1.1 Tb/s/λ at 9.8 bit/s/Hz DWDM transmission over DCI distances supported by CMOS DACs

Fred Buchali[1], Vincent Lauinger[2], Mathieu Chagnon[1], Karsten Schuh[1], Vahid Aref[1]
[1]*Nokia Bell Labs, Lorenzstraße 10, 70435 Stuttgart, Germany*
[2]*Karlsruhe Institute of Technology, Karlsruhe, Germany*
Fred.buchali@nokia-bell-labs.com

Abstract: We report on a 16-nm CMOS DAC based transmitter optimization enabling bitrates up to 1.15 Tb/s. We successfully demonstrate DWDM transmission over DCI distances up to 118 km at 1.1 Tb/s and spectral efficiencies of 9.8 bit/s/Hz.

1. Introduction

Forecasts continue to predict exponential growth in data transmission capacity over the Internet. Economic constraints exert constant pressure on the cost per Gbit/s of transceivers. To match the required throughput, we are observing a steady increase in data rates per wavelength through (i) an increase in the number of bits transported per symbol and (ii) an increase in the symbol rate, where the former leads to an improved utilization of the transmission channel. However, imprinting more bits per symbol requires a larger signal-to-noise-and-distortion ratio which translates to transmission over shorter distances. Fortunately, next-generation networks are targeting shorter point-to-point reaches, interconnecting regional data centers into an Edge Cloud. A typical distance to bridge for these data center interconnects (DCI) is around 80 km, with capacity targets met by dense wavelength division multiplexing (DWDM) in the entire C-band. While recent DWDM systems multiplex up to 80 or 96 wavelengths at lower symbol rates to cover the C-band, increasing the signaling rate to higher values such as 100 GBaud allows reducing the carrier count. In such systems, total capacities of up to 40 or 50 Tb/s have been achieved in current laboratory and field trials [1,2]. These experiments employ transmitters based on an arbitrary waveform generator at 1 Tb/s/λ or on SiGe-digital to analog converters (DAC) arriving at 1.3 Tb/s/λ. Transceivers using CMOS converters, which are better suited for implementation in future commercial transmission systems, have recently achieved rates of 800 Gb/s and beyond [3,4]. Albeit better suited, CMOS converters suffer from a lower electrical bandwidth, and as a result their usage is typically accompanied by a need for strong digital pre-emphasis to cope for their steadily decaying frequency response. Consequently, the generated electrical signal has a very small amplitude, which will translate to smaller signal-to-noise ratio (SNR). Recently, we have observed a dominant signal distortion in the DAC due to a clock leakage [3], which is superimposed to the balanced DAC output signals as common mode. To help mitigate this common mode distortion, baluns or differential driver amplifiers can be used.

In this paper, to the best of the authors' knowledge, we report on the highest capacity up to 1.15 Tb/s transmitted using a 16-nm CMOS DAC. We detail the transmitter optimization by the introduction of a balun for the suppression of the common mode distortions in conjunction with an optimized signal clipping in the digital signal processor (DSP). We further report on a successfully DWDM transmission experiment using 17 channels carrying 1.1 Tb/s/λ at a spectral efficiency of 9.8 bit/s/Hz over up to 118 km distance.

2. Transmitter optimization and system setup

The test setup, consisting of two transmitters (Tx), the transmission channel and the receiver (Rx), is shown in Fig. 1a). Two 16-nm CMOS-DAC pairs, both sampling at 120 GSa/s, generate the channel under test (CUT) and the DWDM load channels. The CUT is generated with the first CMOS-DAC pair. In previous experiment we achieved a signal-to-noise ratio (SNR - counting the distortions directly to the noise) of 13.2 dB for the optical back-to-back (B2B) system at 105 GBaud and the ENOB per modulated dimension (I or Q) was less than 2 bits and mainly limited by clock leakage distortions [3]. In this work we have introduced a broadband balun (bandwidth 67 GHz @-3dB) that allows for the conversion of the balanced into an unbalanced signal at the DAC output. It outputs the analog difference of inverted and non-inverted lines and may mitigate common mode distortions. At low frequencies the signal difference is attenuated by 6 dB at low frequencies (effective signal attenuation is 0 dB: $0.5 \cdot (S-(-S)) = S$), while at 55 GHz there is a further 1.5 dB drop. The unbalanced/single-ended signal is amplified by a driver with 60 GHz bandwidth. The measured frequency response of the electrical system is shown in Fig. 1b); the -20-dB bandwidth is 48 GHz and at the Nyquist frequency we arrived at -35 dB attenuation. The inverse frequency response is applied as a digital pre-emphasis in a linear filter of the digital signal processor (DSP) in Tx and leads to a

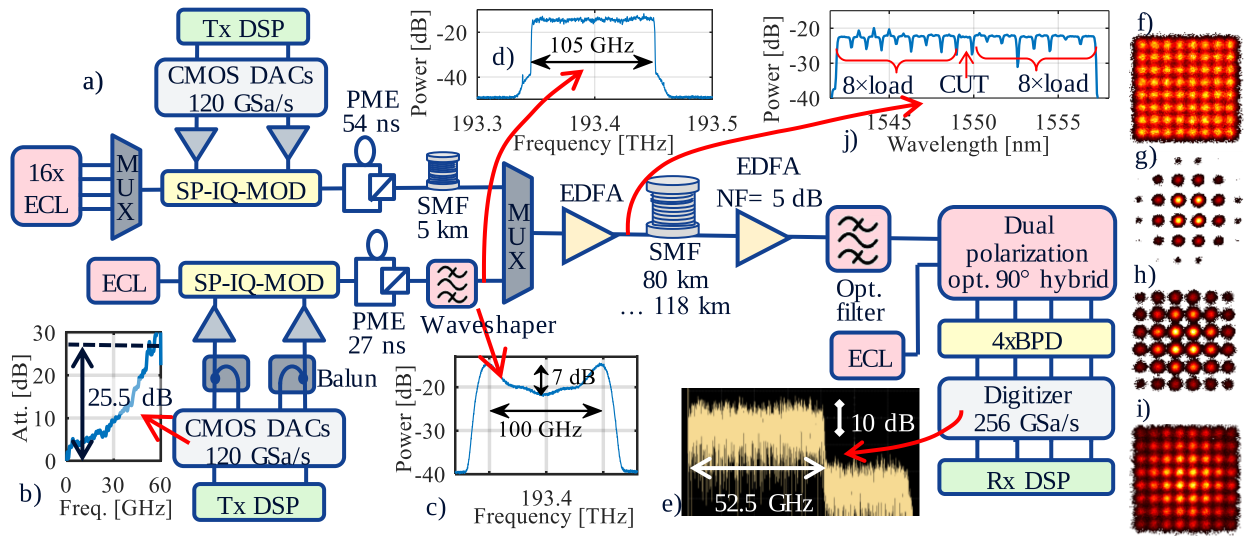

Fig. 1. Experimental setup. The insets show the respective characteristics in the labeled locations in the setup, which are detailed in the text.

frequency-independent DAC output amplitude. If we apply this pre-emphasis to a 105 GBaud signal (raised cosine pulse shape), the output amplitude is attenuated by 25.5 dB compared to the maximum DAC output amplitude. This is equivalent to a voltage attenuation of ×0.05 and can deteriorate the SNR by up to 22 dB, as the noise and distortion remain largely constant. That's why we achieved a low SNR in the first experiment. After passing through the balun, we observed a drastic reduction of clock leakage, resulting in an SNR improvement by 4.4 dB to 17.6 dB for the 105 GBaud signal despite additional attenuation. The pre-equalized signal with a flat frequency response is fed to the $LiNbO_3$ modulator with 32-GHz bandwidth, then the polarization multiplex is emulated. To compensate for the modulators frequency slope, we filtered the optical signal with an M-shaped characteristic, as shown in Fig. 1c), in order to achieve a flat optical spectrum again (cf. Fig. 1d).

In the receiver we o/e converted the signal using a state-of-the-art coherent frontend with 70-GHz bandwidth balanced photodiodes (BPD) and real-time oscilloscope-based signal digitization at 256 GSa/s and 80-GHz bandwidth. The spectrum of the received electrical signal is still flat (cf. Fig 1e). A standard DSP is applied offline. We used the mutual information (MI) and the general mutual information (GMI) for the assessment of the information rates (IR). To determine the maximum achievable net bitrate we FEC decoded the data using a family of LDPC codes with variable overhead [2].

In a further optimization of DSP, we have clipped the amplitudes of the signal before quantization. As shown in the amplitude histogram (see Fig. 2), the low and high amplitudes are used extremely rarely without clipping, the converter quantization levels are used less effectively. The clipping ratio refers to the maximum signal power after pulse shaping, pre-emphasis and resampling to 120 GSa/s and all amplitudes exceeding this relative limit are clipped at this. With clipping the distribution of the amplitudes becomes wider, the outer bins are used more frequently, and the distribution becomes largely symmetrical. The mean power increases sharply already with minimal clipping. If clipping is below 0.98, the further increase in mean power is lower. Already with minimal clipping the MI is increased. A gain of 0.07 bit/symbol is achieved at 0.98. For further testing, we selected the optimal clipping ratio.

In a single-channel B2B experiment we measured the achievable information rate for different formats. We selected probabilistically shaped QAM formats (PCS,[5]) with an entropy of 4 to 6.5 bits per symbol based on fundamental 36QAM, 64QAM and 100QAM as well as unshaped 16QAM, 32QAM and 64QAM (see Figs. 1f to 1i). For the implementation of non-power of 2 PCS formats, we chose the next higher power of 2 formats and truncated the

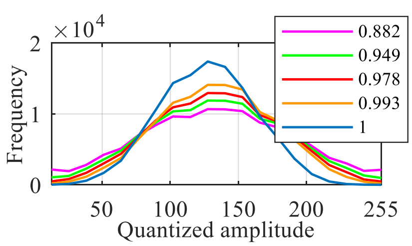

Fig. 2. Histogram of quantized amplitudes for variable clipping ratios.

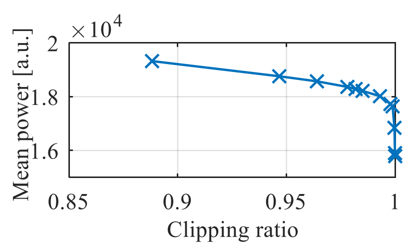

Fig. 3. Mean power at quantizer for versus the clipping ratio.

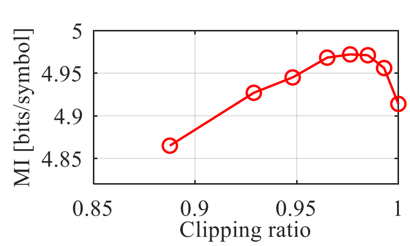

Fig. 4. MI versus clipping ratio for PCS 64QAM at H=5.9 bit/s, OSNR=30 dB.

outer rows and columns by setting their probabilities to zero. The mapping scheme of the truncated PCS formats is the same Gray mapping as for the next higher power of 2 formats. Fig. 4 shows the MI versus entropy (H) at 32-dB OSNR. Beyond H=4 bit/symbol, we observed a further MI increase with small deviation from the theoretical limit up to 5.5 and 5.0 bit/symbol for PCS and QAM. The maximum MI was found at an entropy of 5.9 and 6 bits/symbol, a further H increase then leads to MI degradation. The maxima at 5.35 and 5.2 bits/symbol (2.7 and 2.6 bit/dimension) are in good agreement with the transponder SNR of 17.6 dB [6]. Any PCS gain is not visible in this plot. At variable OSNR, we have determined the required OSNR at a net bitrate=0.833×gross bitrate (see Fig. 5). As expected, the PCS outperforms the pragmatic QAM by 0.9 to 1.0 dB. The maximum implementation penalty for PCS is only 3.4 dB at a net bitrate larger than 1.0 Tb/s. At the Shannon limit the required OSNR scales with +3 dB OSNR per net bitrate increase of 2x105 Gb/s, in the B2B experiments the required OSNR scales slightly stronger. However, the required OSNR values are much lower than the available OSNR in typical 80 km DCI systems. Hence any reach extension should lead to a much lower net bitrate drop.

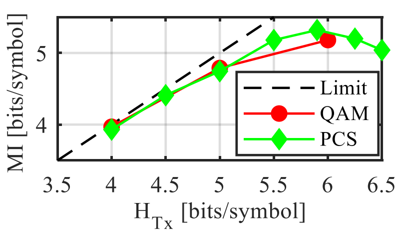

Fig. 4. MI of PCS and pragmatic QAM formats for formats of different entropies at 32 dB OSNR.

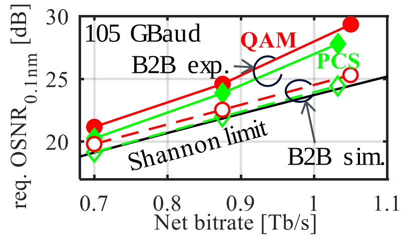

Fig. 5. Required OSNR -experiment (solid) and simulation (dashed) in B2B versus net bitrate for QAM and PCS formats at 20% OH.

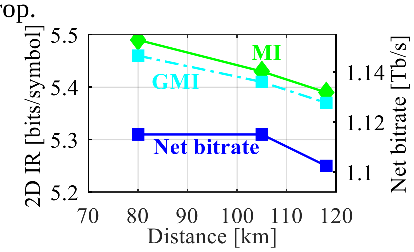

Fig. 6. 2D-IR (MI and GMI) and net bitate/λ from successful decoding versus distance for PCS at H=5.9 bit/Symbol.

3. Fiber transmission experiments

For DWDM experiments, we have added 16 load channels around the CUT, all operating at 105 GBaud in a 112.5 GHz grid (see Fig. 1j). The load channels are generated with the second CMOS-DAC pair and modulated with a QAM signal. To decorrelate the channels we used a 5 km fiber and delay/decorrelate adjacent channels by 8 symbols each. We transmitted the signal over 80, 105 and 118 km on a G.652 single mode fiber having an attenuation of 0.2 dB/km. The optimal launch power is 15 dBm for the shorter distance and 18 dBm for 105 and 118 km. With increasing fiber length, the available OSNR is reduced by 3 dB for each 3-dB fiber attenuation (extension of distance by 15 km) at constant launch power. In our experiment we arrived at 38 dB down to 33 dB OSNR. The determined 2D IRs are 5.46 to 5.37 bits/symbol in GMI (cf. Fig. 6). Note that the differences between MI and GMI are negligible and less than 1%. After FEC decoding, we achieved a net bitrate of 1.15 Tb/s at 80 and 105 km, while it is slightly reduced to 1.1 Tb/s at 118 km. This extremely small reduction of the net bitrate is due to dominating noise and distortions from the transponders, while the optical noise of the transmission system has a minor impact even with 5 dB variation. The spectral efficiencies are 9.9 and 9.8 bit/s/Hz.

4. Conclusion

We have reported a 16-nm CMOS DAC based transmitter and demonstrated an SNR improvement to 17.6 dB by rejection of common mode distortions and by clipping. Using probabilistically shaped formats we achieved information rates up to 5.46 bits/symbol. In a DWDM experiment over up to 118 km we transmitted 17 carriers at 105 GBaud in a 112.5 GHz grid utilizing 93% of the bandwidth. We demonstrated error free transmission after FEC decoding for up to 1.15 Tb/s per λ at a spectral efficiency of 9.69 bit/s/Hz. To the best of our knowledge this is the highest bitrate so far reported for CMOS DAC based transmitters and demonstrates that CMOS DACs are available today for implementation of 1-Tb/s class transmitters.

5. References

[1] A. Matsushita et al., "41-Tbps C-band transmission with 10-bps/Hz spectral efficiency using 1-Tbps 96-GBd PS-256QAM for DCI," European Conference on Optical Comm., Dublin, Ireland, 2019, Tu2D1.

[2] F. Buchali et al., "1.3-Tb/s Single-Channel and 50.8-Tb/s WDM Transmission over field-deployed fiber", European Conference on Optical Comm., Dublin, Ireland, 2019, PDP.1.3.

[3] F. Buchali et al., "Beyond 100 GBaud Transmission Supported by a 120 GSa/s CMOS Digital to Analog Converter," European Conference on Optical Communications, Dublin, Ireland, 2019, pp. 1-4.

[4] A. Arnould et al., "Net 800 Gb/s transmission over 605 km using 99.5 GBaud PDM-64QAM with CMOS digital to analog converters", proc. ECOC 2019, paper Tu2D2."

[5] F. Buchali et al., "Rate Adaptation and Reach Increase by Probabilistically Shaped 64-QAM: An Experimental Demonstration," IEEE Journal Lightwave Technology, Vol. 34, no. 7, p. 1599 (2016).

[6] W. Kestner, "The Data Conversion Handbook", Newnes, 2005.