# LATTICE PILOT AIDED DMT TRANSMISSION FOR OPTICAL INTERCONNECTS ACHIEVING 5.82-BITS/HZ PER LANE

*Lu Zhang[1,2], Jiajia Chen[1*,6], Aleksejs Udalcovs[3], Hadrien Louchet[4], Thomas Dippon[4],*
*Markus Gruen[4], Xiaodan Pang[1,3,5], Richard Schatz[1], Urban Westergren[1], Sergei Popov[1],*
*Shilin Xiao[2] and Oskars Ozolins[3*,1]*

[1]*KTH Royal Institute of Technology, Kista, Sweden*
[2]*Shanghai Jiao Tong University, Shanghai, China*
[3]*RISE Research Institutes of Sweden AB, Kista, Sweden*
[4]*Keysight Technologies GmbH, Böblingen, Germany*
[5]*Infinera, Stockholm, Sweden*
[6]*Chalmers University of Technology, Gothenburg, Sweden*
*\* jiajiac@chalmers.se; oskars.ozolins@ri.se*

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## Abstract

We experimentally demonstrate 276-Gbps net rate 128QAM-DMT transmission at soft-FEC limit in an IM/DD system with a single C-band packaged EML, a DAC and a photo-detector, proposing a lattice pilot algorithm for channel equalization with only 1% overhead reaching spectral efficiency of 5.82-bits/Hz per lane.

## 1 Introduction

The increase in datacentre traffic gives a rise to large capacity requirements for optical short-reach interconnections [1]. There are currently many research activities around 400-GbE interfaces employing wavelength division multiplexing (WDM) for short-reach applications. In [2], IEEE Standard has proposed O-band eight-channel (800 GHz spacing) WDM 400-Gbps short-reach interface. For future capacity upgrade, C-band intensity-modulation direct-detection (IM/DD) system becomes more attractive owning to the maturity in dense-WDM (DWDM) technology. Among many IM/DD transmission works that attempt to achieve beyond 200-Gbps per lane for short reach interconnections [3-9], [8] reported 333-Gbps net rate discrete multi-tone (DMT) transmission with C-band InP Mach-Zehnder modulator. It used two 80-GHz sub digital-to-analogue converters (sub-DACs), image suppressed analogue multiplexer (AMUX) circuit. [9] reported 460.9-Gbps net rate transmission, which uses entropy loading and ~100-GHz digital band interleaved DAC (DBI-DAC). Besides, [10] reported 1.02-Tbps net rate transmission with an 86-GHz Stokes vector receiver. The use of high modulation bandwidth (>50GHz) makes the interconnection system incompatible with standard 100-GHz DWDM technology, increasing the spectral efficiency instead could be a promising solution.

In this paper, we demonstrate a 330-Gbps line rate (276-Gbps net rate) 128QAM-DMT IM/DD transmission with a single packaged externally modulated laser (EML), a DAC and a packaged InP photo-detector (PD). The system has an end-to-end 3-dB bandwidth of ~13-GHz and 6-dB bandwidth of ~42-GHz, and 47.8-GHz is used for modulation. We introduce a novel channel equalization algorithm using lattice pilot,

resulting in only 1% pilot overhead. The demonstrated spectral efficiency reaches 5.82-bits/Hz per lane.

## 2 Operation principle and experimental setup

The system setup is shown in Fig. 1 (a). The DMT samples are generated offline and loaded into a 120-GSa/s DAC (Keysight M8194A). The signal from the DAC is amplified by an electrical amplifier with 11-dB gain before applying on the EML for modulation. The EML is composed of a monolithically integrated distributed feedback (DFB) laser with a travelling-wave electro absorption modulator (TWEAM) [5]. We use current of 120 mA @20°C for the DFB and voltage of -1.8 V for the TWEAM resulting in ~4.5dB extinction ratio. The PD is a high-speed InP-based O/E converter packaged prototype photo-detector with a responsibility of 0.5-A/W. The electrical signal from direct-detection is captured by one 256-GSa/s digital storage oscilloscope (DSO, Keysight UXR1102A). In the experiment, the length of inverse fast Fourier transform (IFFT) for DMT modulation is set to 2048, which corresponds to 58.6-MHz subcarrier spacing. The clipping ratio of the DMT signal is set to 0.75 to improve the
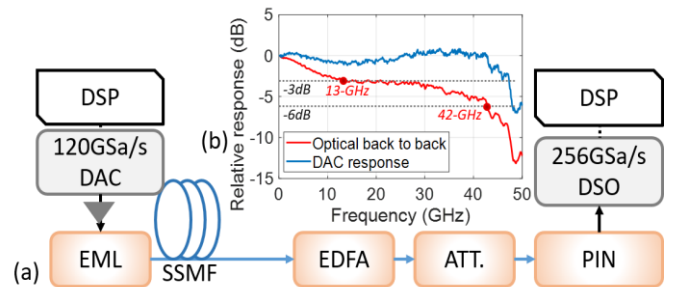


Fig. 1. (a) Experimental setup, and (b) S21 response of DAC and optical back-to-back transmission.

signal to noise ratio (SNR) out of the DAC. The output amplitude of the DAC is set to 700-mV. The measured central wavelength under above driving condition is ~1549.8-nm.

The modulated optical signal from the EML (~0.5-dBm) is fed into a spool of 400-m standard single mode fibre (SSMF). Because of the lack of trans-impedance amplifier (TIA), one erbium doped fibre amplifier (EDFA) together with a variable optical attenuator (VOA) is used before PD to study the receiver sensitivity. The relative S21 response of the DAC and optical back-to-back (OBtB) channel are shown in Fig. 1 (b). While the DAC shows a 3-dB bandwidth of ~46-GHz, the 3-dB bandwidth of the OBtB transmission is ~13-GHz and the 6-dB bandwidth is ~42-GHz, where 400-m transmission performs similar response since chromatic dispersion induced power fading does not influence the bandwidth here. Finally, 816 subcarriers of the DMT are loaded with 128QAM symbols for OBtB and 400-m fibre transmission, which corresponds to 47.8-GHz (816/2048×120-GSa/s) modulation bandwidth.

The time-frequency lattice of the DMT signal composing payload, preamble and pilot is shown in Fig. 2. The preamble here is used for training Volterra nonlinear filtering and DMT frame synchronization. Here, only one DMT symbol is used as preamble for equalization with Volterra kernels up to the third order. Instead of traditional linear channel equalization with block pilot based intra-symbol frequency-domain averaging (ISFA) algorithm [11], a lattice pilot based two-dimensional (including both time and frequency domain) algorithm is introduced for the linear channel equalization (see Fig. 2). The pilot symbols are interleaved in different time and frequency lattice points. Assuming $G$ is the pilot interval, the lattice pilot positions at $m$-th subcarrier corresponds to symbol positions at $m\%G$, $m\%G+G$, $m\%G+2G$, …, where $\%$ represents modulo calculation. The pilot positions at each symbol also follow the same rule, and the lattice pilot positions at the $n$-th symbol correspond to subcarrier indexes at $n\%G$, $n\%G+G$, $n\%G+2G$, ...

We denote the transmitted pilot symbol before IFFT at the $m$-th subcarrier and $n$-th DMT symbol as $P_{m,n}$, and the received pilot symbol after FFT at the $m$-th subcarrier and $n$-th DMT symbol as $P'_{m,n}$. The channel response at lattice pilot is first estimated by least square algorithm shown in Eq. 1.

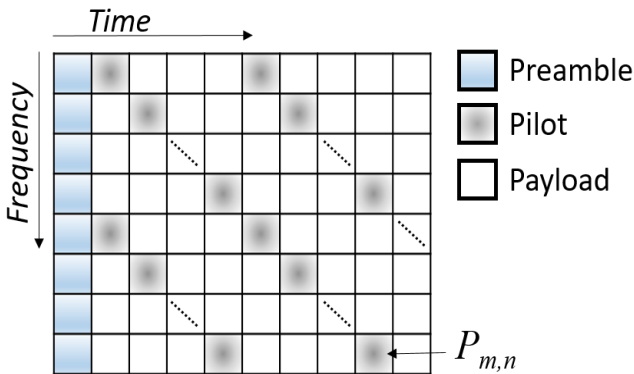$$H_{m,n} = \frac{P'_{m,n}}{P_{m,n}} \Big|_{m=n\%G,n\%G+G,...} \tag{1}$$

Then the channel response of all subcarriers at the $n$-th symbol is estimated by interpolation of the pilot response with the symbol. The linear interpolation is used in this paper because of its low complexity.

$$H_{m,n|m=1,2,3,...} = \text{interp}(H_{m,n})_{|m=n\%G,n\%G+G,...} \tag{2}$$

After interpolation operations of each symbol, the final response is obtained by averaging the response of all DMT symbols to reduce the influence coming from channel additive noise.

$$H_{m|m=1,2,3,...} = \sum_{n=1}^{N} \frac{H_{m,n}}{N} \tag{3}$$

Since the lattice pilot symbols are interleaved in both time and frequency domain, a better estimation of the linear response with much smaller pilot overhead can be achieved. Besides, the pilots are distributed in both time and frequency domain, which could also lead to a better transmission performance. As a result, the system spectral efficiency and capacity are significantly enhanced with the proposed lattice pilot-based channel equalization.

## 3    Results and discussions

First, the lattice pilot-based channel equalization algorithm is verified at OBtB case, which is shown in Fig. 3. With the increase of pilot overhead for channel equalization, bit error ratio (BER) of the proposed lattice algorithm and ISFA algorithm drops and the SNR correspondingly increases. When the pilot overhead is only 1%, the proposed lattice pilot channel equalization algorithm already reaches the soft decision forward error correction limit (low-density parity-check convolutional codes), where 20% overhead LDPC-CC FEC is at BER of 2.7e-2, and the pre-FEC BER was calculated from the given Q factor in dB as $(1/2)erfc(10^{5.7dB/20}/\sqrt{2})$ [12]. Comparatively, the BER of the ISFA with 1% pilot overhead is 6.2e-2, and reaches the LDPC-CC FEC limit when its overhead is increased to 20%. This also reflects that the equalized SNR of the proposed lattice algorithm is higher than that of the ISFA, especially at low pilot overhead. As a result, compared to the ISFA, to achieve the LDPC-CC FEC limit the pilot overhead in the proposed lattice pilot algorithm is able to be reduced from 20% to 1%, and hence the system gross rate is increased by ~ 63-Gbps (47.8-GHz ×7-bit/Hz × (20%-1%)).

The transmission performance is shown in Fig. 4. The BER without any equalization is around 0.34, which is not shown in
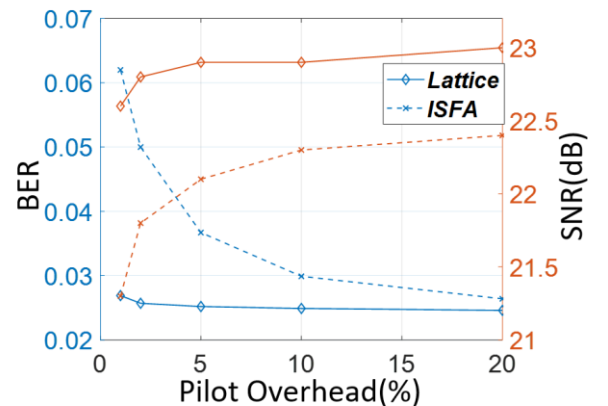


Fig. 2. Time-frequency lattice of DMT.



Fig. 3. BER and SNR versus the pilot overhead.

the figure. With the increase of received optical power (RoP), the OBtB and 400-m fibre transmissions reach the LDPC-CC FEC limit at around 7-dBm RoP. Finally, the net data rate is 276-Gbps (47.8-GHz ×7-bit/Hz ×(1-1%) / (1+20%)).
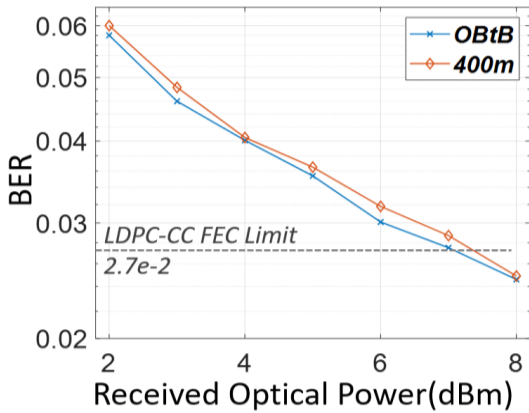


Fig. 4. Transmission performance.

Since LDPC based FEC technique belongs soft decision FEC, generalized mutual information (GMI) of the signal is calculated in Fig. 5 to verify the performance, where system net rate is also estimated with the GMI [13]. The constellations at LDPC-CC FEC limit is also shown in the inset of Fig. 5. The estimated capacity at 8-dBm optical power is 278-Gbps, which has ~0.8% variation with the calculated post-FEC capacity. The GMI at 8-dBm is 5.82-bits/Hz. The estimated net rate increases from 224-Gbps to 278-Gbps when the RoP changes from 2-dBm to 8-dBm.
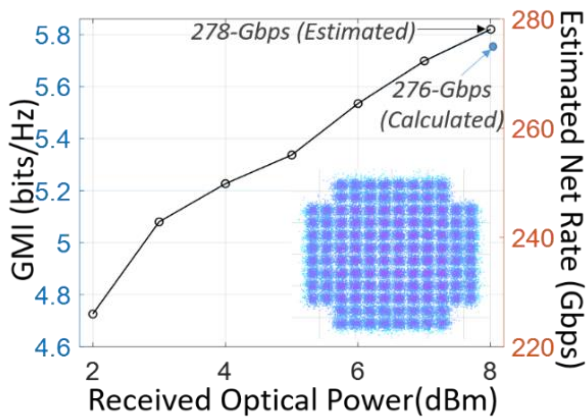


Fig. 5. Estimated net rate and GMI after fibre transmission.

## 4    Conclusion

We experimentally demonstrate a line rate 330-Gbps (net rate 276-Gbps) 128QAM-DMT transmission with a single DAC, EML and PD for short-reach interconnections, achieving high spectral efficiency of 5.82-bits/Hz per lane for optical interconnections. With the proposed lattice pilot algorithm for channel equalization, only 1% pilot overhead is required to reach the LDPC-CC FEC limit of 2.7e-2.

## 5    Acknowledgements

## 6    References

[1] Cisco Visual Networking Index: Forecast and Trends, 2017–2022.

[2] IEEE Standard, Media access control parameters, physical layers, and management parameters for 200 Gb/s and 400 Gb/s operation.

[3] S. Kanazawa, H. Yamazaki, Y. Nakanishi, et al.: '214-Gb/s 4-PAM Operation of Flip-Chip Interconnection EADFB Laser Module', Journal of Lightwave Technology, 2017, **35**, (3), pp.418.

[4] H. Mardoyan, F. Jorge, O. Ozolins, et al.: '204-GBaud On-Off Keying Transmitterfor Inter-Data Center Communications', Proc. OFC, 2018, Th4A.4.

[5] O. Ozolins, X. Pang, M. I. Olmedo, et al.: '100 GHz Externally Modulated Laser for Optical Interconnects', Journal of Lightwave Technology, 2017, **35**, (6), pp. 1174-1179.

[6] X. Chen, S. Chandrasekhar, S. Randel, et al.: 'All-Electronic 100-GHz Bandwidth Digital-to-Analog Converter Generating PAM Signals up to 190 GBaud', Journal of Lightwave Technology, 2017, **35**, pp. 411.

[7] L. Zhang, X. Hong, X. Pang, et al.: 'Nonlinearity-aware 200 Gbit/s DMT transmission for C-band short-reach optical interconnects with a single packaged electro-absorption modulated laser', Optics Letters, 2018, **43**, pp. 182-185.

[8] H. Yamazaki et al.: 'Transmission of 400-Gbps Discrete Multi-Tone Signal Using >100-GHz-Bandwidth Analog Multiplexer and InP Mach-Zehnder Modulator', Proc. ECOC, 2018, PDP.

[9] X. Chen, S. Chandrasekhar, J. Cho, et al.: 'Single-Wavelength and Single-Photodiode Entropy-Loaded 554-Gb/s Transmission over 22-km SMF', in Proc. OFC, 2019, PDP, Th4B.5.

[10] D. Che, S. Chandrasekhar, X. Chen, et al.: 'Single-Channel Direct Detection Reception beyond 1 Tb/s', in Proc. OFC, 2019, PDP, Th4B.7.

[11] X. Liu and F. Buchali.: 'Intra-symbol frequency-domain averaging based channel estimation for coherent optical OFDM', Optics Express, 2008, **16**, (26), pp. 21944-21957.

[12] D. Chang, F. Yu, Z. Xiao, et al.: 'LDPC Convolutional Codes using Layered Decoding Algorithm for High Speed Coherent Optical Transmission', Proc. OFC, 2012, OW1H.4.

[13] A. Alvarado, E. Agrell, D. Lavery, et al.: 'Replacing the soft-decision FEC limit paradigm in the design of optical communication systems', Journal of Lightwave Technology, 2015, **33**, (20), pp. 4338–4352.