Single-Laser 32.5 Tbit/s Nyquist-WDM
Transmission over 227 km with Real-Time Nyquist Pulse Shaping

D. Hillerkuss, R. Schmogrow, M. Meyer, S. Wolf, M. Jordan, P. Kleinow, N. Lindenmann, P. C. Schindler, A. Melikyan, M. Dreschmann, J. Meyer, J. Becker, C. Koos, W. Freude, J. Leuthold
Institute of Photonics and Quantum Electronics,
Institute of Microstructure Technology,
and Institute for Information Processing Technologies,
Karlsruhe Institute of Technology (KIT),
Karlsruhe, Germany,
david.hillerkuss@kit.edu

X. Yang, F. Parmigiani, P. Petropoulos
Optoelectronics Research Centre,
University of Southampton,
Southampton, United Kingdom,

S. Ben-Ezra
Finisar Corporation,
Nes Ziona, Israel

B. Nebendahl
Agilent Technologies,
Boeblingen, Germany

B. Resan, A. Oehler, K. Weingarten
Time-Bandwidth Products,
Zurich, Switzerland,

L. Altenhain, T. Ellermeyer
Micram Microelectronic GmbH,
Bochum, Germany

M. Moeller
Department of Electronics and Circuits,
Saarland University,
Saarbruecken, Germany

M. Huebner
Embedded Systems in Information Technology (ESIT),
Ruhr-University,
Bochum, Germany

Abstract— Single-laser 32.5 Tbit/s 16QAM Nyquist-WDM transmission with 325 carriers over 227 km at a net spectral efficiency of 6.4 bit/s/Hz is reported.

Communication systems; Optical fiber communication; Pulse shaping methods; Quadrature amplitude modulation

I. INTRODUCTION

Single-laser multi-Tbit/s super-channels [1-4] are interesting candidates for future optical networks [5]. Such channels typically consist of one carrier or several frequency-locked carriers onto which data are encoded.

With optical time division multiplexing (OTDM) [1, 2], data rates have reached 10.2 Tbit/s within roughly 30 nm of optical bandwidth, corresponding to a net spectral efficiency (SE) of 2.6 bit/s/Hz [2]. Transmission of 10.2 Tbit/s over 29 km of dispersion-managed fiber has been demonstrated.

Multicarrier transmission with schemes like coherent wave-length division multiplexing (CO-WDM) [6] and orthogonal frequency division multiplexing (OFDM) [7-9] have been proposed. After a first demonstration of a 1.0 Tbit/s super-channel [10] with a SE of 3.3 bit/s/Hz, single-laser super-channel data rates have subsequently reached 26 Tbit/s transmitted over 50 km of standard single mode fiber at 5.0 bit/s/Hz SE [3].

Nyquist pulse shaping [11] can reduce the spectral footprint of single-channel signals and therefore the required channel spacing in WDM systems [12, 13]. Sinc-shaped Nyquist pulses have a rectangular spectrum [11, 14, 15] and confine the signal to its Nyquist bandwidth [11]. This enabled transmission at intra-channel net SE up to 15 bit/s/Hz [16]. The rectangular spectra can be combined without the need for a guard band, ending up with the so-called Nyquist WDM, where the carrier spacing is equal to the symbol rate (when using identical symbol rates in all bands). Recently, this has been discussed as an option for Tbit/s super-channels [12] and favorable transmission properties have been predicted [14]. In a first demonstration, Nyquist WDM at 400 Gbit/s with a SE of 3.7 bit/s/Hz has been shown [17]. An arbitrary waveform generator (AWG) generated a Nyquist signal that was computed offline using a 601-tap finite impulse response (FIR) filter.

Nyquist WDM transmission with real-time sinc-pulse shaping and 16QAM has not yet been shown. The challenge lies in
the limited-length representation of acausal sinc-pulses in systems with real-time signal processing, where a practicable number of FIR filter taps has to be used.

In this paper, we report on a single-laser Nyquist WDM super-channel transmission experiment at a record high aggregate line rate of 32.5 Tbit/s [18]. The electrical Nyquist signals are computed in real-time using a 64-tap FIR filter. The net SE is 6.4 bit/s/Hz. We show transmission over 227 km.

II. NYQUIST PULSE SHAPING

Nyquist transmitters with sinc-pulse shaping generate signals with a rectangular spectrum with a total bandwidth equal to the symbol rate [14, 15]. This confines the signal to its Nyquist bandwidth. Our simulations indicate [14] that Nyquist pulse shaped signals have a lower peak to average power ratio (PAPR) when compared to OFDM. Two real-time Nyquist transmitters as in [15] are implemented to modulate odd and even carriers. Each transmitter generates a PRBS \((2^{15}-1)\) in real-time. After symbol mapping, Nyquist sinc-pulse shaping is implemented in a FIR filter. The signal is converted to the analog domain using two VEGA DAC25 or VEGA DAC-II, respectively. Low pass filters (12 GHz 3 dB bandwidth) remove image spectra before amplification and IQ modulation.

III. NYQUIST WDM

The Nyquist WDM system (Figure 1) consists of an optical comb source as a cost effective and energy efficient multi carrier source, two Nyquist transmitters [15], a polarization multiplexing emulator, and a pre-amplified receiver. In the optical comb source, a pulse train from an ERGO mode locked laser (MLL) is amplified, filtered and split. One part is spectrally broadened in a highly nonlinear fiber [3]. The two paths are equalized and recombined in a waveshaper, forming a stable and flat output spectrum. A number of 325 optical carriers are generated between 1533.47 and 1566.22 nm with a spacing of 12.5 GHz. The spectral lines are separated into odd and even carriers to be modulated in two separate Nyquist transmitters. To generate true Nyquist WDM, the symbol rate of 12.5 GBD is equal to the carrier spacing of 12.5 GHz. Separate RF synthesizers provide the respective sampling clock for both transmitters. After modulation, odd and even carriers are combined in an optical coupler to form the Nyquist WDM signal. After polarization multiplexing with a de-correlation delay of 5.3 ns, the signal is amplified to be transmitted over distances of 75.78 km and 227.34 km using Corning SMF-28 with EDFA-only amplification. After transmission, the wavelength to be measured is selected in a waveshaper, amplified and received in an optical modulation analyzer (OMA). In the OMA the error vector magnitude (EVM) is measured for all carriers. The bit error ratio (BER) performance has been verified for selected carriers to support the EVM-to-BER relationship. Our results are in good agreement with previous experiments [3, 15, 19].

IV. EXPERIMENTAL RESULTS

Back-to-back measurement results, Figure 2(a), serve as a reference for the overall system performance. The EVM for most carriers was below the threshold for the second generation forward error correction (FEC). The average EVM was 10.3 %. After transmission over 75.78 km and 227.34 km, Figure 2(b,c), the average EVM degraded to 11.3 % and 12.1 %, respectively. For all carriers and distances, the EVM was below the EVM corresponding to the BER threshold of \(1.8 \times 10^{-2}\) for next generation soft decision FEC [20]. The non-ideal real-time transmitters introduce crosstalk due to the spectral overlap of Nyquist WDM channels, Figure 2(d). This crosstalk adds

![Figure 1. Experimental setup. The optical carriers are generated by an optical comb generator based on spectral broadening of a pulse train from a mode locked laser (MLL) in a highly nonlinear fiber (HNLF), and on spectral shaping and slicing in a waveshaper (WS). An optical interleaver (IL) separates odd and even carriers, which are subsequently encoded with separate Nyquist-pulse shaped 16-QAM signals. Polarization multiplexing is emulated. The signal is transmitted over one or three spans of Corning SMF-28 with EDFA-only amplification, and is received in a coherent Nyquist WDM Receiver. Optical spectra are shown for various points in the setup as indicated. Constellation diagrams are measured for various transmission distances and are shown for the carrier closest to 1550 nm.](image-url)
Figure 2. Experimental Results for the transmission experiment. (a) back-to-back performance, (b) transmission over 75.78 km and (c) transmission over 227.34 km. (d) Output spectrum of the Nyquist transmitter (—) and its neighbors (—) in the WDM experiment

less than 1.5 % to the EVM of the channel without neighbors. The line rate of 32.5 Tbit/s corresponds to a net data rate of 26 Tbit/s (20 % FEC overhead [20]).

V. CONCLUSION

We show the first 32.5 Tbit/s single laser 16QAM Nyquist WDM transmission experiment. The symbol rate is equal to the carrier spacing and the pulse shaped signals are generated in real time. The net SE is 6.4 bit/s/Hz.

REFERENCES

[1] H. C. H. Mulvad et al., "Demonstration of 5.1 Tbit/s data capacity on a single-wavelength channel," Opt. Express, vol. 18, pp. 14387-1443, 2010.
[2] T. Richter et al., "Single wavelength channel 10.2 Tbs TDM-data capacity using 16-QAM and coherent detection," in OFC, 2011, paper PDP9.
[3] D. Hillerkuss et al., “26 Tbit s⁻¹ line-rate super-channel transmission utilizing all-optical fast Fourier transform processing,” Nature Photonics, vol. 5, pp. 364-371, Jun 2011.
[4] J. Yu, Z. Dong, and N. Chi, “30-Tb/s (3×12.84-Tb/s) signal transmission over 320km using PDM 64-QAM modulation,” in OFC, 2012, paper OMA2.4.
[5] S. L. Jansen, "Multi-carrier approaches for next-generation transmission: Why, where and how?" in OFC, 2012, paper OTh1B.1.
[6] A. D. Ellis and F. C. Gunning, "Spectral density enhancement using coherent WDM," Photonics Technology Letters, IEEE, vol. 17, pp. 504-506, Feb 2005.
[7] A. Sano et al., "30 × 100-Gb/s all-optical OFDM transmission over 1300 km SMF with 10 ROADM nodes," in ECOC, 2007, paper PDP1.2.
[8] W. Shieh and I. Djordjevic, *OFDM for optical communications.* Amsterdam Heidelberg [u.a.]: Elsevier Academic Press, 2010.
[9] R. Schmogrow et al., "Real-time OFDM transmitter beyond 100 Gbit/s," Opt. Express, vol. 19, pp. 12740-12749, Jun 20 11.
[10] Y. Ma, Q. Yang, Y. Tang, S. Chen, and W. Shieh, "1-Tb/s single-channel coherent optical OFDM transmission over 600-km SMF fiber with subwavelength bandwidth access," Opt. Express, vol. 17, pp. 9421-9427, 2009.
[11] H. Nyquist, "Certain topics in telegraph transmission theory," *T. Am. Inst. Electr. Eng.*, vol. 47, pp. 617-644, 1928.
[12] G. Bosco, V. Curri, A. Carena, P. Poggiolini, and F. Forghieri, "On the performance of Nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers," JLT, vol. 29, pp. 53-61, 2011.
[13] S. Kilmurray, T. Fehenberger, P. Bayvel, and R. I. Killey, "Comparison of the nonlinear transmission performance of quasi-Nyquist WDM and reduced guard interval OFDM," Opt. Express, vol. 20, pp. 4198-4205, 2012.
[14] R. Schmogrow et al., "Real-time Nyquist pulse generation beyond 100 Gbit/s and its relation to OFDM," Opt. Express, vol. 20, pp. 317-337, 2012.
[15] R. Schmogrow et al., "150 Gbit/s real-time Nyquist pulse transmission over 150 km SMF enhanced by DSP with dynamic precision," in OFC, 2012, paper OMA2.6.
[16] R. Schmogrow et al., "512QAM Nyquist sinc-pulse transmission at 54 Gbit/s in an optical bandwidth of 3 GHz," Opt. Express, vol. 20, pp. 6439-6447, 2012.
[17] M. Yan et al., "Experimental comparison of no-guard-interval-OFDM and Nyquist-WDM superchannels," in OFC, 2012, paper OTh1B.2.
[18] D. Hillerkuss et al. (2012). Single-laser 12.5 Tbit/s Nyquist WDM transmission. *ArXiv e-prints Available: http://arxiv.org/abs/1203.2516v1*
[19] R. Schmogrow et al., "Error vector magnitude as a performance measure for advanced modulation formats," Photonics Technology Letters, IEEE, vol. 24, pp. 61-63, 2012.
[20] T. Mizuochi, "Recent progress in forward error correction and its interplay with transmission impairments," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 12, pp. 544-554, Jul-Aug 2006.