable with 6 bits resolution for 32-QAM.

These simulation results are also applicable for other subcarrier modulations because of the independency of subcarrier modulation in Fig. 3a. The lines for BER of $1\text{x}10^{-3}$ for QPSK, 8-QAM and 16-QAM are also shown in Fig. 3b. From the simulation results, the required bits for resolution to obtain BER of less than $1\text{x}10^{-3}$ are 3 bits for QPSK with 18 dB of P/N_{add}, 4 bits for 8-QAM with 22 dB of P/N_{add}, and 5 bits for 16-QAM with 20 dB of P/N_{add}, respectively.

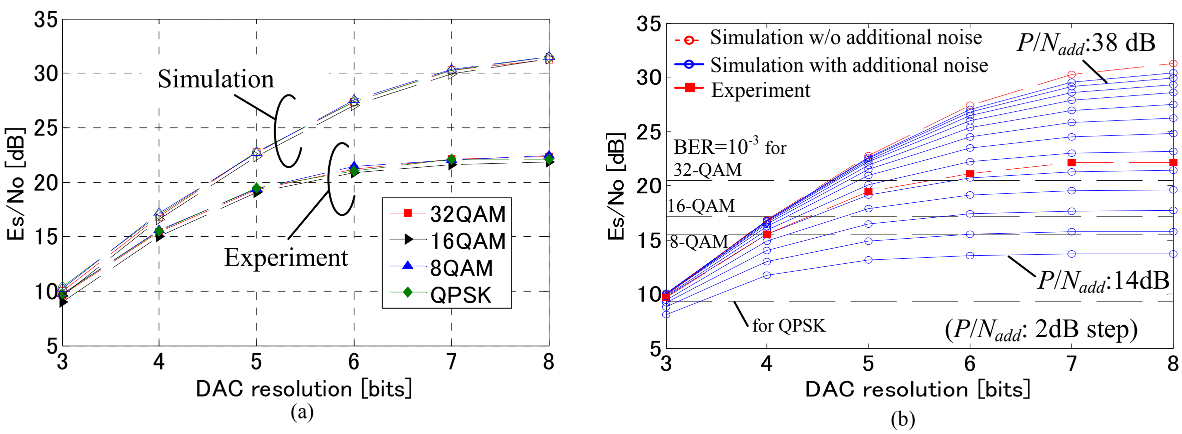

Figure 3: Simulated and Experimental results of the Es/No as a function of DAC resolution, a) keeping symbol rate and the number of subcarriers as 9.57 MHz and 668, b) keeping bit rate before coding as 32.5Gbit/s with 32 QAM.

5. Conclusion

The required resolution of a digital-analog-converter for optical coherent OFDM was evaluated by simulation and experiment. We found that Es/No degradation caused by the quantization is independent of subcarrier modulation, and the improvement using higher resolution is tend to saturate around 7 bits. With the criteria for the BER of $1\text{x}10^{-3}$, the required DAC resolution is 3 bits for QPSK, 4 bits for 8-QAM and 5 bits for 16-QAM and 32-QAM.

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