SOCIETY FOR SCIENCE AND EDUCATION
UNITED KINGDOM

TNC TRANSACTIONS ON NETWORKS AND COMMUNICATIONS

VOLUME 5, ISSUE 1
ISSN: 2054 -7420

Toward 1.8 Tb/s CAP Schemes for Short Reach Optical Communication Systems

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ABSTRACT

Wavelength-division multiplexed (WDM)carrierless amplitude/phase (CAP) modulation is proposed for1.8 Tb/sfor short reach optical communication system. The system uses 16 channels, each operates at 112 Gb/s. A single-band (SB) CAP and multiband (MB) CAP are adopted for each channel as advanced modulation format with high spectral efficiency. The system performance at C and O operating bandsare investigated withchannel spacing of 100 GHz.The system is simulated using OptiSystem14.0 software package and the results reveal that the maximum allowable distance at BER of 〖10〗^(-3) is 3.45km and 2.11 km for SB-CAP and MB-CAP operating at C-band with 0 dB laser power, respectively. These values to be compared with 4.5 km and 1.8 km, respectively, for O-band operation.

Keywords: Multiband CAP, single-band CAP, WDM-CAP

1 Introduction

The increasing cloud computing and multimedia services has driven the speed of short reach optical data communication links to higher data rate. In fact, 100 Gbit/s bit rate has been addressed comprehensively for this application [1–4] while discussion has been actively started for 400 Gbit/s and above data links [5-6]. To reduce the cost of the optical data link, directly modulated lasers with direct detection (DD) schemes have been adopted [7-10]. To increase the spectral efficiency of these links, higher-order modulations formats have been proposed [11,12]. Recently, different direct detection schemes have been investigated for advanced short reach applications such as orthogonal frequency-division multiplexing (OFDM) [13,14], multitone (DMT) modulation [15,16], Pulse amplitude modulation (PAM) [17-19], and CAPmodulation [20,22].

The CAP modulation attracts increasing interest as an efficient modulation format for short reach optical communication. In fact CAP implementation is relatively simple since it uses analogue transversal filters and does not need digital signal processing (DSP) [23]. This gives the potential of both improved cost and energy efficiency while also having excellent performance. These features have enhanced the researches to investigate single- band CAP (SB-CAP), multiband CAP (MB-CAP), and hybrid CAP/QAM schemes. Tao et al. [24,25] investigated the performance of 40 Gb/s SB-CAP32 and 10Gb/s SB-CAP128/256 systems with decision-directed least mean square (DD-LMS) adaptive equalization algorithm for short-reach optical transmissions. An overlap frequency-domain equalization (OFDE)scheme proposed and

DOI: 10.14738/tnc.51.2802
Publication Date: 05th March 2017
URL: http://dx.doi.org/10.14738/tnc.51.2802

experimentally demonstrated by He et al. [26] in an intensity modulation and direct detection optical communication system with SB-CAP32/64/128 modulation. Zhang et al. [27] proposed and demonstrate a wavelength-division multiplexed(WDM) MB-CAP with direct detection. The experiment successfully demonstrates 11 WDM channels, 55 subbands, for 55 users with 9.3-Gb/s per user in the downstream over 40-km single mode fiber (SMF). Recently, A 100 Gb/s MB-CAP was successfully demonstrated over 15 km SMF by Olmedo et al. [28]. Their results show an increases tolerance towards dispersion and bandwidth limitations, and reduces the complexity of the transceiver. Unfortunately, CAP receivers have relatively low tolerance to high frequency jitter and therefore desirable to propose an alternative approach with simple implementations.

Recently, a hybrid CAP/quadrature amplitude modulation (QAM) transmitter/receiver scheme was proposed to be used instead of a conventional non phase compensated CAP transceiver to improve both the system jitter tolerance and optical link power margin. An experimental demonstrations of a 10 Gb/s hybrid SB-CAP-2/QAM-2 and a 20 Gb/s hybrid SB-CAP-4/QAM-4 transmitter/receiver-based optical data link were performed by Wei et al. [29]. The work was extended to MB-CAP system by the same research group [23].

It is clear from the forging survey that the performance investigation of CAP system is limited to a maximum bit rate of 100Gb/s. To the best of authors knowledge, the performance of CAP system for bit rate beyond 100Gb/s has not addressed in the literature. This paper presents performance investigation for a1.8Tb/s WDM-CAP system. The system uses 16 x112Gb/s CAP/QAM channels operating either in single band or multiband formats. Results will be reported for both C-band and O-band operating regions.

The remainder of the paper is organized as follows: Section two demonstrates the architecture of proposed WDM single-band and multiband CAP-16 systems. The simulation setup and the results are presented in Section 3 which discusses the performance of the system at channel-spacing 100 GHz. The conclusions deduced from this work are presented in Section 4.

2 Proposed 1.8 Tb/s WDM-CAP System

The architecture of the proposed 1.8 Tb/s WDM-CAP system is illustrated in Figure 1. The sixteen 112Gb/sWDM channels operating either atC-bandor O-band. The transmitter and receiver use either single-band CAP (SB-CAP)or MB-CAP modulation format. Each channel uses a CAP-M signal (M is the modulation order where M=16 is applied here). This is similar to QAM-M signaling, however, it neither needs RF local oscillator nor mixer. Figure 2 shows the schematic diagram of the transmitter and the receiver for WDM CAP system.ThePAM mapper is used to map the binary datainto the orthogonal in-phase (I) and quadrature (Q) components of complex symbols. The RF CAP signal is created by combining the outputs of two orthogonal filters that are called Hilbert pair. The MB-CAP designed with four subbands(K=4) requires four orthogonal filter pairs having different center frequencies to prevent the overlapping between two adjacentsubbands. Each of the sixteen channel signals modulates single continuous wave (CW)optical carrier using intensity modulatorMach-Zenhder (MZM) modulator. Thesixteen signals arewavelength-division multiplexed to propagate simultaneously through SMF.At the receiver side, direct detection is applied to the received de-multiplexed signal followed by QAM demodulator for each channel. The two matched filters used here will separate the I and Q components; these filters are of complex conjugate of the shaping filters in the frequency domain.The signals at thefilters outputare off-line processed using digital signal processing (DSP) then the decision is made using decision device to get the real and imaginary components that are decoded by QAM decoder to get the original data.

The MB-CAP modulation utilizes multi-filter pairs located at different center frequencies 〖f〗_(k,c). For each sub-band, two transversal filters are generated by time multiplication the impulse response of square root-raised cosine (SRRC) shaping filter with a sine or cosine waveform. The center frequencies of the kthsubbandpair transversal filters is given by equation 1

$$f_{k,c} = \frac{1}{2T}(1+r)(2k-1) \qquad k=1, 2, 3, \ldots K \tag{1}$$

where T is the symbol period, r is the roll-off of the SRRC filter and is set to 0.2 here, K is the total number of subbands. The SB-CAP format can be considered as a special case of MB-CAP with number of subbands equals one.

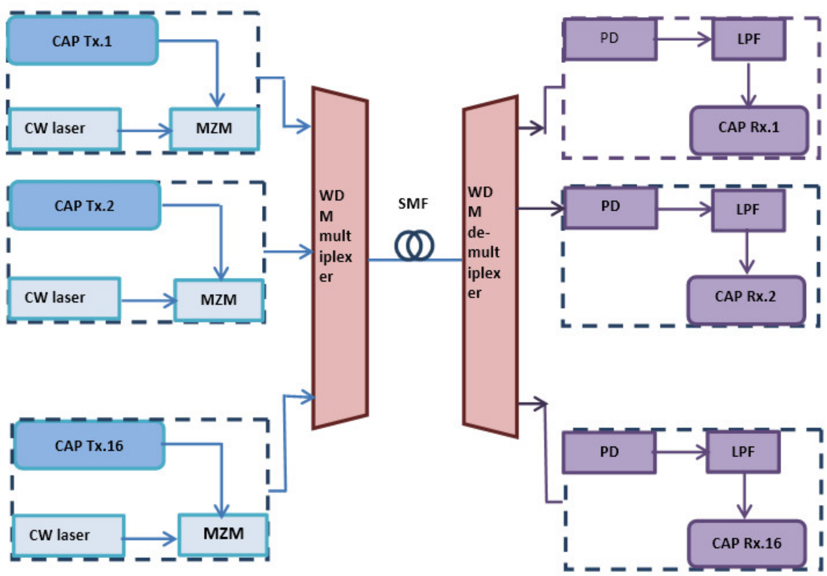
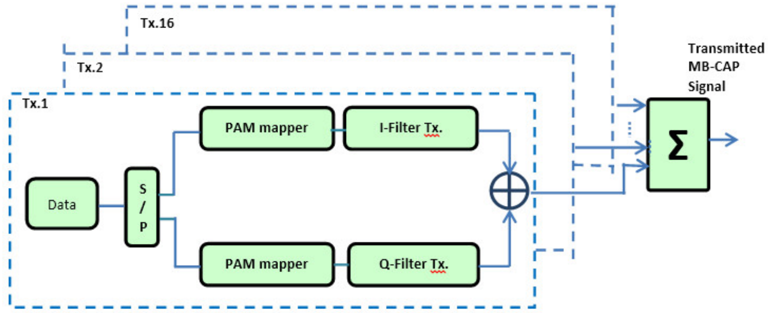


Figure. 1 Architecture of WDM CAP system.The CAP transmitter (CAP-Tx) and CAP receiver (CAP-Rx) can be implemented using single-band or multiband CAP schems.

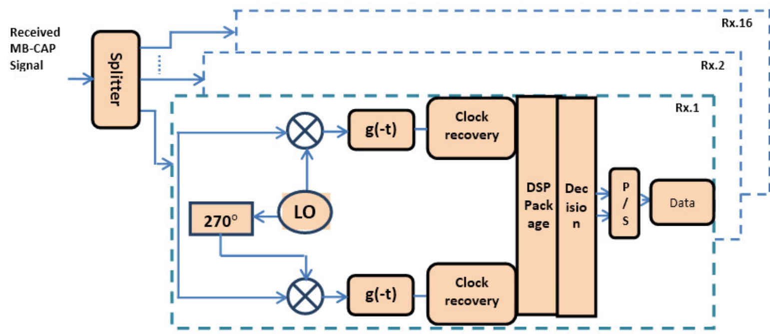
The impulse response of the orthogonal SRRC shaping filters is given by

$$R_{k,c}(t) = g(t)\cos(2\pi f_{k,c}\ t) \tag{2a}$$

$$\overline{R_{k,c}}(t) = g(t)\sin(2\pi f_{k,c}\ t) \tag{2b}$$



(a)



(b)

Figure.2Schematic diagram of MB-CAP system (a) transmitter. (b) receiver.

where g(t) is the impulse response of SRRC filter of and $f_{k,c}$ is the center frequency of k[th]subband

The MB-CAP signal can be expressed by

$$S(t)=\sum_{k=1}^{K}\{\sum_i X_{k,i}g(t-iT)\cos[\omega_{k,c}(t-iT)]-\sum_i Z_{k,i}g(t-iT)sin[\omega_{k,c}(t-iT)]\} \quad (3)$$

where $X_{k,i}$and $Z_{k,i}$ are the I and Q parts of the k[th]subbandPAM-M symbols, and$\omega_{k,c}$ =2πf$_{k,c}$.

At the receiver, the orthogonal matched filters having the following impulse responses

$$U_{k,c}(t) = g(-t)\cos(2\pi f_{k,c}t) \quad (4a)$$

$$\overline{U_{k,c}}(t) = g(-t)\sin(2\pi f_{k,c}t) \quad (4b)$$

3 Simulation Setup and Results

The investigation of 1.8 Tb/s WDM system implemented with sixteen channels, each of 112 Gb/s SB-CAP or MB-CAPscheme,is performedand simulated using OptiSystem version 14.0. The sixteenCW lasers are combined with channel spacing of 100 GHz. Thechannel wavelength of the WDM are chosen according to spectral grids for WDM applications that are recommended by International Telecommunication Union (ITU). Table 1 listed the frequencies of the optical carrier (channel frequency) for two operating bands,C-band and O-band, for channel-spacing of 100 GHz.

The bandwidth of each channel of the WDM system is 70 GHz when M=16 (CAP-16). The multiplexer and de-multiplexer filters are designed using 6th order bandpass Bessel filter having bandwidth of [0.75 times the bit rate (GHz)]. The orthogonal SRRC shaping filters at the transmitter and the matched filters at the receiver are located at different center frequencies with roll-off factor of 0.2. The BER performance of the MB-CAP scheme is tested for B2B case and after transmission distance of 1 km. The results of MB-CAP are compared with that of the SB-CAP. The target of the investigation is to compare the performance of MB-CAP with SB-CAP at the value of aforementioned channel-spacing. The gained results are summarized by the following subsections. Unless otherwise stated, the parameters of the simulated system are as given in Table 2.

3.1 Performance of the System at Channel-spacing of 100 GHz

First, the results are obtained using CW laser, each has a power PT = 0 dBm, operating at C-band or O-band for B2B and after transmission distance of 1 km for channel spacing of 100 GHz. The critical factor in the operation is the bandwidth of the RF power spectral density for the MB-CAP and SB-CAP signals, which equals to 33.9 GHz. This bandwidth is divided into four subbands for MB-CAPas shown in Figure 3 which is obtained for C-band operation. The optical power spectral density of the

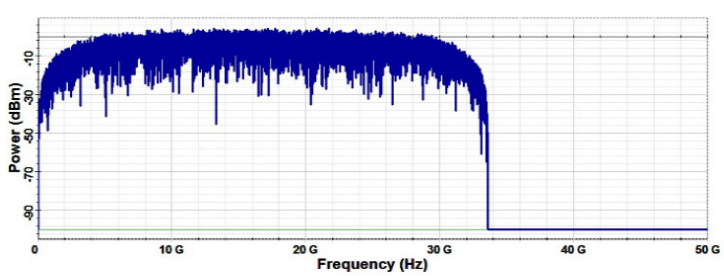
Table.1 Channel frequencies at 100Ghz channel-spacing

Channel number	Channel frequency at C-band (THz)	Channel frequency at O-band (THz)
1	193.1	228.3
2	193.2	228.4
3	193.3	228.5
4	193.4	228.6
5	193.5	228.7
6	193.6	228.8
7	193.7	228.9
8	193.8	229.1
9	193.9	229.2
10	194.1	229.3
11	194.2	229.4
12	194.3	229.5
13	194.4	229.6
14	194.5	229.7
15	194.6	229.8

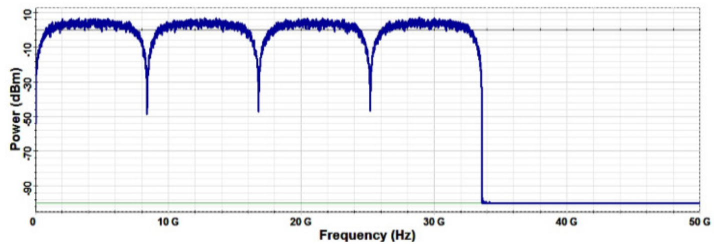
Table 2. Parameters values of the simulated system.

Component	Property	Value
NRZ Pulse Generator	Rise time	0.25 bit
	Fall time	0.25 bit
CW laser	Line width	50 MHz
	operation	C-band or O-band
	Power	0 dBm
Optical fiber link	Length	1 km
	Attenuation	0.2 dB/km @ C-band 0.4 dB/km @ O-band
	Dispersion	16.75 ps/nm/km @ C-band 0.01 ps/nm/km @ O-band
	Dispersion slope	0.075 ps/(nm^2 km) @ C-band 0.09 ps//(nm^2 km) @ O-band
PIN PD	Responsivity	1 A/W
	Power spectral density of the thermal noise	331.92×10^{-24} W/Hz

multiplexed 16 channels' signals is given in Figure 4. The dispersion between the received adjacent channels is obviously appeared at the de-multiplexed optical power spectral density of the first, ninth and sixteenth channels as illustrated in Figure 5. At the receiver side, the fiber optics nonlinearity and dispersion effects along the fiber link influence the constellation diagram at the QAM demodulation output. The rotation in the received electrical signal constellation for the 1st, 9th, and 16th channels is evident in Figure 6. Figure 7a clarifies the signal constellation at the output of transmitter SRRC shaping filters. While Figure 7 b, c and d are the signal constellation at the output of DSP package after off-line signal processing, Note that the signal points are equally-spaced for the first, ninth and sixteenth but, are totally shifted to the above in the (x-y) plane of the constellation for the first channel.



(a)



(b)

Figure. 3 RF power spectral density at PT = 0 dBm, L=1 km, and C-band operation for (a) SB-CAP signal (b) MB-CAP signal.

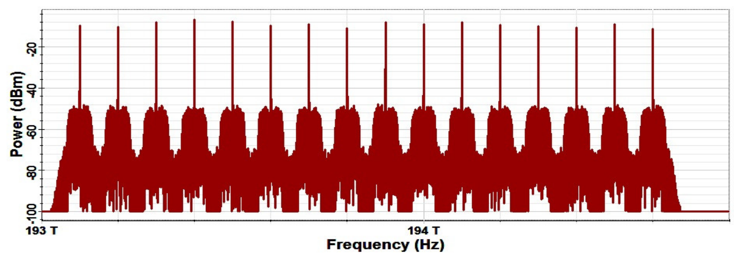
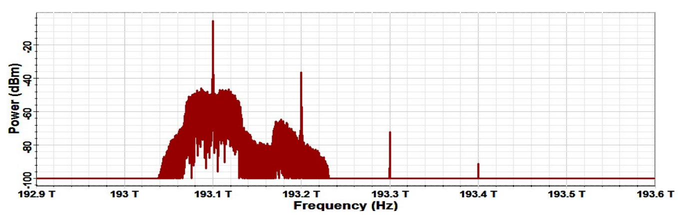
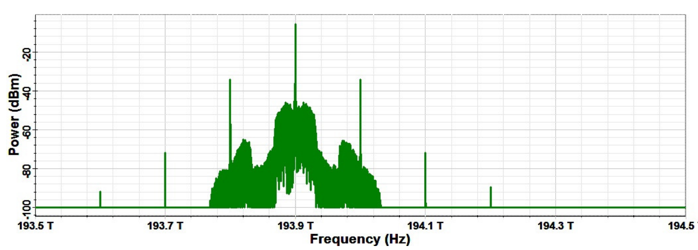


Figure. 4 Optical power spectral density at the output of the WDM multiplexerat P_T = 0 dBm, L=1 km, C-band operation



(a)



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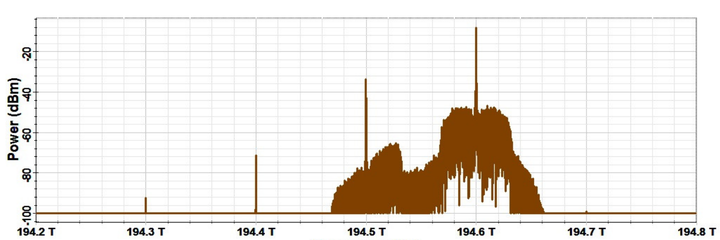


(c)

Figure. 5 Optical power spectral density at the output of the WDM de-multiplexer at P_T = 0 dBm, L=1 km, and C-band operation for the (a) 1st channel (b) 9th channel (c) 16th channel

For B2B transmission and 1 km transmission distance along fiber link operating at C-band operation, the BER performance of the SB-CAP system is approximately the same, as shown in Figure 8. The MB-CAP has higher BER compared with SB-CAP counterpart, the case is different for higher values of CW laser power (-3.5 to 4) dBm. It is also deduced that the 16th channel has the best performance among other channels due to the absence of the effect of cross phase modulation phenomena whose effect is clearly appears in the BER performance of the 9th channel. As consequence of this phenomena, the overlapping between the previous and the following channels' signals makes the ninth channel 's BER to be of the highest value.

The 1st channel's BER curve is in between that of the 9th channel and that of the 16th channel for the single-band as shown in Figure 8. For MB-CAP system, the BER of the 1st channel is approximately the mirror image of that of the 16th channel as shown in Figure 9.

The simulation and the calculation are repeated for WDM system operating at the O-band and the results are presented in Figures 10 and 11. The power improvement for B2B of MB-CAP and SB-CAP compared with 1 km transmission distance with respect to the 1st channel is 0.6 dBm and 0.5 dBm, respectively.

3.2 Summary of the Results

This section summarizes the main results for 1.8 Tb/s SB-CAP and MB-CAP WDM systems operating with 100 GHz channel-spacing at either C-band or O-band. The results are given for CAP-16 and SRRC filters having 0.2 roll-off factor. The maximum allowable distance that could be reached by 1.8 Tb/s SB- CAP-16 and MB-CAP-16 systems at channel-spacing of 100 GHz are listed in Table 3. The results are obtained for BER of 10^{-3} and P_T = 0 dBm.

Table 4 compares the performance of single-band and multiband CAP-16 systems for channel-spacing Δf =100. Two operating bands, namely C and O are considered.

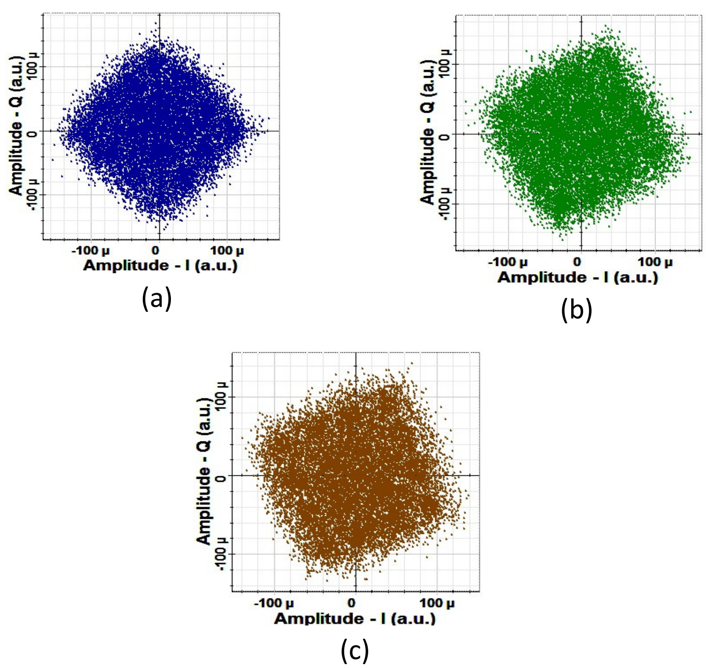


Figure. 6 Signal constellation at the output of receiver matched filter for the (a) 1st channel (b) 9th channel, (c)16th channel at PT = 0 dBm, L=1 km, and C-band operation.

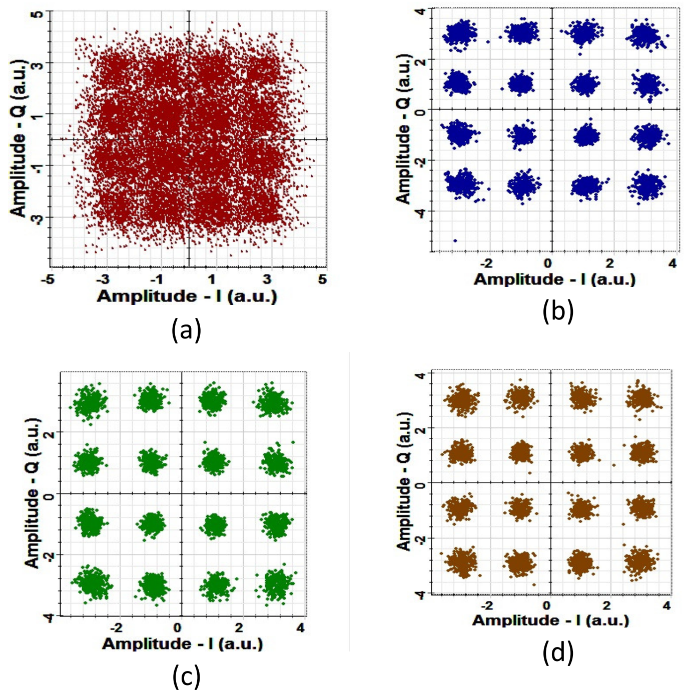


Figure. 7 (a) Constellation of at the output of SRRC shaping filter constellation after off-line processing at the receiver for the (b)1st channel, (c) 9th channel (d) 16th channel at PT = 0 dBm, L=1 km, and C-bandoperation.

4 Conclusions

A 1.8 Tb/s WDM consisting of sixteen 112 Gb/s SB-CAP and MB-CAP channels' are proposed for short reach through applications. The system operates at either C-band or O-band with 100 GHz channel spacing. Simulation results have been reported for CAP-16 signaling while the detection is achieved using hybrid CAP-16/QAM-16 scheme. The results reveal that maximum allowable distance at BER of 10^{-3} is 3.45 km and 2.11 km for SB-CAP and MB-CAP operating at C-band with 0 dB laser power, respectively. These values to be compared with 4.5 km and 1.8 km, respectively, for O-band operation

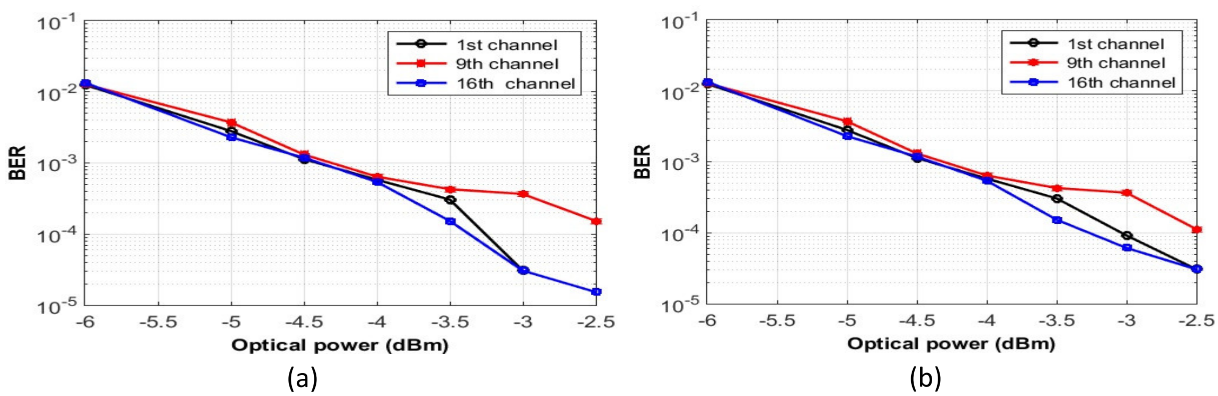
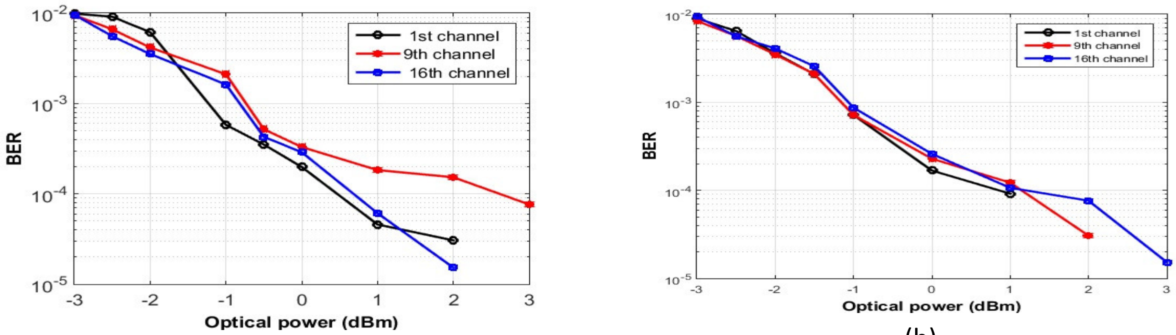
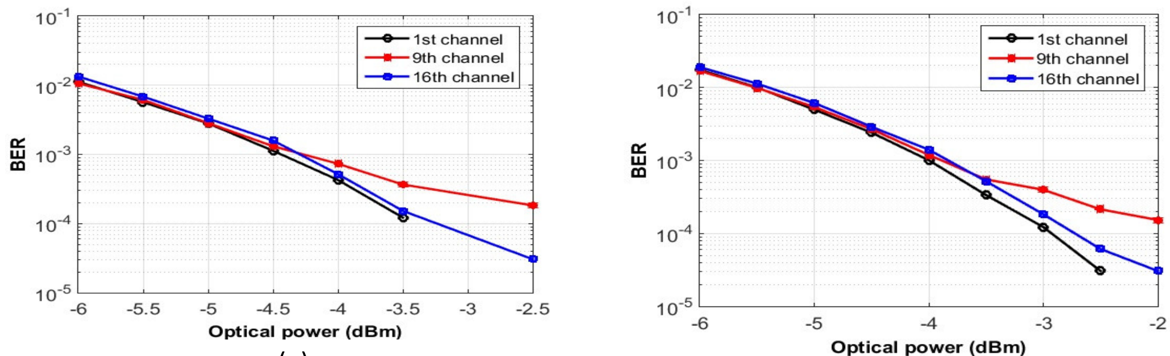


Figure. 8 System performance of SB-CAP operating at C-band and channel-spacing of 100 GHzfor (a) B2B (b) after 1 km transmission distance.



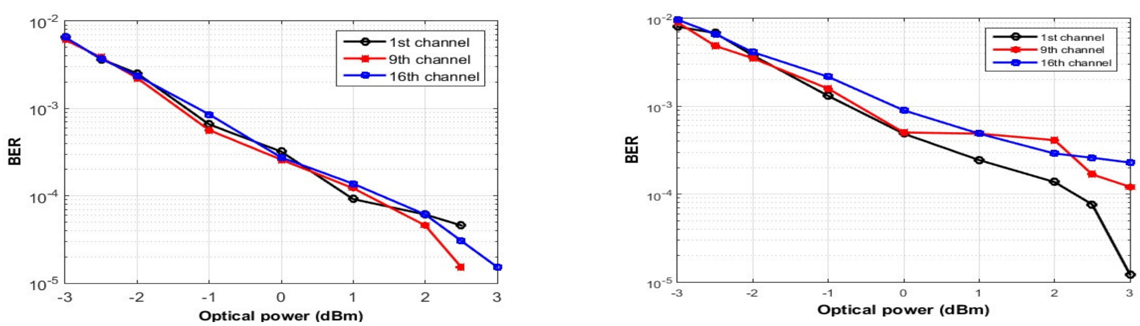
(a) (b)

Figure. 9 System performance of MB-CAP operating at C-band, channel-spacing of 100 GHzfor (a) B2B (b) after 1 km transmission distance.



(a) (b)

Figure. 10 System performance of SB- CAP operating at O-band, channel-spacing=100 GHz for (a) B2B (b) after 1 km transmission distance.



(a) (b)

Figure. 11 System performance of MB-CAP operating at O-band, channel-spacing=100 GHz for (a) B2B (b) after 1 km transmission distance.

Table 3. Maximum allowable distance to achieve a BER of10^{-3} for SB-CAP and MB-CAP systems, at channel-spacing of 100 GHz and PT=0 dBm

Channel Number	Maximum allowable distance to achieve a BER of10^{-3} (km)			
	C-band		O-band	
	SB-CAP	MB-CAP	SB-CAP	MB-CAP
1	3.45	2.4	5.25	1.76
9	3.45	2	4.5	1.8
16	3.625	2.475	5	1.8

Table 4. Performance comparison of SB-CAP and MB-CAP at channel-spacing of 100 GHz and PT=0 dBm

Property	C-band		O-band	
	SB-CAP	MB-CAP	SB-CAP	MB-CAP
BER at 1 km	The lowest BER is obtained at -2.5 dBmas follows 1stchannel, BER=4.521×10^{-5} 9thchannel BER=1.012×10^{-5} 16th channel, BER=4.521×10^{-5}	The lowest BER obtained at 3 dBm as follows 1st channel, BER=0 9th channel BER=0 16th channel, BER=3.052×10^{-5}	While in O-band The BER is better than that of C-band it decrease considerably even if for higher laser power, there is 0.5 dBm laser power improvement for B2B compared to 1 km fiber link 1st channel, BER=0 9th channel BER=3.052×10^{-5} 16th channel, BER=4.251×10^{-5}	The shape of BER is better than that of C-band there is 0.6 dBm laser power improvement for B2B compared to 1 km fiber link 1st channel, BER=1.521×10^{-5} 9th channel BER=1.521×4 16th channel, BER=3.521×10^{-5}
Maximum allowable distance(km)	3.45	2.11	4.50	1.80

Table 4. Continued

Property	C-band		O-band	
	SB-CAP	MB-CAP	SB-CAP	MB-CAP
Operation of the system	There is interference between the 16 subbands, but it is lessthan that of MB CAP-16	The effect of 64 subbandsincreas s the interference between the in-phase and quadrature channels, in addition to the effect of the attenuation and CD of the fiber link	Better than that of C-band	Same as in MB-CAP in the C-band, despite the zero dispersion of this band .

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