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Complexity-reduction for the Digital-filtered AWGR-based 2D IR Beam-steered OWC System by using Non-integer Oversampling

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Abstract *Digital Nyquist filtering improves the capacity of our 12.5-GHz channel-spaced 6-GHz bandwidth-limited AWGR-based 2D infrared beam-steered OWC system but introduces additional complexity. Experiments demonstrate the practicability of non-integer oversampling at 1.1× symbol rate with root-raised-cosine filtering to reduce data converter sampling rate and power consumption.*

Introduction

Beam-steered infrared (IR) optical wireless communication (OWC) employing narrow IR beams is a promising solution to solve the current radio spectrum congestion problem[1]. The license-free IR spectrum brings a huge amount of bandwidth intrinsically, and the steered free-space narrow IR beams offer non-shared connections only to users where and when needed which brings better privacy protection and exclusive high capacity for individual user without congestion. A cost- and power-efficient wavelength-controlled two-dimension (2D) IR beam-steered system using a passive high port-count arrayed waveguide grating router (AWGR) has been proposed and experimentally demonstrated[2]. In this system, beam-steering is realized by just tuning the wavelength of each beam remotely. Each beam can carry more than 20-Gb/s capacity by using 4-level pulse amplitude modulation (PAM4)[3],[4]. However, the channel capacity per beam is compromised with the spatial resolution of the AWGR-based beam-steering. A higher spatial resolution requires a higher port-count AWGR which features a smaller AWGR channel spacing for a limited spectral range. The smaller channel spacing causes inter-channel crosstalk and requires spectral guard bands for crosstalk mitigation, leading to a shrunk channel bandwidth, thus a smaller channel capacity. To address this problem, we make use of the digital Nyquist pulse shaping to squeeze the signal bandwidth for scaling up the capacity of the AWGR-based 2D IR beam-steered system with a high spatial resolution[5].

However, the employment of Nyquist pulse shaping increases the implementation complexity. For example, 2× the symbol rate is required for generating Nyquist pulse-shaped signals, which doubles the required data converter sampling rate. Unfortunately, high-speed data converters with a high sampling rate above 10 GS/s are complex and costly. Taking advantage of the III-V technologies, sampling rates of tens of GS/s are attainable[6]. However, sophisticated high-speed interfaces are required since digital signal processing is normally implemented in Complementary Metal Oxide Semiconductor (CMOS) technology. CMOS data converters can benefit from the advanced process technology nodes and ride Moore's Law to higher speeds[7]. However, the data converters fabricated in advanced technology are extremely costly and the resolution is compromised which will decrease the precision of the digital Nyquist pulse-shaped signals. By utilizing parallel approaches such as time-interleaving techniques, CMOS data converters with sampling rates approaching or above 100 GS/s come within reach[8],[9]. However, complex calibration is required to compensate for the mismatch between the parallel sub-channels.

In this work, we propose to use a non-integer oversampling method[10],[11] to lower the sampling rate requirement of data converters, reducing the implementation complexity and power consumption of our digital Nyquist filtered AWGR-based 2D IR beam-steered OWC system. We experimentally investigated the performance impact of using the non-integer oversampling approach in our 12.5-GHz channel-spaced 6-GHz bandwidth-limited AWGR-based 1.1-m OWC link with 20-Gb/s capacity and PAM4 format for the first time. The oversampling rate is minimized to 1.1× the symbol rate with an 11-GS/s digital-to-analog converter (DAC) sampling rate. Compared

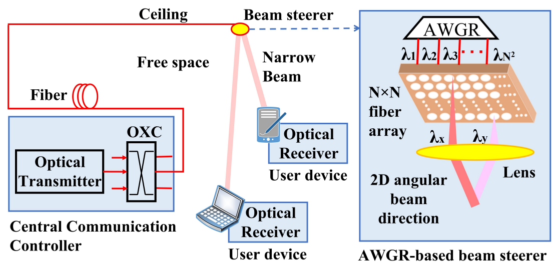

Fig. 1: Regular system architecture of the indoor AWGR-based 2D IR beam steering down-link.

to the 2× oversampling, the required DAC sampling rate is relaxed by 55%, with the cost of a 2.3-dB power penalty at the 7% FEC limit of 1×10^{-3}.

AWGR-based 2D IR beam-steered system

Fig. 1 shows the simplified indoor AWGR-based 2D IR beam-steered system. In this system, beam-steering is realized by just tuning the wavelength of each beam remotely in the Central Communication Controller (CCC). Intensity modulation direct detection (IM/DD) is used in these cost-sensitive indoor networks. The transmitted signal is modulated onto the optical carrier with the optical transmitter, then switched and fed to the desired beam-steerer through an optical cross-connect (OXC) and fibers. The AWGR-based beam steerers are mounted on the ceiling. The signal is λ-split after the filtering at the AWGR. The output ports of the AWGR are regrouped into a 2D fiber array and this fiber array is placed in the focal plane of a lens. The position of the fiber in the focal plane of the lens determines the angular direction of the collimated beam after the lens. Thus, each wavelength which fits on the grid of the AWGR maps to a specific 2D angular beam direction for an individual user device. To cover the user devices anywhere in the room, a high spatial resolution of the beam-steering is needed, resulting in the requirement of AWGRs with dense grids. AWGRs with dense grids feature smaller bandwidth and smaller channel spacing for a limited spectrum, leading to a compromised channel capacity and inter-channel crosstalk. To efficiently make use of the spectrum for channel capacity improvement and to avoid inter-channel crosstalk between the dense adjacent channels of steered beams, the transmitted signal is squeezed for a narrow spectrum occupation by using digital Nyquist filtering.

Minimizing the sampling rate requirement

Nyquist pulse-shaped signals offer an optimum spectral efficiency close to a theoretical limit and feature a high out-of-band suppression. The signal bandwidth can be halved theoretically and exhibits a rectangular spectrum by using ideal Nyquist filters. However, the abrupt transition of the rectangular spectrum results in long pulse tails in the time domain, and ideal "brick wall" filters with infinite filter length are non-realizable. A widely-used Nyquist filter is the root-raised-cosine (RRC) filter pair which features a smoother roll-off shaped spectrum. The signal bandwidth with RRC pulse shape depends on the roll-off factor, β. The stopband frequency of the RRC filtered signal (signal bandwidth) is $0.5(1+\beta)R_S$, where R_S is the symbol rate and β ranges from 0 to 1.

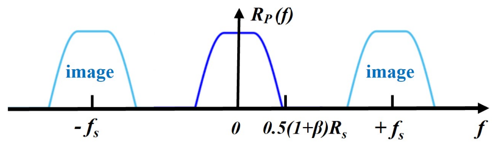

Fig. 2: Electrical spectra of the transmitted RRC pulse-shaped signal with oversampling/interpolation.

According to the Nyquist sampling theorem, the minimum sampling rate is 2× the signal bandwidth, which is $(1+\beta)R_S$ for RRC filtered signals theoretically. As shown in Fig. 2, the signal spectra measured at the DAC outputs contain both the spectrum of interest and the so-called image spectra that repeat infinitely for an ideal DAC. The image spectra can be removed by low-pass filters. To sample at the symbol rate would call for non-realizable "brick wall" filters, thus oversampling is required. To avoid aliasing between the spectrum of interest and the image spectra, the minimum sampling rate is $(1+\beta)R_S$. Thus, the oversampling factor q which is defined by f_S/R_S can be minimized to $1+\beta$, where f_S is the sampling rate.

Experimental setup and results

The experimental setup is presented in Fig. 3. A Gaussian-shaped commercial AWGR[12] featured 6-GHz 3-dB bandwidth and 12.5-GHz channel spacing is adopted in this experimental demonstration. The inset shows part of the AWGR response (Ch6 - Ch10). Multiple optical carriers of various wavelengths (1549.3 nm - 1550.8 nm) can be fed to the AWGR, and the optical carrier with a wavelength fitting the corresponding AWGR channel will be received. Here, the AWGR channel labeled as Ch8 is investigated and the optical carrier is set at the center of the Ch8 (1550.02 nm) using a tunable laser. Due to the hardware limitation in the lab, we make use of an arbitrary waveform generator (AWG, Tektronix, AWG7122B) as the DAC and take a digital phosphor oscilloscope (DPO, Tektronix,

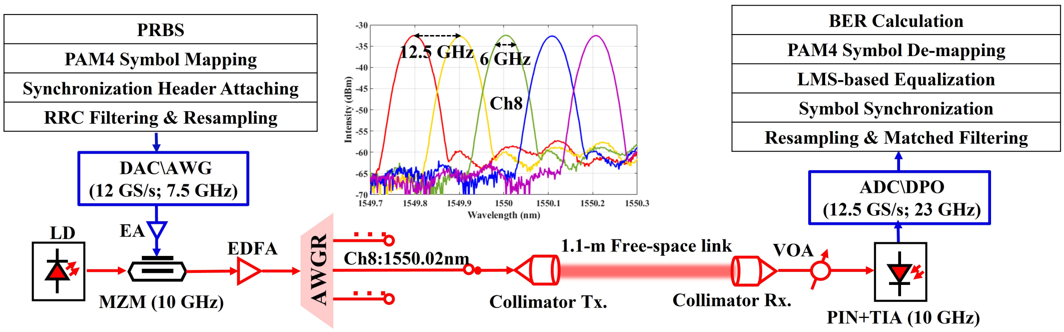

Fig. 3: Experimental setup.

DPO72304DX) to act as the analog-to-digital converter (ADC). The PAM4 signal is used in this experimental demonstration. On the digital transmitter side, the Pseudo-Random Binary Sequence (PRBS) is firstly mapped on the PAM4 symbols. After attaching the synchronization header, the PAM4 symbol stream is pulse shaped by the RRC filter with a length of 21 taps and a roll-off factor of 0.1. Then the filtered PAM4 signal is resampled and uploaded to the AWG featuring a maximum sampling rate of 12 GS/s, 7.5-GHz output bandwidth, and 10-bit resolution. The PAM4 signal generated by the AWG is amplified by an electrical amplifier (EA), and modulated onto the optical carrier via a 10-GHz Mach-Zehnder modulator (MZM). After amplified by an Erbium-Doped fiber amplifier (EDFA) and filtered by the AWGR, the λ-split signal is transmitted and received over a 1.1-m free-space link (about 3.5-dB loss) via a pair of collimators (Thorlabs TC18FC and Thorlabs F810APC-1550). The received signal is detected by a commercial photo-detector which includes a 10-GHz pin-photodiode (PIN) and a trans-impedance amplifier (TIA). And a variable optical attenuator (VOA) is used for adjusting the received optical power, for performance measurements. The detected signal is sampled by the 23-GHz DPO at 12.5 GS/s and post-processed digitally. The digital signal processing at the receiver side mainly contains resampling, RRC matched filtering, symbol synchronization, least mean square (LMS)-based equalization, PAM4 symbol de-mapping, and BER calculation.

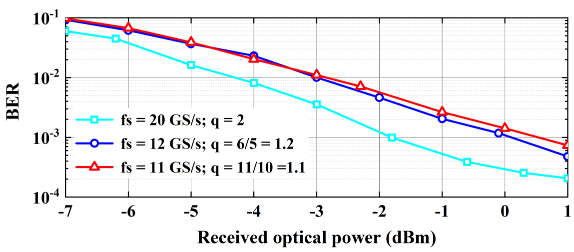

Fig. 4: Measured BER versus received optical power curves with different DAC sampling rates (f_s) for a transmission symbol rate of 10 GBaud.

The BER curves across the received optical power are measured for the system performance evaluation. We have firstly verified the feasibility of non-integer oversampling with an oversampling factor of 1.1 and 1.2 for the 10 GBaud Nyquist PAM4 signal transmission when the AWG operates at 11 GS/s and 12 GS/s. As depicted in Fig. 4 (triangle and circle), the receiver sensitivity is 0.5 dBm (1.1×) and 0.2 dBm (1.2×) at the 7% FEC limit of 1×10^{-3}, respectively. By using the interleaving option which enables a AWG sampling rate of 20 GS/s, we also measure the BER performance of the 2× oversampling for the 10-GBaud Nyquist PAM4 signal transmission, as shown in Fig. 4 (square). A 25-GS/s DPO sampling rate is required when the AWG operates at 20 GS/s. The 25-GS/s DPO sampling rate results in higher noise suppression, thus better BER performance. Compared to the 2× oversampling, a 2.3-dB power penalty is observed for the 1.1× oversampling at the 7% FEC limit of 1×10^{-3}, which is the cost of complexity reduction.

Conclusion

Digital Nyquist filtering benefits the capacity improvement of our AWGR-based 2D IR beam-steered OWC system with high spatial resolution, but introduces additional hardware implementation complexity. We have proposed to use a non-integer oversampling method to lower the required sampling rate, relaxing the requirement of complex and costly high-speed data converters, and reduce the power consumption. We have experimentally verified and investigated the performance impact of the non-integer oversampling in a 12.5-GHz channel-spaced 6-GHz bandwidth-limited AWGR-based 1.1-m OWC link with a 20-Gb/s capacity. The oversampling rate is minimized to 1.1× the symbol rate with a DAC sampling rate of 11 GS/s. The DAC sampling rate requirement is relaxed by 55%, with a cost of a 2.3-dB power penalty at the 7% FEC limit of 1×10^{-3} in comparison to the 2× oversampling system.

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