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CO-OFDM for bandwidth-reconfigurable optical interconnects using gain-switched comb

LAKSHMI NARAYANAN VENKATASUBRAMANI,[1,*] YI LIN,[2] COLM BROWNING,[2] ANIRUDH VIJAY,[1] FRANK SMYTH,[3] R. DAVID KOILPILLAI,[1] DEEPA VENKITESH,[1] AND LIAM P BARRY[2]

[1] *Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai, Tamil Nadu, India*
[2] *Radio and Optical Communications Laboratory, School of Electronic Engineering, Dublin City University, Dublin 9, Ireland*
[3] *Pilot Photonics Ltd., Invent Building, Dublin City University, Dublin 9, Ireland*
[*] *ee14d402@ee.iitm.ac.in*

Abstract: We experimentally demonstrate superchannel transmission using CO-OFDM with higher cardinality QAM corresponding to total data rates up to 760 Gbps over 25 km fiber using optical carriers generated from an externally injection locked gain-switched comb source with linewidth ≈19 kHz. Bandwidth re-configurability is demonstrated by operating the comb with different line spacing (20 GHz, 11 GHz) for the choice of (16-/32-/64-) QAM considered and we show the BER performance is within the SD-FEC limit. The system proposed can be used in any short reach application including DCIs and in access networks.

1. Introduction

The proliferation of wireless networks and cloud based storage and computing has led to increasing demand for capacity in data-center interconnects (DCI). Traditional intensity modulated systems are now getting replaced by coherent (both intensity and phase modulated) systems as the latter is an appealing solution even for such short reach (< 80 km) applications due to the advances in integrated photonics and the ability to achieve larger data rates with higher spectral efficiency (SE) [1–3]. Coherent optical OFDM (CO-OFDM) for DCI application has been investigated as an alternate candidate to Nyquist shaped QPSK/16QAM single carrier transmission because of its improved SE, simplified channel equalization and inherent robustness to chromatic dispersion [4].

In contrast to Nyquist WDM, CO-OFDM exhibits multi-dimensional optical system agility, and this aspect is shown in Fig. 1(a). The use of CO-OFDM can be advantageous in flex-grid optical networks as it exhibits flexible data (QPSK/16QAM/64QAM) assignment to subcarriers, software controllable subcarrier spacing and fragmentation of its subcarriers, which aids in bandwidth allocation based on demand and also exhibits easier integration in superchannel systems. This feature can significantly improve the capacity of the optical network [6] and can be embedded easily into a software defined networking platform. Single sideband direct detection OFDM (SSB DD-OFDM) also offers spectral efficiency similar to CO-OFDM but with poor sensitivity due to large carrier to single power ratio.

Capacity scaling in DCIs can be achieved by using superchannels where the data is multiplexed over multiple optical carriers, considering it as a single unit of traffic [5]. Optical frequency combs have naturally lent themselves as the most suitable candidate for such multi-wavelength optical sources in superchannel systems, as the generated lines are correlated. Interference due to the relative drift between wavelength channels is minimal in the case of correlated lines compared to the case that employs independent laser sources. Comb sources also allow for a smaller footprint and lower cost transceiver design. Tunability of the comb, combined with the ability to easily tailor OFDM signal bandwidth, results in a highly flexible superchannel transmission

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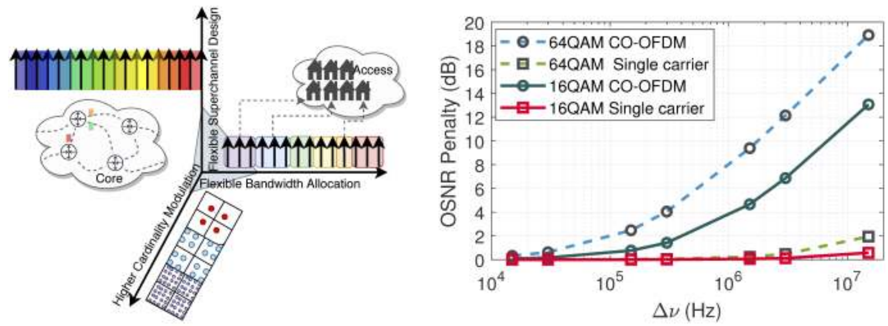

(a) (b)

Fig. 1. (a) Multi-dimensional agility of coherent optical OFDM (b) OSNR penalty evaluated for a BER of 1×10^{-3} at various linewidth for systems employing 16/64QAM CO-OFDM and Nyquist shaped single carrier modulation with baseband sampling rate/symbol rate of 30 GS/s.

system. Frequency combs for Terabit/s transmission with CO-OFDM have been investigated in the past using comb generation based on cascaded intensity modulators [7–9]. However, such modulator based comb generators are bulky and expensive to the alternatives available in current deployments. Hence, comb sources that allows dense photonic integration are more advantageous from a practical and economic perspective. Sources based on mode locked lasers (MLL), gain-switching and Kerr combs are excellent options for photonic integration [10]. MLL based comb sources are typically used in the generation of all-optical OFDM signals [11]. In [12], authors have shown Terbit/s CO-OFDM using Kerr combs and to the best of our knowledge, there has been no demonstration of CO-OFDM with gain-switched combs (GSC).

We recently demonstrated the use of GSC for 16QAM CO-OFDM transmission over 25 km SMF [13]. Transmission of CO-OFDM with higher cardinality of the constellation points necessitate the comb lines to have lower linewidths to avoid significant deterioration due to phase noise [14]. The optical signal to noise ratio (OSNR) penalty as a function of linewidth for both 16/64QAM CO-OFDM and 16/64QAM Nyquist WDM signals at a baseband sampling rate of 30 GS/s and evaluated at a BER of 1×10^{-3} is shown in the Fig. 1(b). It can be seen that OSNR penalty for CO-OFDM systems is very large compared to the single carrier system and hence the effect of phase noise can be detrimental to the performance. It is obvious from Fig. 1(b) that the demonstration of CO-OFDM poses completely different challenges in comparison with single-carrier Nyquist shaped systems. The optical carrier should have low linewidth in-order to reduce the penalty due to phase noise in the case of CO-OFDM. In our demonstration, comb is formed by gain-switching a distributed feedback (DFB) laser. A master low-linewidth external cavity laser (ECL) is injected into the slave DFB laser to reduce the linewidth of the generated comb lines.

Previously, Nyquist WDM with GSC has been demonstrated in [15]. Here, we demonstrate that the generated GSC is a suitable source as a flexible optical superchannel transmitter by using 8 lines of the comb for the transmission of 608/760/480 Gbps using 16/32/64 QAM respectively over 25 km standard single mode fiber (SSMF). We show the flexibility of the comb spacing by choosing the free spectral range (FSR) of 20 GHz or 11 GHz for 16/32 QAM or 64 QAM respectively. We show that the received bit error rate (BER) falls below the 25% forward error correction (FEC) limit of 3.8×10^{-2}.

The paper is organized as follows: Section 2 presents details of the generation and characterization of the gain-switched comb, Section 3 & 4 describes the details of the experimental setup and the results of the transmission of CO-OFDM superchannel and Section 5 concludes our findings.

2. Gain-switched comb source

Figure 2 shows the schematic of the gain-switched comb generation setup. Gain switching is achieved by driving the DFB slave laser diode ($\lambda_{slave} = 1549.978\ nm$) with a large sinusoidal signal (12 dBm, 2.52 V_{pp}), with the frequency f_{RF} corresponding to the desired comb spacing and with the DC bias current much larger than the threshold value ($I_{th} = 12.5\ mA$) [16] .

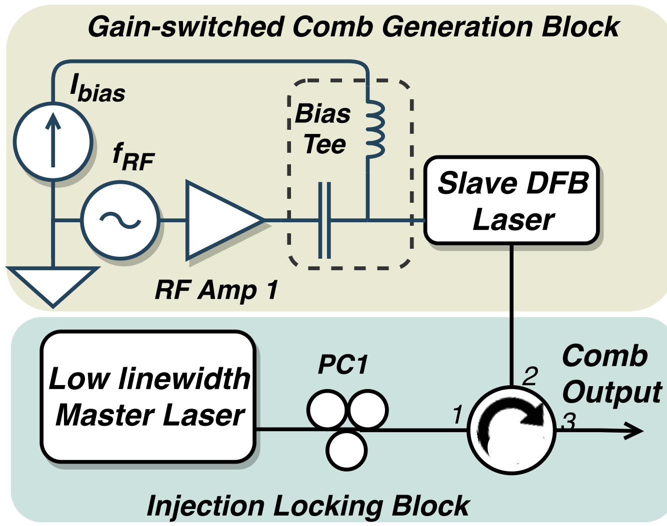

Fig. 2. Schematic of the gain-switched comb generation.

The spectrum of the generated comb with 20 GHz comb spacing is shown in Fig. 3(a). Increasing the driving voltage, increases the strength of the generated comb lines and in experiment, the allowed voltage is restricted by the allowed maximum ratings of the instruments. Due to the longer symbol duration (T_s) of the CO-OFDM system (4.5 ns for 19 GHz per comb line) compared to single carrier system (≈ 52 ps 19GBd), the CO-OFDM system is more susceptible to phase noise and hence suffers performance degradation due to common phase error (CPE) and inter-carrier interference (ICI) [17]. Hence, it is necessary to use external injection with the gain-switched DFB laser from a source with lower linewidth. It is also necessary to estimate the linewidth of the comb before and after injection of the master and here, we use the FM-noise spectrum method. An external cavity laser (ECL, Agilent N7711A, $\lambda_{slave} = 1549.988\ nm$) with linewidth of ≈ 19 KHz is used as the master laser to injection lock the gain-switched laser through a polarization controller and circulator, thereby establishing coherence and transferring the phase noise of the master laser to the gain-switched slave laser.

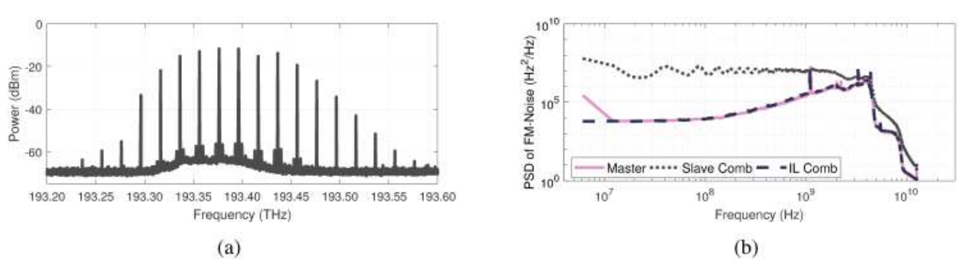

Fig. 3. (a) Output spectrum of the injection locked gain-switched comb (b) FM-noise spectrum of the master laser and that of a comb line before and after the injection.

Polarization controllers are used to align the polarization state of the injected master laser to that of the laser to the gain-switched slave laser. One of the comb lines is filtered (193.4162 THz) using a Yenista filter (XTM-50, bandwidth = 10 GHz) and the FM-noise spectra of the master and that of the line before and after injection locking (IL) is shown in Fig. 3(b). We used the standard coherent technique to measure the FM noise spectrum [18]. The estimated linewidth value of the master from the FM-noise measurement is about 19 kHz while that of the comb lines before injection of the master is about 31 MHz. The FM-noise of the comb lines approaches the same value as the master laser after injection. The increase in the FM-noise at higher frequencies is due to the noise floor of our measurement technique and is determined by photodiode noise and the quantization noise of the real time scope used for signal capture.

3. Experimental setup

The schematic of the experimental setup used to perform the transmission of CO-OFDM data, using the GSC, with fiber transmission is shown in the Fig. 4. An optical comb source with FSR of 20 GHz was used for modulating the lines with 16QAM and 32QAM CO-OFDM signals. The RF oscillator frequency was then tuned from 20 GHz to 11 GHz to generate comb lines with an FSR of 11 GHz for 64QAM CO-OFDM. The generated low linewidth comb is first sent to a wavelength selective switch (WSS, Finisar Waveshaper 4000S) to filter out desired lines ofinterest, which were then amplified using a PriTel in-line erbium doped fiber amplifier (EDFA 1) to overcome filtering and insertion losses of the transmitter before the optical modulation, followed by a Santec 2 nm bandpass filter (BPF 1) to reduce the out-of-band amplified spontaneous noise (ASE). The amplified signal is then fed as the carrier source to the IQ modulator. In the baseband offline signal generation at the transmitter, a PRBS-15 bit sequence is mapped to symbols of the desired modulation format.

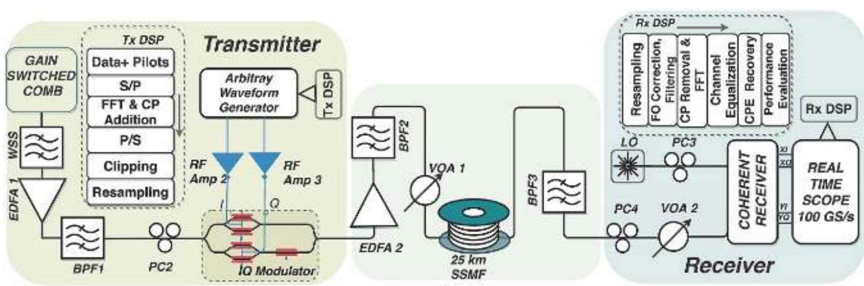

Fig. 4. Schematic of the experimental setup to perform the transmission of 16/32/64QAM CO-OFDM with injection locked gain switched comb.

The serial information data is then converted to parallel streams and is used to modulate the subcarriers of interest. Eight subcarriers loaded with known symbols, designated as pilot symbols, are interspersed across the other information subcarriers and are used for phase noise correction. Figure 5 shows the pictorial representation of such a scheme where, the dots in green show the pilot symbols interspersed across the subcarriers. The frequency domain data is then converted to time domain samples by performing a 128 point IFFT operation. A cyclic prefix of eight samples is added to the end of every OFDM symbol to account for the inter symbol interference (ISI) caused due to chromatic dispersion. The first few symbols are designated as training symbols and are shown as blue dots in Fig. 5, which is used for channel estimation and equalization in the receiver. These parallel time domain samples are then converted to serial data followed by hard clipping to reduce the effect of nonlinearity during the fiber transmission.The spectrum of the generated baseband signal for 16QAM and 64QAM data with 19 GHz and 10 GHz bandwidth respectively is shown in Fig. 6. The use of unfiltered CO-OFDM results is a

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spillover outside the designated bandwidth, resulting in a cross talk between the neighboring channels. This is avoided by using a 1 GHz guard band. Seamless CO-OFDM band stitching is possible with the use of filtered OFDM. The generated digital time domain samples are 3x upsampled and are fed to high-speed Keysight arbitrary waveform generator (AWG, 90 GSa/s) and the output electrical I and Q channels drives the Fujitsu IQ modulator (FTM 7961EX/302, 22 GHz bandwidth) where the generated electrical data modulates each of the optical comb lines.

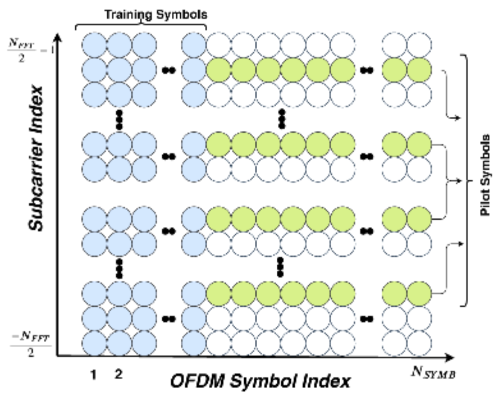

Fig. 5. Time and frequency distribution of OFDM symbols including the training symbols and pilot symbols.

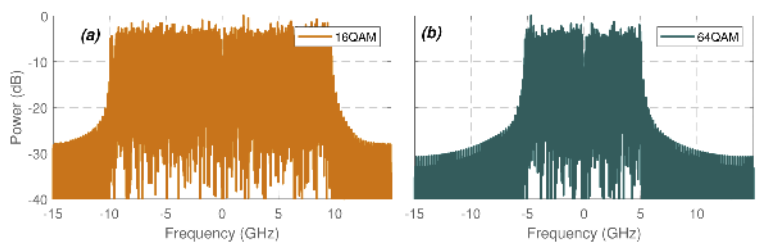

Fig. 6. Baseband spectrum of the generated (a) 16QAM CO-OFDM signal (19 GHz bandwidth) and (b) 64QAM CO-OFDM signal (10 GHz bandwidth).

In all the demonstrations, we had used 8 comb lines and due to limited infrastructure, the same data was used for modulating all the comb lines. The modulated signal is then amplified using a booster amplifier (EDFA 2, Alnair) followed by a Santec 2 nm filter (BPF 2) to reduce the out-of-band ASE and is then transmitted over 25 km SSMF. The channel of interest is first filtered using a Yenista bandwidth tunable band-pass filter (BPF 3) and is then fed to a coherent receiver (Fujitsu, FIM24721) using a low linewidth (≈10 kHz) fiber laser (NKT Photonics) as a local oscillator. The RF signal after the photo-detection is then fed to the high-speed Tektronix ADC (100 GS/s, 33 GHz) and the digitized data is collected for offline post-processing as detailed in [19].

The captured data is first corrected for frequency offset using the fourth power periodogram technique and is then re-sampled from 100 GSa/s to 30 GSa/s. The resampled data sequence is then correlated with one frame of the transmitted OFDM symbol to locate the start of each frame. One frame in each data set is parallelized followed by CP removal and is then converted from time domain to frequency domain by performing a 128-point FFT operation. Channel estimation is performed using the first ten symbols of both transmitted and received frame. Channel equalization is performed over the frequency domain information symbols. Pilot aided

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common phase error (CPE) estimation is performed using the transmitted pilot symbols to correct for the effect of phase noise and the corrected data symbols are then mapped back to bit sequences. Performance is then evaluated from the processed symbols and bits by estimating the bit error rate (BER), error vector magnitude (EVM) and the mutual information (MI). Unlike for Nyquist WDM, no explicit/additional dispersion compensation was performed during the DSP, which accentuates the advantageous implicit compensation of dispersion in CO-OFDM system.

With the use of advanced channel decoders with soft-decision inputs, the MI value gives the maximum achievable rate in the system. MI(X;Y) represents the amount of information about X that is contained in Y given that X is transmitted. Assuming that X and Y are discrete random variables and the symbols transmitted (with modulation order M) are uniformly distributed, MI is calculated as follows

$$MI(X;Y) = \sum_{m=1}^{M} \sum_{Y} \frac{1}{M} p_{Y|X}(y|x_m) log_2 \left[\frac{p_{Y|X}(y|x_m)}{p_Y(y)} \right], \tag{1}$$

where $p_{Y|X}(y|x_m)$ is a conditional probability mass function (pmf) of a received symbol $y \in Y$ for the m^{th} transmitted symbol $x_m \in X$ and $p_Y(y)$ is the pmf of the received symbols [20] and in this paper it is evaluated as explained in [21].

4. Results and discussion

The comb is generated using 8 lines (193.3161 THz + $n \times 0.020$ THz, n = 0 to 7) of the injection locked GSC with 20 GHz FSR. Gain flattening of the comb with WSS is performed by attenuating the center comb lines relative to the power of the outer lines and subsequent amplification as discussed in the previous section. The optical carrier to noise ratio (OCNR) of the gain flattened lines after WSS is measured to be >31 dB, which is good enough to be used at the transmitter for coherent systems. The OFDM data is generated with 16QAM/32QAM modulation with a baseband sampling rate of 30 GS/s and occupying a bandwidth of 19 GHz. The spectrum of the gain-flattened comb lines and with the 16QAM modulated signal is shown in Fig. 7.

Additionally, a tunable optical (BPF3) is used to select the channel of interest prior to coherent detection. The power of the received superchannel was about -27 dBm. The data rate per channel with 16QAM CO-OFDM is 76 Gbps and the total data rate of the entire superchannel is 608 Gbps with a spectral efficiency of 3.57 b/s/Hz. The spectral efficiency is calculated with the OFDM parameters as follows

$$SE(bits/sec/Hz) = \frac{N_{FFT}}{N_{FFT} + N_{CP}} \times \frac{Total\ Data\ Rate}{Number\ of\ channels \times Comb\ FSR}. \tag{2}$$

The factor $\frac{N_{FFT}}{N_{FFT}+N_{CP}}$ is added to account for the overhead due to the cyclic prefix. The data rate per channel with 32QAM CO-OFDM is 95 Gbps and the net data rate of the entire superchannel is 760 Gbps with a SE of 4.47 b/s/Hz.

Nonlinear effects play a critical role in deciding the performance and hence we first optimize the power launched into the fiber. We vary the launched power for both the 16QAM modulated comb and the 32QAM modulated comb as shown in Fig. 8(a) and in Fig. 8(b) respectively.

As expected, the performance improves with an increase in launched power up to the optimal launch power (found to be -1 dBm for both the cases) as the signal to noise ratio improves. With optical launch power increased above this point, distortion due to optical nonlinearities increases, and hence the performance degrades.

Figure 9(a) and (b) show the BER performances of the transmitted 608 Gbps 16QAM and 760 Gbps 32QAM CO-OFDM superchannel versus the sub-channel index, where the optical launch power was set to -1 dBm. The observed BER performance is well within the limits of standard SD-FEC BER limit of 3.8×10^{-2} for both these transmission cases. Figure 9(a) and (b)

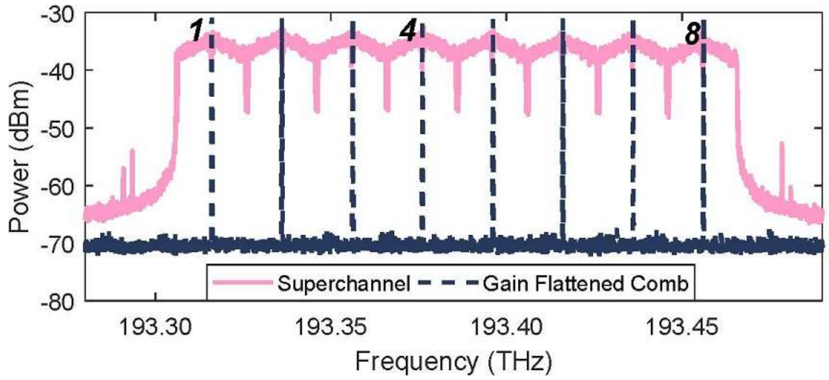

Fig. 7. Spectrum of the 8 channel 608 Gbps 16QAM CO-OFDM superchannel.

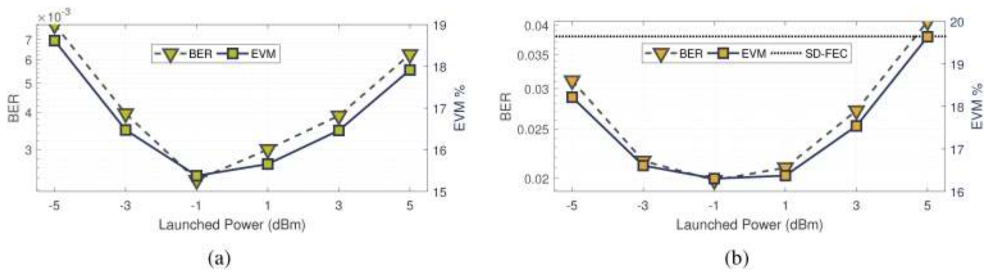

Fig. 8. Launched power optimization performed for 8 channel 16QAM CO-OFDM transmission showing BER and EVM vs launched power (b) Launched power optimization performed for 8 channel 32QAM CO-OFDM transmission showing BER and EVM vs launched power.

also show the MI performance and it is found to be >3.9 bits/symbols and >4.6 bits/symbols for 16QAM and 32 QAM respectively. The above results indicate the capability and scalability of the GSC for the transmission of data with higher order modulation format for a given comb spacing. In order to elucidate the reconfigurability, the injection locked comb is reconfigured to generate 8 lines with 11 GHz FSR. The OFDM data is generated with 64QAM modulation with a baseband sampling rate of 30 GS/s and a signal bandwidth of 10 GHz. Gain flattening and channel selection is performed in the same manner as in the previous transmission cases. The modulated superhannel, which has a total power of -3.5 dBm, is launched into 25 km SMF and the received power per channel at the coherent receiver was about -26 dBm. The data rate per channel with 64QAM CO-OFDM is 60 Gbps and the total data rate of the entire superchannel is 480 Gbps with a spectral efficiency of 5.13 b/s/Hz. Figure 9(c) shows the BER performance of the transmitted superchannel versus the sub-channel index. The observed BER performance is well within the limits of standard SD-FEC BER of 3.8×10^{-2}. Figure 9(c) also shows the mutual information performance versus the sub-channel index of the 64QAM CO-OFDM superchannel transmission. The mutual information across the sub-channels observed is >5.5 bits/symbols.

Table 1 shows the consolidated key parameters such as modulation format, comb spacing/ free spectral range (FSR), total data rate (R), MI and SE of the coherent optical OFDM with the injection locked GSC.

Results with 64QAM CO-OFDM indicates the ability of GSC with CO-OFDM to provide a platform for highly spectrally efficient and highly flexible optical interconnects just by changing the comb spacing and by using appropriate modulation format. The choice of low bandwidth

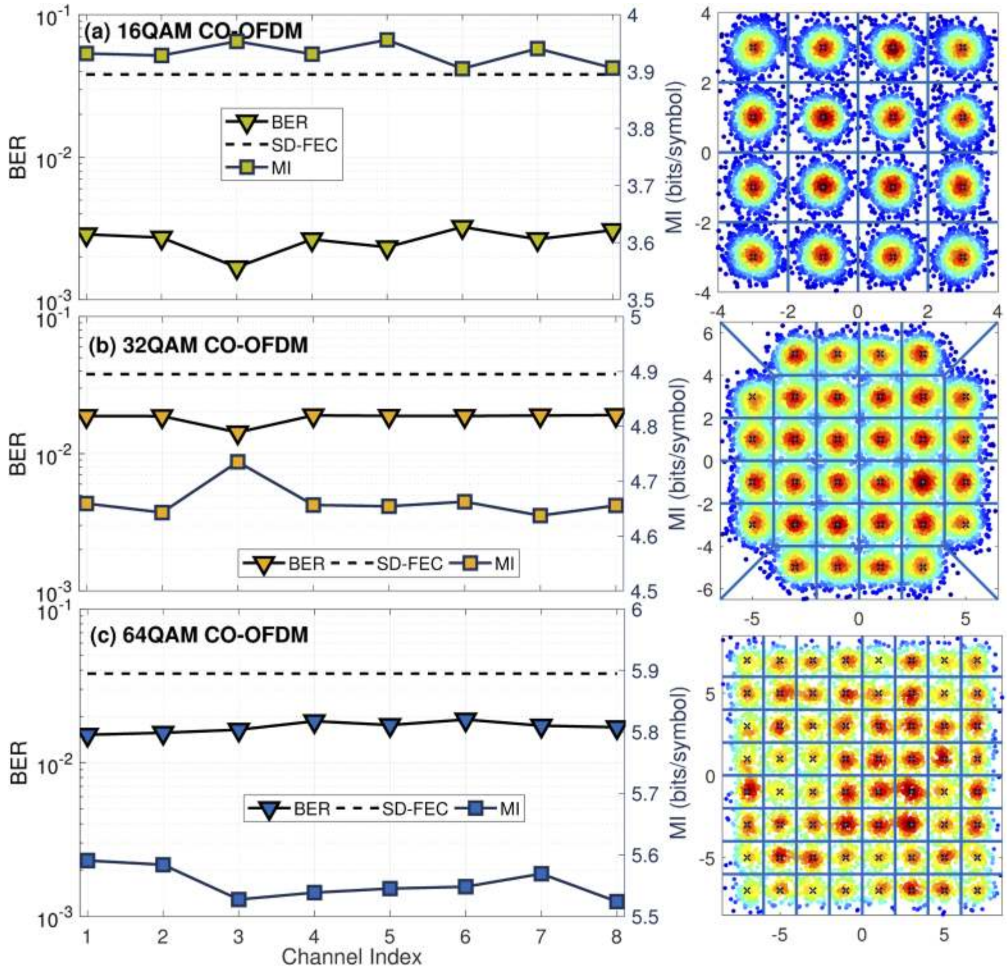

Fig. 9. BER performance and corresponding constellation diagram (CH4 data) of (a) 608 Gbps 16QAM CO-OFDM data (b) 760 Gbps 32QAM CO-OFDM data and (c) 480 Gbps 64QAM data at every channel of the three superchannel configurations.

Table 1. CO-OFDM with GSC Results

Modulation format	FSR (GHz)	R (Gbps)	MI (bits/Symbol)	SE (b/s/Hz/pol)
16 QAM	20	608	>3.9	3.57
32 QAM	20	760	>4.6	4.47
64 QAM	11	480	>5.5	5.13

occupancy of 64QAM is due to the fact that higher order QAM would demand higher receiver power and larger signal to noise ratio. The coherent receiver used in the experiment exhibited a relatively low saturation power of -26 dBm, thus restricting operation at increased received powers. Better performance and a possibility for the use of higher order modulation (above 64QAM) are expected with larger received power. The transmission results were taken over 25 km SMF to show the performance for an application to a short reach system. MI values measured for each case indicate that the transmission when used with an appropriate rate of forward error correction codes will ensure sufficient performance. The number of sub-channels used within

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the superchannel is dictated by the comb spacing, the modulation format used, and the power budget after gain flattening. The number of comb lines is decided by the gain switching process and comb expansion after that. Comb lines covering the C-band with good OCNRs has been already demonstrated [22] and hence the comb source itself does not pose a limitation in the C-band operation.

5. Conclusion

We demonstrate the transmission of greater than 400 Gbps (and up to 760 Gbps) spectrally efficient CO-OFDM data over 25 km SMF using injection locked gain switched-comb source. We also report the reduction in the linewidth of the generated optical comb lines to $\approx$ 19 kHz after injection, which is a key parameter when using advanced modulation formats and in phase noise less tolerant CO-OFDM systems. The ability of GSC with CO-OFDM in providing a platform for highly flexible interconnects is demonstrated by transmitting data at 608/760 Gbps 16QAM/32QAM data and at 480 Gbps 64QAM data using different combs with FSR's of 20 GHz and 11 GHz respectively. The key benefit of injection locking of a low linewidth master to that of the DFB slave is elucidated by using modulation order of higher cardinality. Although the demonstrations shown here were carried out using a GSC using discrete components, we are working on a photonic integrated comb source [23] to realize small form factor modules. Ability of scalable and flexible optical interconnects and with capability of photonic integration to produce small form factor modules makes GSC with CO-OFDM a very strong and potential candidate in the emerging coherent short reach systems such as metro DCIs.

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Disclosures

The authors declare no conflicts of interest.

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