120 Gbaud IM/DD PAM-4 Transmission over 1.5 km SMF Using a Single CMOS DAC with <20 GHz Analog Bandwidth

Qian Hu, Karsten Schuh, Robert Borkowski, Fred Buchali, Henning Bülow

Nokia Bell Labs, Lorenzstr. 10, 70435 Stuttgart, Germany, qian.hu@nokia-bell-labs.com

Abstract *We experimentally demonstrate 1.5-km C-band transmission of 120-Gbaud (240-Gbit/s) PAM-4 signal using DAC/ADCs with bandwidths compatible with CMOS technology. This ultrahigh symbol rate is enabled by a combination of a precoder and a bandwidth-constraining filter at the transmitter and a 1-to-4 analog demultiplexing frontend at the receiver.*

Introduction

In short reach applications, operating at high serial interface rates is desirable in order to reduce transceiver footprint, power consumption and cost. PAM-4 transmission at a high line rate exceeding 200 Gbit/s/lane, is targeted for next-generation datacenter applications. Nonetheless, achieving ultrahigh symbol rates (> 100 Gbaud) is challenging due to a large analog bandwidth required. State-of-the-art digital-to-analog (DAC) converters based on a complementary metal-oxide-semiconductor (CMOS) technology exhibit limited analog bandwidth despite their high sampling rate achieved by interleaving. Digital pre-emphasis filter can be applied at the transmitter to overcome this bandwidth limitation, which however leads to a significant reduction of the effective DAC resolution and output swing, in turn degrading optical signal quality due to increased quantization noise and poor extinction ratio. To circumvent transmitter bandwidth limitation, few approaches were proposed to achieve ultrahigh symbol rates using either spectral sub-band interleaving[1],[2] or time interleaving[3]. Both approaches require either more than one optical modulator to perform optical spectrum stitching[1], or multiple DAC outputs to be multiplexed in time or frequency domain[2],[3], significantly increasing the transmitter complexity. Silicon-germanium (SiGe) or BiCMOS technology can be used to increase the DAC analog bandwidth[4]. However, practical applications are prevented by high cost and power consumption required by these devices. On the other hand, CMOS technology is widely accepted and well-proven in the industry, and hence generation of ultrahigh symbol rate signals directly from a single CMOS DAC is desirable. The previous record for CMOS DAC was 105 Gbaud employing a probabilistically-shaped quadrature amplitude modulation format[5].

In this paper we further increase the symbol rate to 120 Gbaud with PAM-4 modulation (240 Gbit/s line rate). We report on the highest, to the best of our knowledge, symbol rate using converters with limited bandwidth: a single <20 GHz CMOS DAC and 16 GHz ADCs. We successfully receive this signal after 1.5 km fiber in a C-band intensity modulation/direct detection (IM/DD) system. The bandwidth of the transmitted signal is digitally constrained to facilitate ultrahigh-symbol-rate signal generation using a low-bandwidth DAC, while the inter-symbol interference (ISI) is pre-compensated via a digital precoder preceding the bandwidth-constraining filter[6]. The comparison with conventional PAM-4 transmission (without precoder and bandwidth-constraining filter) reveals that the bit error ratio (BER) performance can be significantly improved at the same baud rate by constraining the signal bandwidth. Reception of the precoded 120 Gbaud PAM-4 signal is enabled by a 112 GSa/s 1-to-4 analog

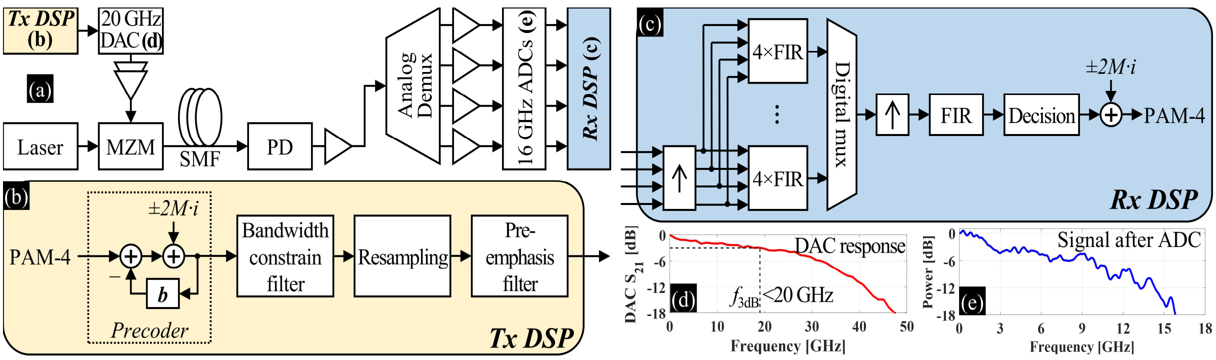

Fig. 1: (a) Experimental setup; (b) transmitter DSP; (c) receiver DSP; (d) DAC frequency response; (e) received signal spectrum after one of the ADCs.

demultiplexing frontend, which requires four ADCs sampling faster than 28 GSa/s. It is important to mention that the symbol rate demonstrated in this work is higher than the sampling rates of the DAC, ADC and the analog demultiplexing frontend.

Experiment

The experimental setup is shown in Fig. 1(a). At the transmitter, the optical carrier originates from a 1550 nm laser source, which has 16 dBm output power thus allowing IM/DD transmission without any optical amplification. The optical carrier is modulated by a Mach-Zehnder modulator (MZM) with 6 dB bandwidth of 50 GHz. The modulator is biased at a quadrature point and driven by a 110 GSa/s CMOS DAC. Measured frequency response of the DAC, shown in Fig. 1(d), exhibits an analog 3 dB bandwidth below 20 GHz. The DAC output is amplified by two cascaded 55 GHz driver amplifiers, providing 30 dB gain in total. At the receiver side, the optical signal is detected by a 65 GHz single-ended p-i-n photodiode (PD), followed by a 55 GHz post-amplifier. The electrical signal is fed into a 112 GSa/s 1-to-4 analog demultiplexing frontend[4], which consists of four time-interleaved samplers at 28 GSa/s. The four parallel signals at the demultiplexer outputs are amplified and sampled using four channels of a 50 GSa/s oscilloscope with a 16 GHz brick-wall anti-aliasing filter. Fig. 1(e) shows an example of the signal spectrum collected at one of the channels.

Digital signal processing (DSP) chains used at the transmitter and at the receiver are shown, respectively, in Figs. 1(b) and (c). In the transmitter DSP, PAM-4 signal is first precoded according to the principle of Tomlinson-Harashima precoding[7]. The feedback filter in the precoder is designed to mitigate the ISI at the output of the transmitter DSP, while the modulo operation is used to limit the amplitude of the precoded signal. The precoder allows to subsequently constrain the signal bandwidth using a raised-cosine (RC) filter with a bandwidth below the signal Nyquist bandwidth. The filter bandwidth is varied during the experiment to find the best performance. Next, the signal is resampled to the DAC sampling rate (110 GSa/s) and convolved with the pre-emphasis filter. An additional low-pass filter with a linear slope down to –3 dB at 55 GHz is applied to reduce the pre-emphasis strength and thus increase the DAC output swing. The ISI caused by the bandwidth constraining filter and low-pass filter is mitigated using the precoder, which expands the number of signal amplitude levels, as compared to the PAM-4 input[7]. A symbol rate higher than the DAC sampling rate can be achieved using the described transmitter DSP. For performance comparison, a conventional PAM-4 signal without precoding is transmitted using the same experimental setup, while the signal is shaped by an RC filter with a bandwidth equal to the signal Nyquist bandwidth.

In the receiver DSP, four parallel sample streams from the 50 GSa/s ADCs are first resampled to 56 GSa/s, which is twice the sampling rate of time-interleaved samplers. The resampled signal is equalized using four individual multiple-input single-output (MISO) equalizers. Each equalizer consists of four T/2 fractionally spaced finite impulse response (FIR) filters, to compensate the inter-channel and inter-symbol interference of the four demultiplexer paths. Second-order terms (squares of the input samples) are also used to compensate nonlinear distortions in the system. Outputs of the four equalizers at 28 GSa/s are then interleaved to generate a 112 GSa/s representation of the signal at the input of the demultiplexing frontend. The obtained signal is resampled to 2 Sa/symbol and fed into another linear T/2 fractionally-spaced FIR filter to mitigate residual channel distortions. Modulo operation is used to fold the

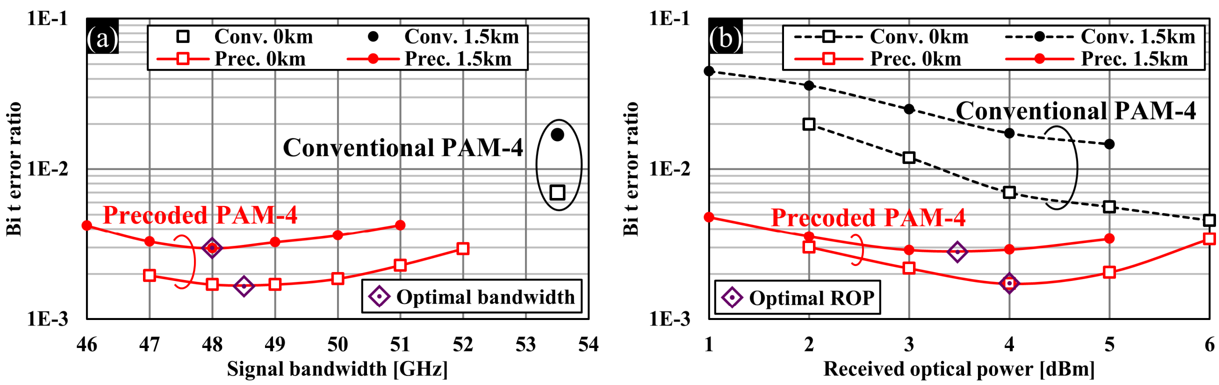

Fig. 2: (a) Performance comparison of 107 Gbaud precoded and conventional PAM-4 transmission at the received optical power of 4 dBm. Bandwidth of the precoded signal is swept while bandwidth of conventional PAM-4 signal is fixed to 53.5 GHz. (b) Performance comparison of 107 Gbaud precoded and conventional PAM-4 transmission at as the received optical power is swept. Optimal bandwidth constraint indicated in subfigure (a) is used for the precoded PAM-4.

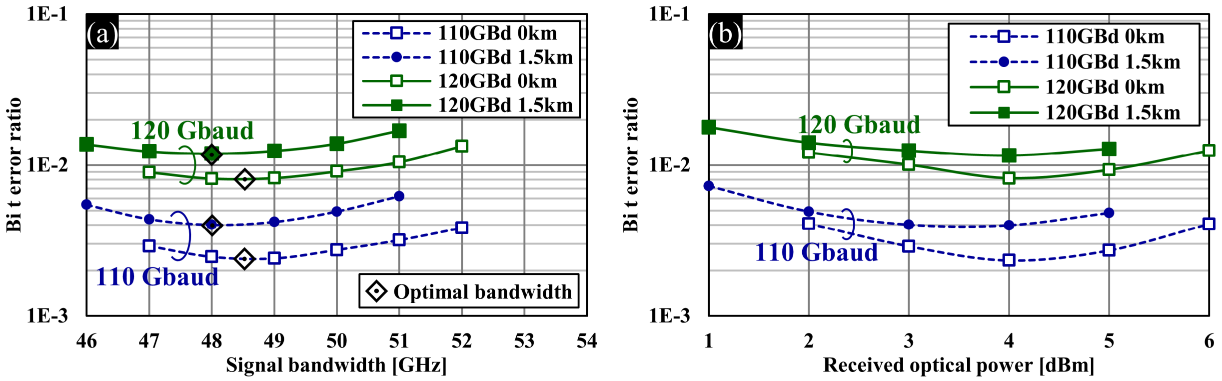

Fig. 3: (a) Performance of 110 Gbaud and 120 Gbaud precoded PAM-4 transmission at received optical power of 4 dBm when the bandwidth constraining filter is swept. (b) Performance of 110 Gbaud and 120 Gbaud precoded PAM-4 transmission when the received optical power is swept. Optimal bandwidth constraint indicated in subfigure (a) is used.

expanded number of signal amplitude levels caused by the transmitter precoder, back to four signal amplitude levels of original PAM-4. Subsequently, obtained symbols are converted to bits, and bit error ratio is counted.

Results

The performance is measured in back-to-back (BTB) configuration and after 1.5 km transmission over a standard single-mode fiber (SMF). We compare the performance of precoded and conventional PAM-4 signal at 107 Gbaud. Fig. 2(a) shows the comparison at a received optical power of 4 dBm. The bandwidth of conventional PAM-4 is fixed as described above, while the bandwidth of the precoded PAM-4 is varied by adjusting the bandwidth constraining filter. We find the best performance at signal bandwidth of 48.5 GHz in BTB configuration, and 48 GHz after 1.5 km fiber transmission. A trade-off exists between the DAC output swing (which increases with the bandwidth constraint due to gentler pre-emphasis), and the expanded number of signal amplitude levels caused by the precoder (which also increases with the bandwidth constraint). We observe significant performance improvement of the precoded PAM-4 with reduced bandwidth compared to the conventional PAM-4. Fig. 2(b) shows a performance comparison at various received optical power levels for conventional PAM-4 and precoded PAM-4 at the optimal signal bandwidth. The comparison shows three advantages of the precoded PAM-4 signal: (1) The performance is significantly improved, achieving BERs of 1.7×10^{-3} in BTB configuration and 2.9×10^{-3} after 1.5 km fiber transmission, while conventional PAM-4 only yields 4.5×10^{-3} and 1.5×10^{-2}. (2) The optimal received optical power is reduced to 4 dBm in BTB configuration and 3.5 dBm after 1.5 km SMF transmission. Conventional PAM-4 performs best at the highest received optical power in both cases. (3) Precoded PAM-4 shows improved tolerance to the power fading effect (caused by chromatic dispersion in a direct-detection system), in comparison to the conventional PAM-4.

For the precoded PAM-4 we increase the symbol rate to 110 Gbaud and 120 Gbaud, which is beyond the DAC sampling rate. Fig. 3(a) shows the performance versus signal bandwidth at the received optical power of 4 dBm. The best performance is achieved for a signal bandwidth of 48.5 GHz in BTB configuration and 48 GHz after 1.5 km fiber transmission at both symbol rates. Applying the optimal bandwidth constraint, the performance at various received optical power is shown in Fig. 3(b). At 4 dBm received optical power, 110 Gbaud precoded PAM-4 reaches BERs of 2.4×10^{-3} and 4.0×10^{-3}, respectively in BTB configuration and after 1.5 km fiber transmission. These BERs then increase to 8.2×10^{-3} and 1.2×10^{-2} at a symbol rate of 120 Gbaud. For 120 Gbaud transmission, the required FEC overheads are 11.11% in BTB configuration and 16.67% for 1.5 km transmission, which correspond to net bitrates of 216 Gbit/s and 205 Gbit/s respectively.

Conclusion

We demonstrate, for the first time to our knowledge, a 120 Gbaud symbol rate IM/DD transmission system based on a commercially available CMOS DAC with less than 20 GHz 3-dB bandwidth and ADCs with only 16 GHz bandwidth. The signal generation at such high symbol rate is augmented with transmitter DSP techniques: a precoder for ISI mitigation followed by a bandwidth constraining filter, while the signal reception is enabled by a 1-to-4 analog demultiplexing frontend. 120 Gbaud PAM-4 signal is successfully generated, transmitted over fiber and received, yielding 216 Gbit/s post-FEC bitrate in back-to-back and 205 Gbit/s after 1.5 km SMF.

References

[1] R. Rios-Müller *et al.*, "1-Terabit/s net data-rate transceiver based on single-carrier Nyquist-shaped 124 Gbaud PDM-32QAM", in *Proc. Optical Fiber Communications Conference (OFC)*, San Diego, CA, USA, Mar. 2015, p. Th5B.1.

[2] M. Nakamura *et al.*, "192-Gbaud signal generation using ultra-broadband optical frontend module integrated with bandwidth multiplexing function", in *Proc. Optical Fiber Communications Conference (OFC)*, San Diego, CA, USA, Mar. 2019, p. Th4B.4

[3] H. Mardoyan *et al.*, "84-, 100-, and 107-GBd PAM-4 intensity-modulation direct-detection transceiver for datacenter interconnects", *J. Lightw. Technol.*, vol. 35, no. 6, pp. 1253–1259, 2017.

[4] F. Buchali, K. Schuh, S. T. Le, X. Du, M. Grözing, and M. Berroth, "A SiGe HBT BiCMOS 1-to-4 ADC frontend supporting 100 Gbaud PAM4 reception at 14 GHz digitizer bandwidth", in *Proc. Optical Fiber Communications Conference (OFC)*, San Diego, CA, USA, Mar. 2019, p. Th4A.7.

[5] F. Buchali, V. Lauinger, M. Chagnon, K. Schuh and V. Aref, "1.1 Tb/s/λ at 9.8 bit/s/Hz DWDM transmission over DCI distances supported by CMOS DACs", in *Proc. Optical Fiber Communications Conference (OFC)*, San Diego, CA, USA, Mar. 2020, p. Th3E.2.

[6] Q. Hu, M. Chagnon, K. Schuh, F. Buchali, and H. Bülow, "IM/DD beyond bandwidth limitation for data center optical interconnects", *J. Lightwave Technol.*, vol. 37, no. 19, pp. 4940–4946, 2019.

[7] Y. Zhu and K. B. Letaief, "Frequency domain equalization with Tomlinson-Harashima precoding for single carrier broadband MIMO systems", *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4420–4431, 2007.

[8] L. M. Zhang and F. R. Kschischang, "Staircase codes with 6% to 33% overhead", *J. Lightw. Technol.*, vol. 32, no. 10, pp. 1999–2002, 2014.