Single-Carrier Coherent 930G, 1.28T and 1.60T Field Trial

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Abstract *We report, single-carrier net bitrate transmissions of 930-Gb/s over 1105 km, 1.28-Tb/s over 452.4 km, and 1.60-Tb/s over 153.4-km links, which are part of the R&D field test network of the German operator Deutsche Telekom.*

Introduction

Since the introduction of the first 100 Gb/s systems, coherent technology has kept evolving over time in response to the challenges of ever-increasing network capacity demands.

Fig. 1 shows the evolution of coherent optics across different generations. Higher transmission speeds require an increase in the number of constellation points (higher modulation order) or the number of symbols sent every second (higher symbol rate). Increasing the modulation order decreases the distance that a signal can travel since the waveforms become more complex and more sensitive to noise. To reduce inter-symbol interference, more precise lasers, more linear electro-optical components and more complex digital signal processing (DSP) are needed. Increasing the symbol rate allows to transmit up to the same distance but does not improve spectral efficiency. However, the required electronics and optics with larger bandwidth can be a difficult and expensive engineering problem to solve. Evolution is also driven by technical capabilities, cost, and target applications leading to a divergent set of coherent solutions: performance-optimized and footprint-optimized solutions. For metro and long-haul infrastructure applications, where there is a growing need for an agile, resilient, ROADM-based architecture, performance-optimized coherent solutions that can be tuned to provide optimal capacity across any network path are required. In these scenarios fiber resources are usually limited and maximum spectral efficiency is the predominant requirement. Such high performance solutions usually migrate from on board module to pluggable as technology matures. For data center interconnect (DCI) applications, coherent optics can be integrated in the same platform with packet switching and footprint-optimized solutions were introduced, e.g. 4th generation optics with the introduction of 400ZR/ZR+. While various laboratory and field trials with coherent transponders of the 5th generation, operated up to 800 Gb/s, have been reported to date [1-3], research and development is currently ongoing to establish the next generation of coherent optics with transmission rates up to 1.6 Tb/s and symbol rates beyond 120 Gbaud.

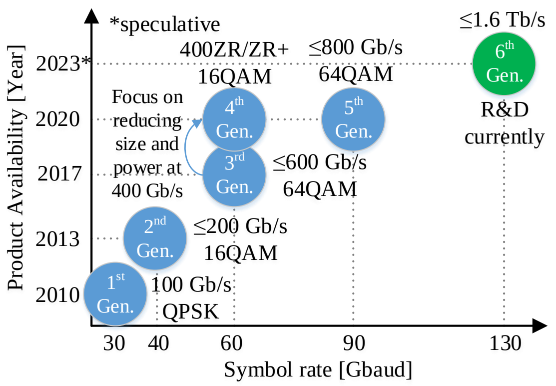

Fig. 1: Evolution of coherent optics.

Within the scope of the research activities for the 6th generation, we report a field trial on single-carrier flexible coherent transmission demonstrating net bitrates up to 1.6 Tb/s using the German nationwide fiber infrastructure of the R&D field test network of Deutsche Telekom consisting of field-deployed standard single mode fiber (SSMF), optical add-drop multiplexers (OADMs) and Erbium-doped fiber amplifier (EDFA)-only amplification. We demonstrate net bitrates of 930 Gb/s over 1105 km, 1.28 Tb/s over 452.4 km, and 1.6 Tb/s over 153.4 km links.

Experimental Setup

The schematics of the transmitter and receiver are shown in Fig. 2-a. The data signal, consisting of four real components, is generated by four SiGe digital-to-analog converter (DAC) application-specific integrated circuits (ASICs) [4] operated at 130 GSa/s by overclocking and careful temperature control. The electrical

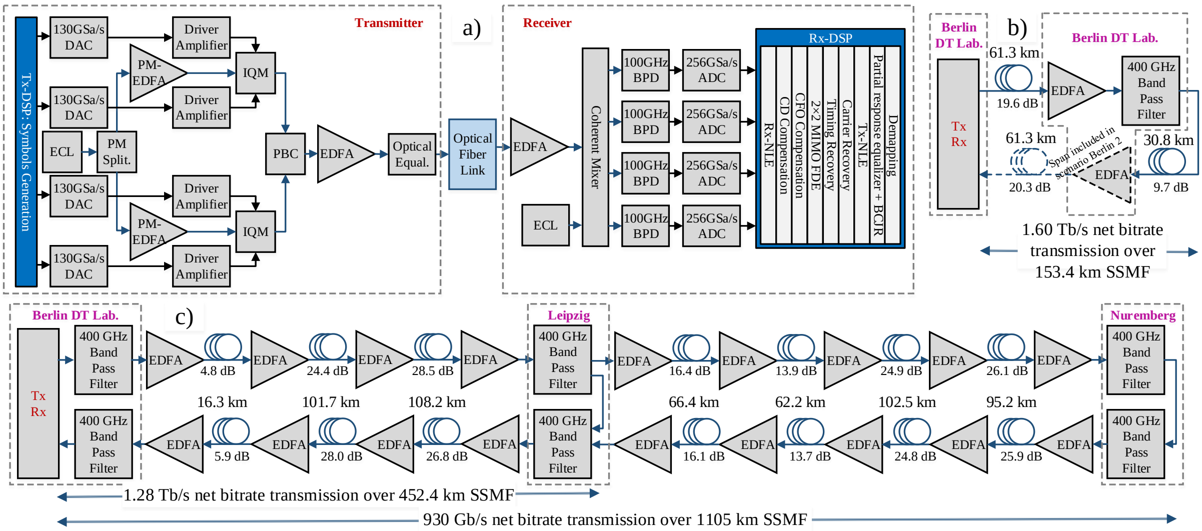

Fig. 2: Schematic of the experimental setup: a) flexible transmitter and receiver, b) city network configuration achieving 1.60 Tb/s net bitrate transmission, c) metro/long-haul configuration achieving 1.28 Tb/s and 930 Gb/s net bitrate transmissions.

outputs of the DACs are connected to four single-ended RF amplifiers with 72 GHz 3 dB-bandwidth and 11 dB gain driving two electro-optic GaAs IQ modulators having 6 dB-bandwidth exceeding 50 GHz, as used in [5]. The output optical signal of a tuneable external cavity laser (ECL) with <100 kHz linewidth is split in a polarization maintaining (PM) splitter and amplified by two PM-EDFAs before feeding the IQ modulators with 18 dBm optical power. The dual-polarization (DP) signal is obtained by recombining the output of the IQ modulators using a polarization beam combiner (PBC). The DP signal is amplified by an EDFA before a configurable optical filter (waveshaper) that, with 8 dB pre-emphasis, flattens the power spectral density of the modulated signal. The transceiver can be tuned over 5.36 THz from 191.1 THz to 196.46 THz. The optical power of the modulated signal at the output of the waveshaper can reach up to 12 dBm.

The receiver consists of an EDFA used to keep the optical power at the input of the receiver constantly at 7 dBm, a coherent mixer and four 100 GHz balanced photodetectors (BPDs) connected to a 256 GSa/s 80 GHz oscilloscope. Another ECL with linewidth <100 kHz is used as local oscillator.

The DSP makes use of advanced and fully adaptive nonlinear component equalizers, targeting imperfections such as bandwidth limitations, frequency-dependent I/Q imbalance and skew, phase ripple, I/Q crosstalk and high-order nonlinearities at transmitter and receiver. A first digital Volterra equalizer (Rx-NLE in Fig. 2-a) addresses the imperfections of the receiver components, i.e. optical-electronic front-end and analog-to-digital converter (ADC). After multiple-input and multiple-output (MIMO) channel equalization and demodulation (including carrier phase recovery), another Volterra equalizer (Tx-NLE in Fig. 2-a) compensates for the imperfections of the transmitter. Since the transponder imperfections arise mostly in the electrical domain, where the two tributaries are independently processed, also the equalizers operate on the real tributaries rather than on the complex baseband signal. Finally, partial-response equalization (PREQ) with impulse response 1+αD is implemented to whiten the noise, followed by a complex-valued BCJR algorithm with one memory tap used for sequence detection, similarly to [2-3,5].

Fig. 2-b shows the city network configuration to demonstrate feasibility of 1.6 Tb/s net bitrate transmission. Transmitter, receiver and other network elements are installed in a Deutsche Telekom laboratory in Berlin while the SSMF is deployed within the city area. This network configuration is based on a star topology with a central passive OADM. This bi-directional OADM is implemented by a pair of 12×12-port arrayed waveguide grating (AWG) devices subdividing the extended C-band of 4.8 THz band into 12 bands of 400 GHz bandwidth each. The measured non-flat transmission profile of a single OADM (AWG pair) at band number 6 within the 400 GHz window can be found in [6]. The scenario Berlin 1 consist of two spans while the scenario Berlin 2 is extended by a third span as described in Table 1.

Fig. 2-c shows the links of the field-deployed

Tab. 1: Details of the transmission links.

City of loopback	Distance [km]	Num. of spans	Num. of OADMs	Accumulated loss [dB]
Berlin 1	92.1	2	1	38.6
Berlin 2	153.4	3	1	58.9
Leipzig	452.4	6	4	121.25
Nuremberg	1105	14	6	284.6

German nationwide R&D test network of Deutsche Telekom used to demonstrate ≥800 Gb/s and ≥1.2 Tb/s net bitrate transmission. They consist of multiple spans of SSMF with EDFA-only amplification and OADMs.

The loopback in Leipzig is performed using band 10 (191.925 THz – 192.325 THz), while the one in Nuremberg is done using band 3 (194.725 THz – 195.125 THz). The details of the link configurations are included in Table 1.

Experimental Results

Measurements are performed using a family of probabilistic constellation shaping (PCS) formats of variable entropy (H) obtained from square quadrature-amplitude modulation (QAM) formats, compatible with probabilistic amplitude shaping (PAS) [7]. The net bitrates reported are obtained using a set of practical codes with similar FEC margins requiring less than 32% overhead [8].

The experimental results in terms of net bitrate and achievable information rate (AIR) vs launch power, considering the city network configurations, are shown in Fig. 3. The modulation format selected for these transmission experiments is DP-PCS400QAM with H=8.44 bit/2D-symbol. With 10 dBm launch power, net bitrates of 1.65 Tb/s and 1.60 Tb/s are achieved in scenario Berlin 1 and Berlin 2, respectively.

Fig. 4 shows the experimental results obtained with the transmission link configured with the loopback in Leipzig. Since the EDFAs of a third party in this network are configured in automatic power control which prevents a power sweep, the results are plotted in terms of bitrate vs entropy. Using DP-PCS64QAM with H=5.6 bit/2D-symbol, the highest net bitrate achieved is 1.28 Tb/s.

Fig. 5 summarizes the transmission results obtained over the 1105 km link configured with the loopback in Nuremberg. Three modulation formats are considered: DP-PCS16QAM, DP-PCS36QAM and DP-PCS64QAM. With DP-PCS16QAM, the highest net bitrate of 900 Gb/s is obtained for H=3.9 bit/2D-symbol. Using DP-PCS36QAM, the highest net bitrate of 930 Gb/s is achieved for H=5 bit/2D-symbol. For DP-PCS64QAM, the highest net bitrate of 925 Gb/s is obtained also for H=5 bit/2D-symbol.

DP-PCS36QAM performs better than DP-PCS64QAM because it has a lower peak-to-average power ratio (PAPR), which is beneficial against quantization noise in the DAC, nonlinear distortion at the transmitter and nonlinear effects in the fiber. In addition, Fig. 5 suggests that the advantage of DP-PCS36QAM over DP-PCS64QAM is more pronounced in net bitrate than in AIR. This, however, is an accidental effect caused by the discrete set of practical FEC codes from which we sample [8,9].

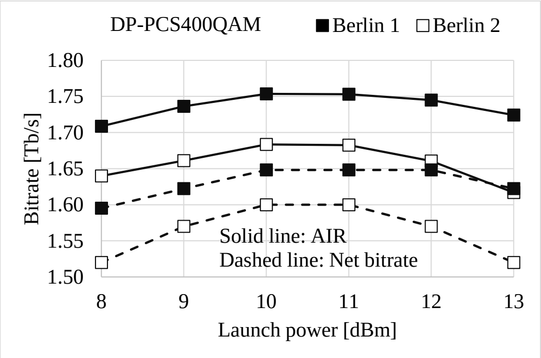

Fig. 3: Bitrate vs launch power for single-carrier 130 GBaud DP-PCS400QAM transmission over scenario Berlin 1 (92.1 km city network link with 2 spans of SSMF and 1 OADM) and Berlin 2 (153.4 km city network link with 3 spans of SSMF and 1 OADM).

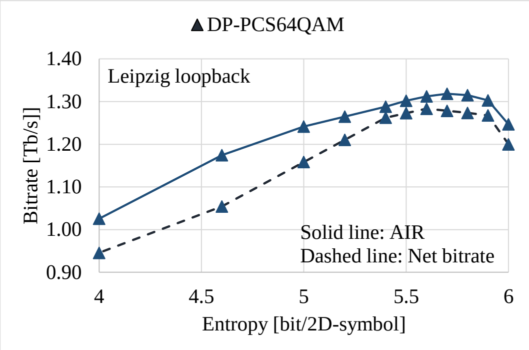

Fig. 4: Bitrate vs entropy for single-carrier 130 GBaud DP-PCS64QAM transmission over 452.4 km metro network link with 6 spans of SSMF and 4 OADMs.

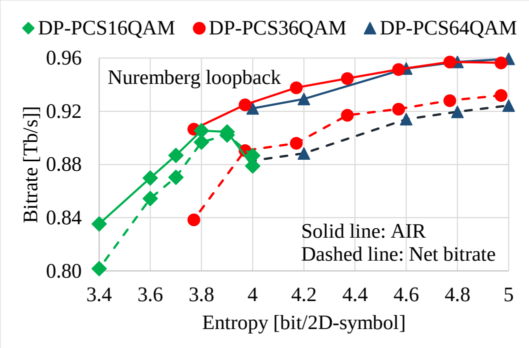

Fig. 5: Bitrate vs entropy for single-carrier 130 GBaud DP-PCSmQAM (m = 16, 36 or 64) transmission over 1105 km metro network link with 14 spans of SSMF and 6 OADMs.

Conclusions

We demonstrated the first proof of concept of the 6th generation coherent technology in a field trial using a German wide R&D field test network infrastructure, with SSMF, EDFA-only amplification and OADMs, provided by Deutsche Telekom. With a single-carrier and symbol rate of 130 GBaud, we achieved DP-PCS400QAM 1.60 Tb/s net bitrate transmission over a 153.4 km city network configuration, DP-PCS64QAM 1.28 Tb/s net bitrate over a 452.4 km metro network link and DP-PCS36QAM 930 Gb/s net bitrate over a 1105 km long-haul network scenario.

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