High-Speed Bi-Directional Transmission Over Multimode Fiber Link in IM/DD Systems

Kaoutar Benyahya, Christian Simonneau, Amirhossein Ghazisaeidi, Pu Jian, Jean-François Morizur, Guillaume Labroille, Marianne Bigot, Pierre Sillard, Jérémie Renaudier, and Gabriel Charlet

(Invited Paper)

***Abstract*—We demonstrate a 14.5-Tb/s bi-directional transmission over 2.2 km of OM2 fiber using the selective excitation of four mode groups based on multiplane light conversion technology, wavelength division multiplexing, and direct detection. Forty wavelengths per mode group are used; each wavelength is modulated with a discrete multitone scheme with a fast Fourier transform length of 1024 subcarriers. An 88-Gs/s digital-to-analog converter is used to drive an external lithium niobate Mach–Zehnder modulator. The impact of each component in the line is studied experimentally. Moreover, Chow's rate-adaptive algorithm for bit and power allocation is optimized and adapted to the region where the bit error rate (BER) increases. In this paper, we are considering a hard-decision forward error correction (FEC) limit corresponding to a BER of 5×10^{-3} and assume a 7% overhead. To the best of our knowledge, the achieved bitrate in this paper is the highest throughput transmitted over multimode fibers using direct detection.**

***Index Terms*—Optical direct detection, optical fiber communication, optical interconnections, optical modulation, spatial division multiplexing.**

I. Introduction

MULTIMODE fiber links are very attractive for short reach transmission due to their easy coupling with low consumption chips such as directly modulated 850 nm vertical cavity surface emitting lasers (VCSELs). However modal dispersion is a major limiting factor within MMF affecting the capacity to meet the ever-growing demand of broadband services. The current products based on MMF links are limited to a maximum reach of 80 m and 550 m at 10 Gb/s using respectively OM2 and OM4 multimode fiber (802.3 -Edition 2015, Clause 52). Several studies focus on overcoming MMF limitations for short reach interconnect with direct detection (DD), notably modal dispersion, for the purpose of increasing the total transmitted throughput and extending the reach [1]–[4]. 100 Gb/s through 100 m of OM4 fiber using 850 nm VCSEL and multiband carrier-less amplitude/phase modulation (MultiCAP) [5] and pulse amplitude modulation (PAM) [6], [7], has recently been demonstrated. Moreover, 112 Gb/s over 300 m of OM4 fiber on a single-transverse-mode 850 nm VCSEL has been achieved using DMT modulation [8]. Reference [9] proposes offset launching, while [10]–[12] employs central launching of wavelength division multiplexing (WDM) on-off keying (OOK) channels onto an MMF, exciting only the fundamental mode. Spatial light modulator has also been proposed for mode selective excitation and bandwidth enhancement [13]. The use of spatial diversity has been proposed [14] and investigated in [15]–[20]. In our previous work [21] we achieved 5 Tb/s bidirectional transmission (2.5 Tb/s in each direction) over 2.2 km of OM2 multimode fiber using DD, WDM multiplexing, Mode Group Multiplexing (MGM) and Demultiplexing (MGD) based on multi-plane light conversion (MPLC) technology. The transmission of the same single channel throughput of 68.5 Gb/s over 2.2 km of OM2 has been reached using a low cost electro-absorption modulated laser (EML) instead of external Lithium Niobate Mach-Zehnder modulator (MZM) [22].

In this paper, we demonstrate 14.5 Tb/s bidirectional transmission over 2.2 km of OM2 fiber using discrete multitone (DMT) modulation, MPLC-based MGM and MGD, multimode WDM demultiplexer and DD. To reach 14.5 Tb/s we use 4 × 40 channels with channel net bit rate ranging from 86 Gb/s to 100 Gb/s depending on different mode group performances. The aim of this paper is to provide more details on the experimental results published in [23] and to present an optimized bit loading algorithm detailed in appendix 1.

II. Mode Group Multiplexer

The mode group multiplexer is based on MPLC technology [17]. The OM2 fiber supports 55 modes divided into 9 mode groups at 1550 nm, we use the first 4 mode groups for transmission as represented in Fig. 1. mode group 1 with LP01 mode, mode group 2 with LP11a and LP11b modes, mode group 3 comprising LP21a, LP21b and LP02 modes and finally mode

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K. Benyahya, C. Simonneau, A. Ghazisaeidi, J. Renaudier, and G. Charlet are with the Nokia Bell Labs Paris-Saclay, Nozay 91620, France (e-mail: kaoutar.benyahya@nokia-bell-labs.com; christian.simonneau@nokia-bell-labs.com; amirhossein.ghazisaeidi@nokia-bell-labs.com; jeremie.renaudiernokia-bell-labs.com; gabriel.charlet@nokia-bell-labs.com).

P. Jian, J.-F. Morizur, and G. Labroille are with Cailabs, Rennes 35200, France (e-mail: pu@cailabs.com; jf@cailabs.com; guillaume@cailabs.com).

M. Bigot and P. Sillard are with Prysmian Group, Parc des industries Artois Flandres, Billy Berclau, 69092 Haines, France (e-mail: marianne.bigot@prysmiangroup.com; pierre.sillard@prysmiangroup.com).

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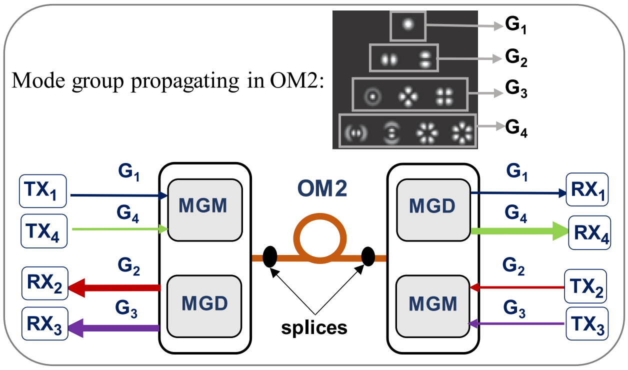

Fig. 1. Bi-directional configuration of the MGM (Mode Group Multiplexer) and MGD (Mode Group Demultiplexer). Thick lines represent OM2 multimode fiber and thin lines represent SMF.

TABLE I
MODAL CROSSTALK IN OUR EXPERIMENT

Mode group	MGD+MGM (dB)	OM2 Fiber (dB/km)
1	-28	-41
2	-14.5	-21
3	-12.7	-20
4	-17.2	-26

group 4 with LP31a, LP31b, LP12a, LP12b. A single Mode Fiber (SMF) is used at the input of MGM and the fundamental mode is converted into one mode of corresponding mode group. Modes within a group of modes are highly coupled, and exchange energy constantly. To avoid large fluctuation on the receiver we need to detect all the modes of a mode group. Therefore, in the demultiplexing side all the modes of a mode group are demultiplexed and send to a multimode OM2 fiber except for mode group 1 where the LP01 mode is sent to a SMF [21]. As represented in Fig. 1 the MGM and MGD have been designed for bi-directional transmission. Mode group 1 and 4 are transmitted in one direction and mode group 2 and 3 in the reverse direction. More details on the MGM and MGD could be found in [21]. Table I shows the modal crosstalk encountered by each mode group from the input of the MGM to the output of the MGD with 20 m of OM2 and the estimated modal crosstalk generated by the fiber. To estimate the modal crosstalk of the fiber, first the crosstalk of the MGD+MGM and 20 m of fiber with 2 splices is measured. Second, we replace 20 m of fiber by 2.2 km of fiber. Finally, we subtract the second measurement from the first one, to extract the modal crosstalk of the fiber alone. The modal crosstalk generated by 20 m of fiber is negligible. As the modal crosstalk induced by fiber splice could be different from one splice to another, we made 3 different splices for each measurement and averaged the value. Moreover, due to the bidirectional transmission, modal crosstalk is generated by the copropagating mode group only. For instance, the crosstalk for mode group 4 is created only by the mode group 1 and the crosstalk for mode group 1 is created only by the co-propagated mode group 4. There is no crosstalk due to the propagated mode groups in the opposite direction and the return loss is lower than −28 dB for all mode groups.

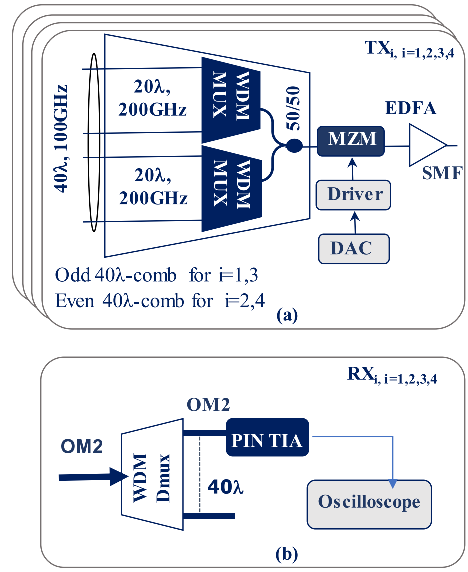

Fig. 2. a) Transmitter. b) Receiver.

III. 14.5 TERABIT/S EXPERIMENT

Schematics of the transmitter and the receiver are displayed in Fig. 2(a) and (b). To compensate for the insertion loss of the MGM and MGD as well as that of WDM Mux/Demux, we use single-mode single stage EDFAs at the output of the WDM multiplexers at the transmitter side. The total output power of each EDFA is 22.5 dBm. Standard OM2 fiber is spliced to the MGM and the MGD. At the transmitter (TX) side (Fig. 2(a)) we use a Mach-Zehnder intensity modulator (MZM) driven by a linear driver with 32 GHz bandwidth. The signal is generated by a 88 Gs/s CMOS digital to analog converter (DAC) with 22 GHz analog bandwidth. The effective number of bit is 5.5. At the receiver (RX) (Fig. 2(b)) the signal is detected with a multimode PIN-TIA photodiode with a 30 GHz bandwidth. The signal is then sampled by a 80 Gs/s oscilloscope with 33 GHz analog bandwidth. We use DMT modulation with a IFFT/FFT length of 1024, a cyclic prefix length of 2 samples, and a subcarrier separation frequency of 52.7 MHz. The typical PAPR value before clipping is 7.2 dB. A 25% maximum amplitude clipping is applied to the generated signal. Moreover, bit and power allocation per subcarrier are applied in order to compensate for the bandwidth limitation and channel impairment without a complex signal processing. The bit loading procedure is described in the Appendix 1.

The 40 channels of each mode group are modulated by a separate modulator. Off-line signal processing is used to demodulate the DMT signal and count the errors. The detected signal is normalized and resampled. A time synchronization is required to determine the beginning of DMT frames. For synchronization, a vector of 256 samples with repeated part is inserted at the beginning of each transmitted frame with 2^{17} samples. The vector of synchronization is detected through an auto-correlation operation over a sliding window [24]. After synchronization, cyclic prefixes are removed, and a FFT operation permits to obtain the data symbols in each subcarrier. A

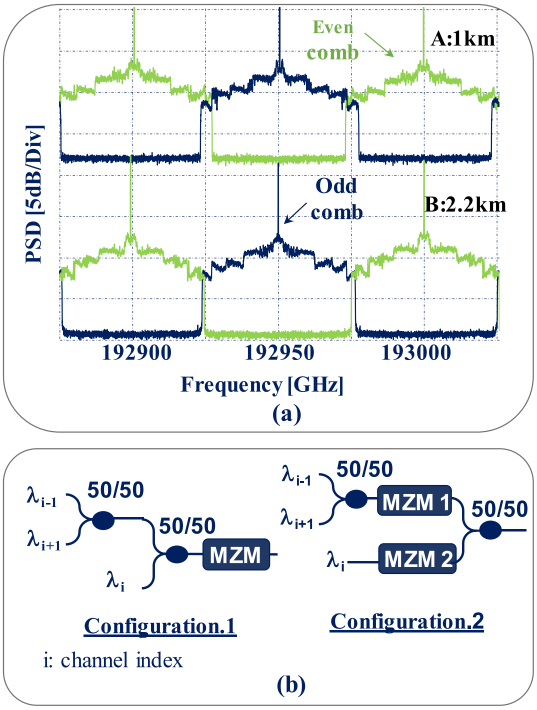

Fig. 3. a) Spectrum of co-propagating mode group 1 and mode group 4 in one direction, A for 1 km experiment and B for 2.2 km. b) 2 different configurations used to measure the penalty due to wavelength crosstalk in the WDM multimode demultiplexer induced by adjacent channels.

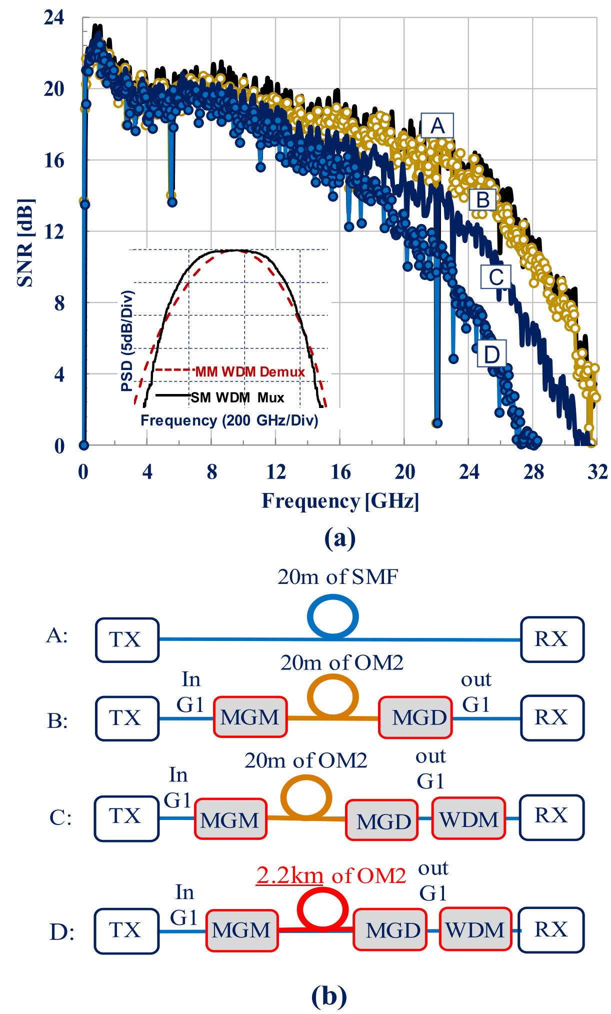

Fig. 4. a) SNR of mode group 1 of the optical channel in several configurations (inset filtering function of the single mode WDM multiplexer and the multimode WDM demultiplexer. b) Experimental configuration used for measurement of a).

blind equalization is used to correct the phase per subcarrier. We are considering a hard decision forward error correction (FEC) limit corresponding to a BER of 5×10^{-3} and assume a 7% overhead [25]. The achieved net bit rate assumes the transmission overhead due to the cyclic prefix, time synchronization and the FEC. At the transmitter side, conventional single mode WDM multiplexers are used. At the receiver side, multimode WDM de-multiplexer is used with multimode OM2 fiber pigtail having FC-PC connectors at both ends. Measured modal crosstalk for both MGD, MGM and OM2 fiber displayed in Table I are high and the use of the same wavelengths for the co-propagating mode group would generate high BER penalty. Therefore, to avoid coherent crosstalk penalty, each co-propagating mode group uses a different wavelength comb with a wavelength spacing of 100 GHz. In our experiment, we used an array of 80 DFB lasers with 50 GHz spacing, partitioned into two interleaved combs of "even" an "odd" sources, each consisting of 40 laser sources of 100 GHz spacing. The odd (even) comb was assigned to the mode groups 1 and 3 (2 and 4), leading to a total number of 160 transmitted channels. The wavelength combination for the mode groups 1 and 4 are indicated in Fig. 3(a). where modulated signals for group 1 and 4 are displayed for two distances 1 km and 2.2 km. Wavelengths are interleaved in such a way that in each direction the same 50 GHz-spaced comb is propagating. The same odd and even wavelength combs are used for mode group 3 and mode group 2 in the opposite direction. Even if the measured modal crosstalk value does not allow for the use of the same wavelengths for co-propagating mode groups, it is nevertheless possible to have a partial spectral overlap as it can be seen in Fig. 3(a). In case of 1 km transmission, the signal bandwidth is less impacted by chromatic dispersion compared to 2.2 km transmission. This overlap would not be possible in case of single mode fiber transmission as it would lead to high inter symbol interference (ISI) penalties due to the impossibility to filter out adjacent channels at the RX. For each mode group, the 40 wavelengths with 100 GHz spacing are modulated with the same MZM modulator. Considering the channel power and the transmission distance in our experiments, there are no cross nonlinear interactions during propagation among WDM channels within a group of modes. Channel propagation is linear and the correlation of data between those channels has no impact on the measured channels BER. However, the filtering function of the multimode WDM multiplexer (displayed in the inset of Fig. 4(a)) generates a small ISI penalty because it is not wide enough considering the spectrum width of the modulated signal. The penalty due to crosstalk induced by adjacent channels is 0.45 dB in terms of Q^2 factor in our experimental configuration. This case corresponds to the configuration 1 dis-

TABLE II
ACHIEVED BITRATE PER CHANNEL FOR EACH MODE GROUP

Modulation format	N° of subcarriers (Group 1)	N° of subcarriers (Group 2&3)	N° of subcarriers (Group 4)
64-QAM	69	44	32
32-QAM	162	177	183
16-QAM	112	91	93
8-QAM	91	60	58
QPSK	55	63	42
BPSK	5	11	25
Gross bitrate [Gb/s]	108.3	96.2	92.6
Net bitrate [Gb/s]	100.8	89.1	86.2

played in Fig. 3(b). To compare our experimental configuration with a more realistic system configuration where each channel would be modulated with independent data, we also measure the penalty caused by adjacent channels in the WDM demultiplexer in the configuration 2 displayed in Fig. 3(b) where adjacent channels are modulated with different data than the measured channel. In this configuration 2, it has been measured the same 0.45 dB penalty than in the configuration 1 which validate that our experimental set-up could be representative of an actual system. The Fig. 4(a) displays the signal to noise ratio (SNR) for a single channel for mode group 1 for an input power of −3 dBm and for several configurations B, C, D. Each configuration is indicated in Fig. 4(b). Case A is the reference back-to-back in single mode. Case B displays the SNR when only the MGM and MGD are inserted showing they have very small impact on the channel. Case C displays the SNR after the insertion of the multimode WDM demultiplexer. Case C shows the impact of the filtering function of the multimode WDM demultiplexer. The filtering function of the multimode WDM demultiplexer is not as wide as a single mode demultiplexer and therefore it reduces the channel bandwidth. The inset of Fig. 4(a) displays the filtering function of a typical single mode (continuous line) and the multimode (dashed line) WDM (de) multiplexer. It has been verified that the flat-top and wide filtering of the typical single mode WDM mux would have no impact on the channel bandwidth in a system. Finally, Case D displays the SNR of the end-to-end transmission with 2.2 km of OM2 fiber. This curve shows further reduction of the channel bandwidth induced by the chromatic dispersion. We applied the optimized bit loading for each of the mode groups. For all mode groups the highest number of bits per subcarrier was 6 (64QAM) in the low frequency region, and the lowest number of bit was 1 (BPSK) in high frequency region. As displayed in Table II, we successfully transmitted a net bit rate of 100.8 Gb/s for the 40 channels of mode group 1 and 89.1 Gb/s per channel for mode Group 2 and 3 and 86.2 Gb/s for mode group 4. The bit allocation for group 1 and 4 are displayed in Fig. 5. The main cause of the channel bit rate reduction comes from the bandwidth reduction induced by the increased chromatic dispersion. At a distance of 4.4 km, a minimum net bit rate per channel of 84 Gb/s for all mode groups is achieved corresponding to a total throughput of 13.5 Tb/s.

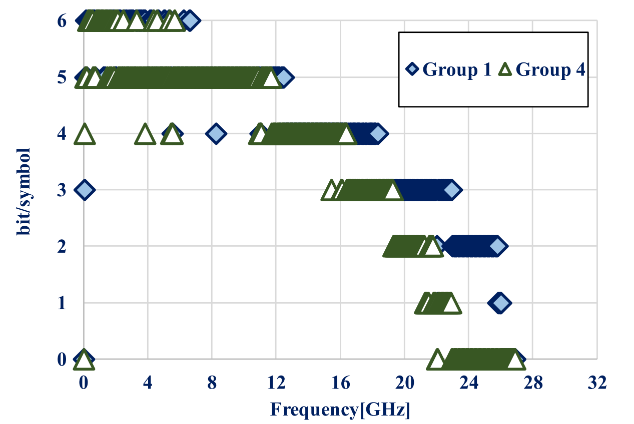

Fig. 5. Bit allocation per subcarrier for groups 1 and 4 corresponding to 2.2 km of propagation.

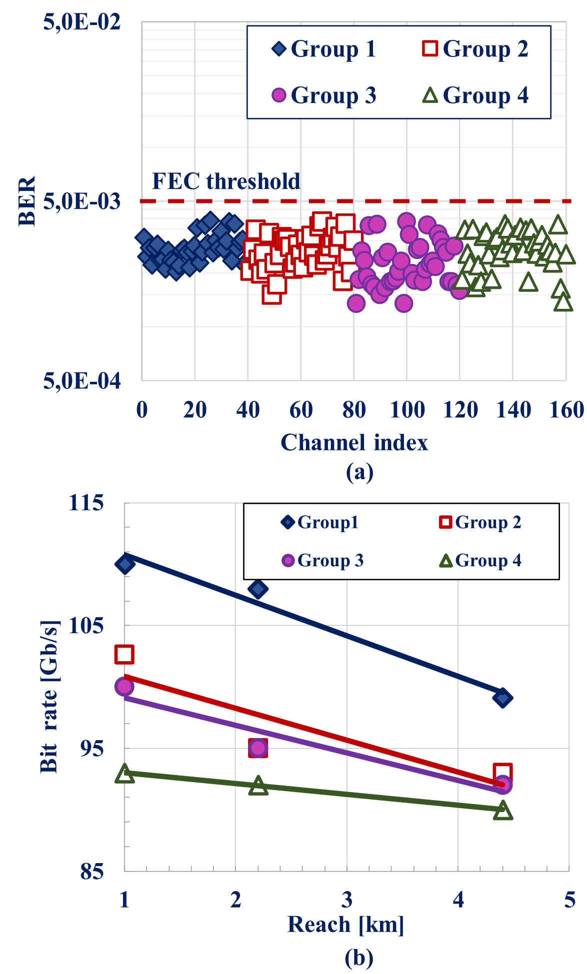

Fig. 6. a) Measured BER for the all 160 channels after 2.2 km of OM2 fiber. b) Gross channel bit rate as a function of distance in WDM regime.

Fig. 6(a) shows the measurement of all the 160 channels. All the channels operate above the FEC limit of a *BER* of 5×10^{-3}. The total transmitted net throughput is 14.5 Tb/s. Fig. 6(b) displays the channel gross bit rate in WDM regime as a function of the distance when the EDFAs output power is 22.5 dBm for all the distances. The bit rate decreases for all the mode groups when the distance increases.

IV. Conclusion

We demonstrated a total net 14.5 Tbs/s bidirectional transmission over 2.2 km of conventional OM2 fiber using DMT modulation scheme and direct detection. We achieved this result by using selective excitation of 4 mode groups and WDM multiplexing of 40 wavelengths for each mode group. To the best of our knowledge this is the highest throughput transmitted over such distance of multimode fiber using direct detection.

Appendix 1
Bit Loading Optimization for High Target BER

In our previous work [23], we used Chow's rate adaptive bit loading algorithm [26] where the total throughput is maximized for a given *BER* target (*B*∗). For a given SNR subcarrier Chow's algorithm gives the number of bits per symbol per subcarrier using the well-known "gap approximation" [26] according to equation 1:

$$b_n = log_2 \left(1 + \frac{SNR_n}{\Gamma}\right) \quad (1)$$

where b_n and SNR_n are respectively the number of bits per symbol and the SNR corresponding to the *n*-th subcarrier. The Γ is the difference between the required SNR to achieve maximum capacity ($\Gamma = 0$ dB) and SNR_n. This bit allocation is more accurate when the *B*∗ is low. As displayed in Fig. 7 for low *B*∗, Γ converges toward the same identical value for all $2^{(2n)}$ QAM modulation format. However, when the *B*∗ is increasing (in this paper our *B*∗ is 5×10^{-3}) the Γ has different values for the different modulation formats. As Chow's bit loading algorithm uses a single value for all formats, it is not possible to reach exactly a high *B*∗ (average over all the subcarriers).

A. Optimized Algorithm

We propose a more accurate method to deal with this problem. Instead of using Eq. (1) to determine the number of bits per symbol that can be allocated to each subcarrier according to their SNR, we compute *S* (*B*∗, k), the required *SNR* for a given *B*∗ for any 2^{k+1}QAM format, using Monte Carlo simulations,

$k = \{0,1,\ldots,k_{max}\}$ and k_{max} is the maximum number of bits per symbol which could be allocated to the subcarrier with the highest *SNR* for a fixed *B*∗. Using these relationships *(BER* vs *SNR* for each *B*∗) we determine SNR thresholds (S_k) for the bit and power allocation. Once the S_k are determined, we allocate the number of bit (b_n) and the energy (e_n) for each subcarrier: the subcarrier energy is increased or decreased depending on whether the sub-carrier SNR is above or below the threshold as indicated Fig. 8 for a *B*∗ of 5×10^{-3}. Fig. 9 and Fig. 10 give respectively steps to compute *SNR* thresholds from *S*(*B*∗, *k*), and the method to allocate the bit per symbol per subcarrier b_n and the power per subcarrier e_n.

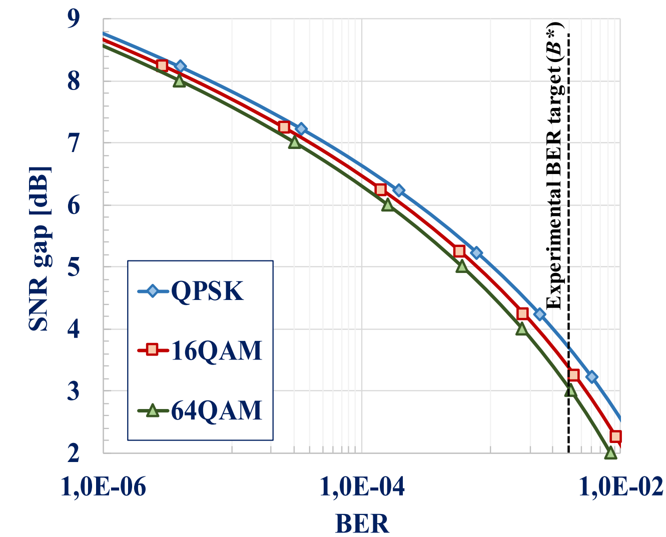

Fig. 7. Monte Carlo simulation of SNR gap (Γ) for different modulation format.

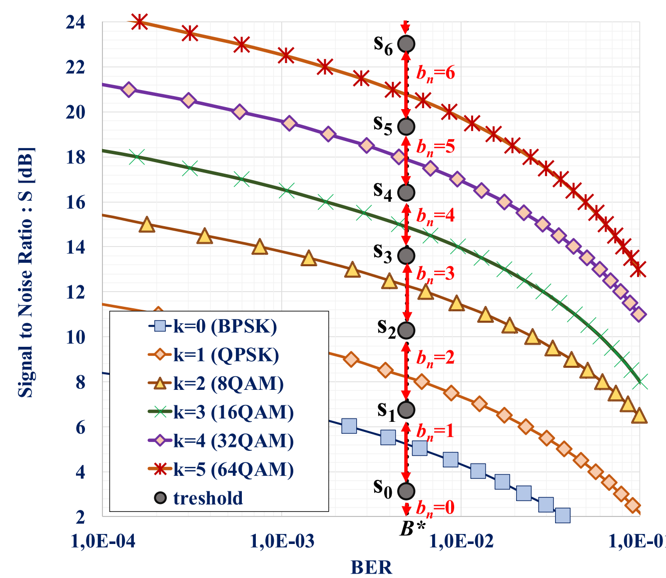

Fig. 8. Example of *SNR* threshold and bit allocation rules for a *B*∗ of 5×10^{-3}.

B. Simulation Comparison

In this section, Chow's bit loading algorithm and the optimized method are compared by simulation. The IFFT/FFT size is 1024 and we consider a dispersive channel H in the frequency domain in a DD system:

$$H(f) = 2.\cos\left(2\pi^2 f^2.\beta_2.L\right) \quad (2)$$

and

$$\beta_2 = -D.\frac{\lambda^2}{2\pi c}$$

L is the fiber length, *D* is the chromatic dispersion, λ wavelength and c the velocity of light. Bit and energy allocation are applied to the *SNR* response in the inset in Fig. 11 correspond-

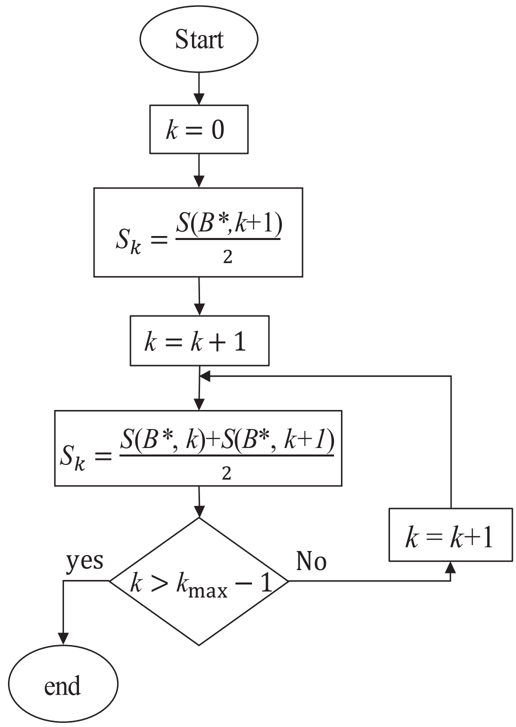

Fig. 9. Generation of SNR thresholds.

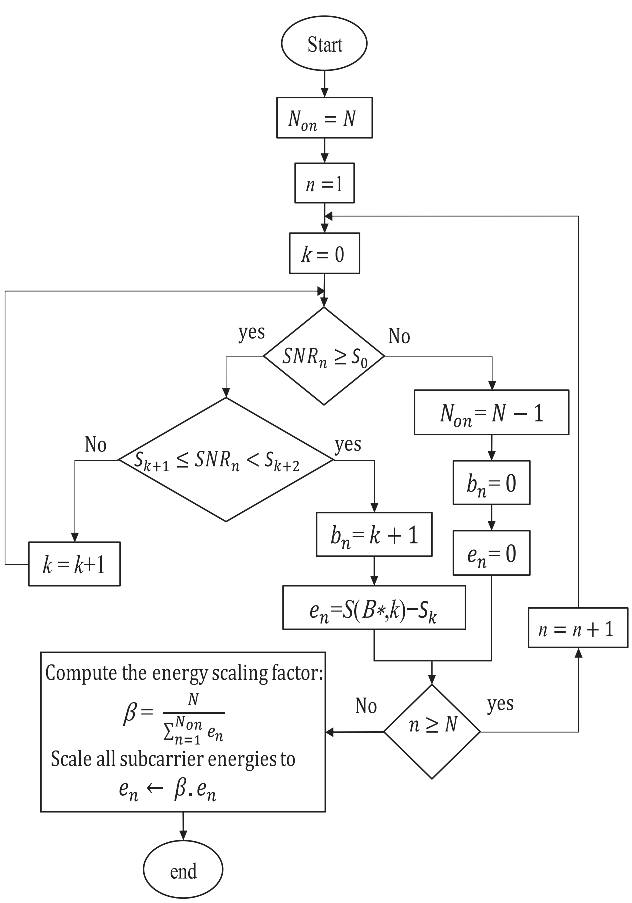

Fig. 10. b_n and e_n attribution.

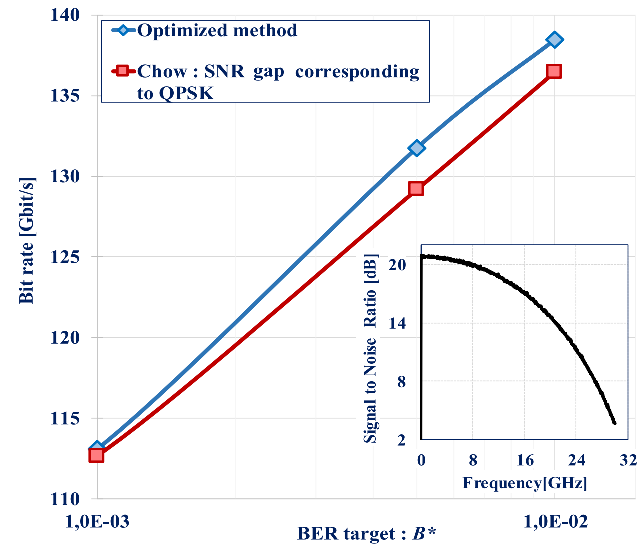

Fig. 11. Computed bit rate for different configurations.

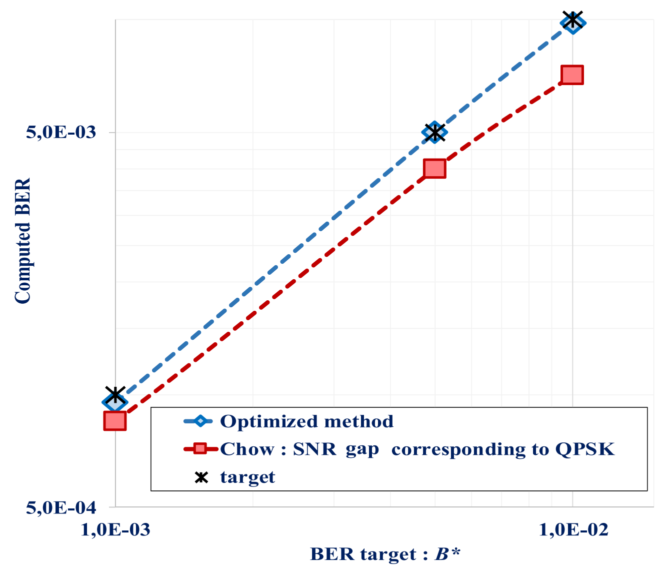

Fig. 12. Average BER computed for different configurations.

ing to a transmission over 2.2 km with $D = 20$ ps/nm/km at 1550 nm. The total SNR is fixed to 18 dB.

Fig. 11 shows the achievable bit rate versus the *BER* target ($B*$) for both algorithms, with Γ corresponding to QPSK modulation to assure that the computed BER is equal or below $B*$. The computed BER for each achievable bit rate is shown in Fig. 12. It is observed that the proposed optimized method results in a higher bit rate while achieving the *BER* target. On the contrary, Chows algorithm results in lower achievable bit rate as the target *BER* is not achieved due to the not optimized value of Γ. For B$*$ lower than 10^{-3}, both methods converge toward the same performance.

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Authors' biographies not available at the time of publication.