Optical Network Design with High Symbol Rate Flexible Coherent Transceivers

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Abstract: We highlight commercial flexible coherent transceivers, including their features and capabilities for optical networks, and present the versatility of a 140-GBd transceiver in typical optical link configurations from short reach to subsea.

1. Introduction

A significant development within optical networking in recent years is the emergence of transceivers with advanced digital coherent modems which offer a high degree of tunability in signal characteristics including data rate, symbol rate and spectral efficiency. A parallel evolution is the steady increase of data rate per channel using higher symbol rates, thus allowing a channel with a single optical carrier to operate at lower bits per symbol for the same data rate. Such flexible transceivers with high symbol rates enable the highest data rate per channel to be achieved on a given link by optimally adapting to link constraints and transmission impairments thus maximizing the total capacity across a network. The latest generation of commercial transceivers operate at net data rates up to 1.2 Tb/s with probabilistically shaped 64QAM and symbol rates up to 130 [1] or 140 GBd [2]. Furthermore, net data rates of 1.6 Tb/s and symbol rates up to 200 GBd have been announced [3]. Today's commercial transceivers are available as single-carrier [1, 2, 4] and multiple-carrier variants, with the latter either using multiple optical sub-carriers [5] or a single optical carrier with digital sub-carriers via frequency-division multiplexing [4, 6].

In this paper, we first review features enabled by the latest generation of high symbol rate flexible coherent transceivers and then report on the system performance of a 140-GBd transceiver across a wide range of network applications from single-span with high spectral density to record-distance subsea links.

2. Recent progress on flexible coherent transceivers

The highest performing coherent transceivers use embedded/on-board modems and include the latest developments in analog, digital and opto-electronic components, the most advanced DSP algorithms and optimum soft-decision FEC. Pluggable coherent transceivers are available in standardized form factors (CFP2, QSFP, and OSFP), have strict limits on geometric dimension, electrical power and thermal dissipation, and need to provide a cost-attractive solution for the market. Consequently, they offer less functionality, lower performance, and less flexibility compared to their embedded counterparts.

Flexibility and adaptability can be realized through different features including selectable net data rates, continuously tunable symbol rate along with the QAM-order, probabilistic constellation shaping (PCS), configurable digital sub-carriers, adjustable pulse shaping, different forward-error correction (FEC), chromatic dispersion (CD) compensation range, and different flavors for mitigation of fiber nonlinearities and tolerance to fast changes in polarization. Figure 1 illustrates a few examples, showing single-carrier and multi-carrier realizations, continuous symbol rate tuning, and modulation formats with different QAM order. 64QAM has become widely available in current embedded transceivers. Continuous tuning of the bit/symbol is available through PCS. In addition to proprietary modes optimized for performance, transceivers often include standardized and interoperable modes known as OIF 400/800ZR, OpenROADM, OpenZR+, and Cablelabs.

Coherent transceivers also provide extensive performance monitoring (PM) which supports channel optimization and provides valuable diagnostics in troubleshooting activities. This includes pre/post-FEC BER and other FEC statistics, Q-factor, total power, signal power, carrier-frequency offset, state-of-polarization vector and change rate, accumulated chromatic dispersion, polarization dependent loss, differential group delay/polarization

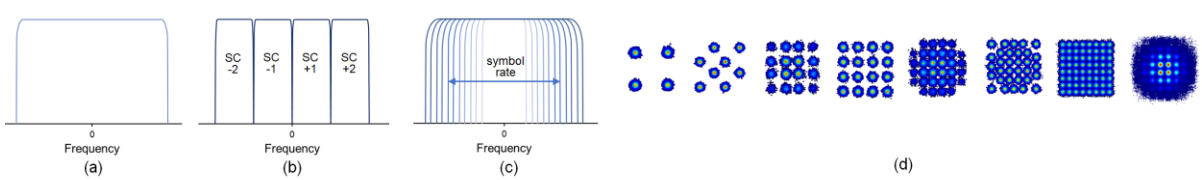

Fig. 1. Illustration of (a) single-carrier and (b) multi-carrier solution, (c) continuous symbol rate tuning, and (e) adaptable QAM order.

mode dispersion, electrical signal-to-noise ratio, optical signal-to-noise ratio, and more. The PM parameters are typically available at intervals of seconds and milliseconds or even faster.

Access at the receiver to analog-digital converter samples (for post processing and e.g. spectral analysis), equalizer taps, and constellation allow further analytics and diagnostics. Due to their high performance and advanced features, transceivers often could be utilized as ‘quasi’ test and measurement equipment. More functions which are currently only available with offline post-processing might become available on-chip in coming generations. This would make analytics like longitudinal link monitoring [7] more accessible and usable and have added value in optical links design [8].

3. 140-GBd single-carrier transceivers in system applications

We previously reported on the system performance of the first commercially available 140-GBd single-carrier coherent transceiver [2], presenting results of a field trial on a live network [9], which showed transmission of 800-Gb/s over a record distance of 2,220 km and 1,422 km with filtering, and transmission of 1-Tb/s over 869 km.

Here, we illustrate the application of the same 140-GBd transceiver in diverse applications emulated in a lab environment, from inter-data center, metro/regional, long-haul to subsea applications and corresponding transmission distances ranging from 100 to 24,000 km at net data rates from 400 Gb/s to 1.2 Tb/s. Details on the tested system configurations are summarized in Table 1 and the experimental setups of the different links are shown in Fig. 2, with results summarized in Fig. 3.

Short reach. A single-span configuration was chosen as a typical inter-datacenter application, as shown in Fig. 2(a), with booster and pre-amp EDFA, transmitting 138-GBd 1.2-Tb/s PDM-PCS64QAM, 5.27 bits/sym./pol., over 100 km standard single-mode fiber (SSMF, loss 20 dB). A dedicated 32-channel grid-less multiplexer and demultiplexer with flat-top 425-GHz passbands is used at Tx and Rx. Shaped ASE-noise loader channels are used along with the 140-GBd test channel at 150-GHz channel spacing. The results including a Tx spectrum are shown in Fig. 3(a), at an optimized per-channel power of 3.8 dBm with a Q-factor around 7 dB and the measured linear OSNR close to 33 dB (including Tx-OSNR) with the transceiver tuned to three different frequencies.

Metro/long-haul. The second configuration consists of a link with ROADMs and 100-km spans with hybrid EDFA/Raman amplification for either 1200 or 1800 km. Metro/regional and long-haul networks rely on ROADMs which enable flexible routing. Wavelength-selective switches (WSS), an integral part of ROADMs, create passband filtering, an aspect which can be addressed by transceivers adapting their symbol rate and modulation to minimize performance degradation from passband filtering as a trade-off between OSNR requirement and filtering tolerance [10]. Figure 2(b) details the setup. The test link includes up to 12 passbands from WSSs of the ROADMs. The cascaded passband of the 12 WSS has a -3-dB value of about 139 GHz. For transmission of 1 Tb/s at 135 GBd PDM-PCS32QAM (4.48 bits/sym./pol.) over 1200 km, results are shown in Fig. 3(b). A transmit spectrum is shown together with the Q-factor when the test channel is tuned to different frequencies. The Q-factor ranges from 6.2 to 6.6 dB at an optimum per-channel power of about 4 dBm with the linear OSNR ranging from 27.8 to 29.7 dB.

For transmission of 800 Gb/s at 138 GBd PDM-PCS16QAM (3.52 bits/sym./pol.) over 1800 km, results are shown in Fig. 3(c). The Q-factor with the test channel tuned to different frequencies ranged from 7.3 to 7.8 dB with the linear OSNR ranging from 25.5 to 27.4 dB. More insight on the impact of passband filtering from the 12 WSS can be gained by detuning the transmitter optical frequency to identify the limits in the configuration with passband filtering present from 12 WSS. A frequency detuning range of +/- 4 GHz was identified with a reduction in Q-factor by less than 0.3 dB when testing in frequency increments of 1 GHz. This is sufficient for expected frequency offsets of typical transmitter lasers and WSSs. Decreasing the number of WSS which apply passband filtering on the signal from 12 to 2 increases the Q-factor by 0.3 dB, indicating a low filtering penalty.

Subsea. The final configuration, Fig. 2(c), is a recirculating loop test bed to test over extended link distances for subsea cables up to 24,000 km. The test channel is coupled with 24 ASE-noise loaders. The loop is composed of 600 km OFS TeraWave SCUBA fiber with attenuation of 0.155 dB/km and total accumulated CD of 13,042 ps/nm per loop. EDFA-only amplification with constant output power is used in the loop. The transceiver has an electrical trigger input which enables loop-synchronous BER measurements. Transmitted spectrum and results of Q-factor over fiber input power per channel are reported in Fig. 3(d). For 800 Gb/s at 138 GBd PDM-PCS16QAM we

Table 1. System configurations in lab measurements with 140-GBd transceiver.

cfg #	distance [km]	data rate [Gb/s]	symbol rate [GBd]	modulation	#WSS	channel spacing [GHz]	# spans	span length [km]	fiber type
1	100	1,200	138	PDM-PCS64QAM	-	150	1	100	SSMF
2	1,200	1,000	135	PDM-PCS32QAM	8	150	12	100	SSMF
3	1,800	800	138	PDM-PCS16QAM	12	150	18	100	SSMF
4	7,200	800	138	PDM-PCS16QAM	-	150	120	60	SCUBA
5	10,800	400	118	PDM-QPSK	-	150	180	60	SCUBA
6	24,000	400	118	PDM-QPSK	-	150	400	60	SCUBA

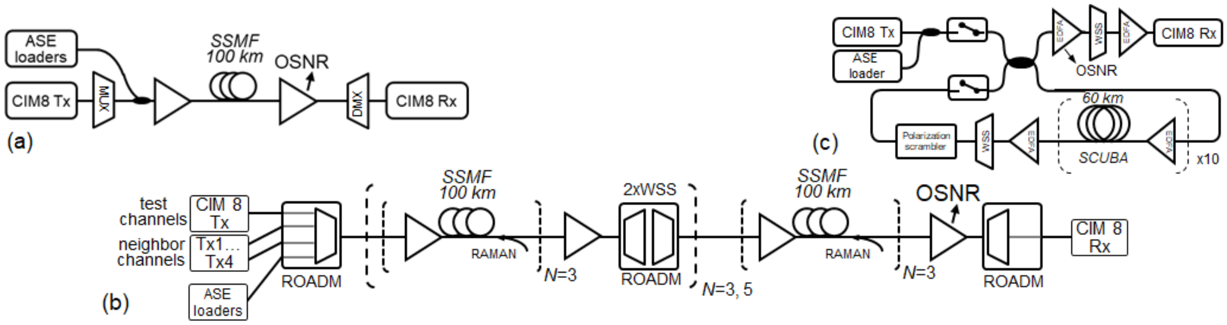

Fig. 2. Lab setups for (a) 1-span inter-data center link [cfg. #1], (b) link with ROADMs [cfgs. #2,3], (c) recirculating fiber-loop [cfgs. #4,5,6].

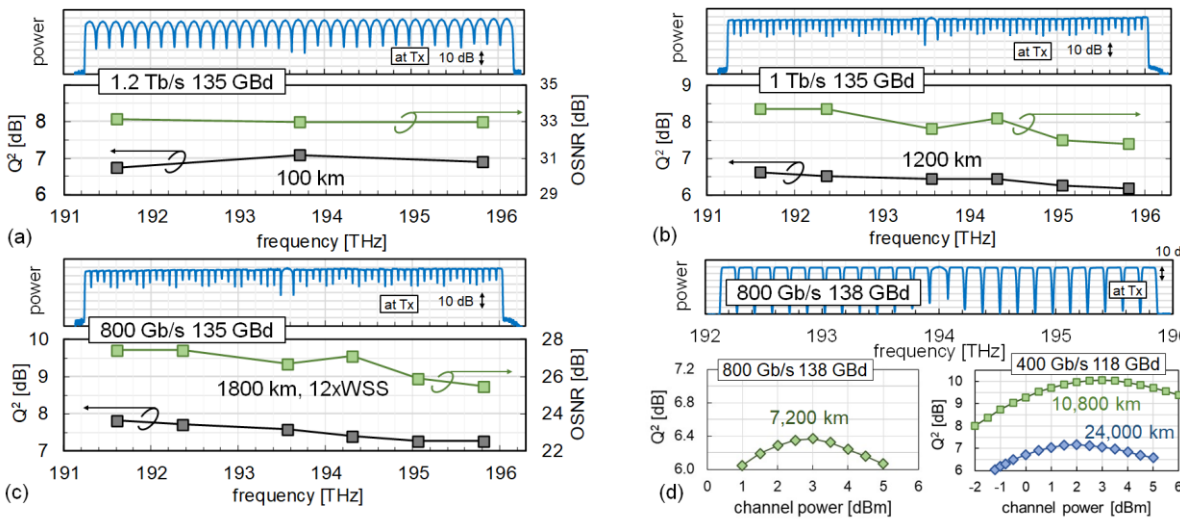

Fig. 3. System performance with 140-GBd transceiver in four different link configurations from 100 to 21,600 km.

achieved transmission over the trans-Atlantic distance of 7,200 km, equivalent to 12 loops and 156,510 ps/nm of CD with a Q-factor of 6.4 dB at an optimum per-channel power of 3 dBm and a corresponding linear OSNR of 23.8 dB. For 400 Gb/s at 118 GBd PDM-QPSK, we achieved transmission over a trans-Pacific distance of 10,800 km, consisting of 18 loops, accumulating 234,765 ps/nm of CD, and over a record distance of 24,000 km, realized with 40 loops, totaling 521,632 ps/nm of CD. At 10,800 km, the highest Q-factor of 10 dB is achieved at 3-dBm per-channel power with an estimated linear OSNR of 21.8 dB. More than doubling the distance to reach 24,000 km the best measured Q-factor is 6.5 dB at 1.5-dBm per-channel power with an estimated linear OSNR of 17.5 dB. All reported results are post-FEC error-free. To our knowledge, these are record distances at 400 and 800 Gb/s for single-carrier transceivers with real-time coherent DSP.

4. Conclusion

We have provided insight into the current generation of flexible transceivers, their features, and capabilities relevant for optical networks. The versatility and adaptability of a commercial 140-GBd transceiver was presented in typical optical network applications from short-reach access at 1.2 Tb/s to record-distance subsea links at 400 and 800 Gb/s.

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