Chapter 4

The Future Electrical Multiplexing Technique for High Speed Optical Fibre

Rahmat Talib and Mohammad Faiz Liew Abdullah

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.68407

Abstract

Advancement in transmission technology based on fiber optic such as multiplexing technique is an attractive research area for future development of high capacity and high speed optical communication system. Typical electrical based multiplexing such as electrical time division multiplexing (ETDM) and duty cycle division multiplexing (DCDM) have difficulty to fulfil the requirements of modern fiber optic communication with practical solution. Multi slot amplitude coding (MSAC) is the latest multiplexing technique that has been proposed as an alternative to ETDM and DCDM. The results show that the spectral width is reduced by around 25%, not less than 55% improvement of chromatic dispersion (CD) tolerance, 0.6 dB better receiver sensitivity, and 1.5 dB better optical signal to noise ratio (OSNR) compared to DCDM for 30 Gbit/s transmission capacity. The spectral width for 3 × 10 Gbit/s, 4 × 10 Gbit/s and 5 × 10 Gbit/s MSAC is 60 GHz, which indicates improvement of spectral efficiency. This advantage is not possible to be achieved through ETDM technique. In addition, 10 GHz clock signal can be extracted from the MSAC signal which is important for recovery circuit at receiver since it is similar to symbol rate.

Keywords: optical fibre communication, multiplexing, optical modulation

1. Introduction

The current trend of internet use for social applications, such as facebook and twitter, is a strong indication of the substantial demand for information and communication technology. Therefore, behind the success story of these popular social applications is the capability of telecommunication infrastructure to handle huge amount of information transfer worldwide.

Optical communications have been widely used for this important task. Advancement in high capacity and high speed optical communication system has always become an important topic of discussion among the communications community. One of the important techniques in optical communication system is to realize high capacity data transportation through multiplexing technique. The technology is moving forward, where innovative alternative to the existing multiplexing method is indispensable to accomplish the future needs in optical communication implementation.

Generally, multiplexing is required to share the huge bandwidth of well-known fibre optic medium with many users, hence provides more cost efficient for practical implementation for high capacity data transformation. Typical implementation of multiplexing can be done in electrical or optical domain. Electrical-based multiplexing is very important technique due to the capability of electronic technology to switch the data with high speed, efficiency and reliability [1].

In this chapter, we report the investigation of system performance for recent electrical-based multiplexing technique known as multi-slot amplitude coding (MSAC) for high speed optical communication link. This work is very important in order to justify the benefit of MSAC as an innovative multiplexing compared to other electrical-based multiplexing such as electrical time division multiplexing (ETDM) and duty cycle division multiplexing (DCDM).

2. Electrical time division multiplexing (ETDM)

ETDM is a technique that adopting electronic circuit to execute multiplexing process in electrical domain. In EDTM concept, the bit from multiple input tributaries is arranged as a single output tributary by allocating all the bits with smaller time slot as compared to the time slot of input channel. As a result, the bit rate or speed of output tributary is higher than the input bit rate so that all the bits at the input can be transferred correctly to the output. The output tributary bit rate, R_T of ETDM is

$$R_T = NR \tag{1}$$

Where N is the number of input tributaries and R is the input tributary bit rate. The bit duration T_b of the input tributary is given by

$$T_b = \frac{1}{R} \tag{2}$$

The basic concept of EDTM implementation based on three input tributaries depicted in **Figure 1**. In this figure, ETDM operates with three input tributaries so the output bit rate of EDTM is $3R$ bits/s and the output bit duration becomes $T_b/3$. The output of ETDM can be used to modulate the light source for data transmission. Due to simple and efficient operation of ETDM technology, it is extensively adopted for commercial application for synchronous optical network (SONET) , synchronous digital hierarchy (SDH) and optical transport network (OTN). Currently, high speed electronic-based ETDM has been reported to support more than 40 Gbit/s serial data using advance material and state-of-the-art technology [2].

http://dx.doi.org/10.5772/intechopen.68407

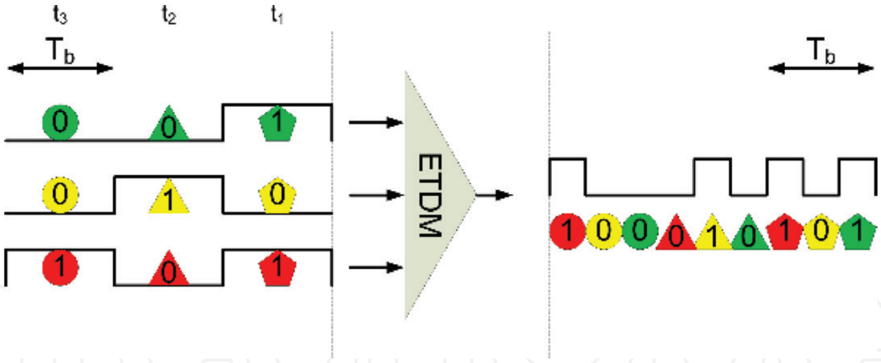

Figure 1. ETDM concept.

3. Duty cycle division multiplexing (DCDM)

Multiplexing process also can be realized using DCDM concept, and it has been proposed as an alternative technique to ETDM [3]. In order to implement DCDM concept, basic components can be used which are return-to-zero (RZ) convertor and electrical adder. Since, RZ convertor has the ability to adjust the duty cycle (DC) parameter, hence various DCs of binary signal can be obtained. In DCDM, each input tributary is applied to RZ convertor with the different predefined DC parameter. The outputs for all RZ convertors are combined by an electrical adder to generate the DCDM signal. This technique requires a synchronize bit and identical amplitude of non-return-to-zero (NRZ) format for all input tributary. **Figure 2** shows an example of DCDM signal generation for three tributaries. **Figure 2**a–c shows the 8 bits sequence (all possible combination) of input tributary 1, 2 and 3, respectively. **Figure 2d**–**f** shows the RZ format with 25% DC of tributary 1, 50% DC of tributary 2 and 75% DC of tributary 2, respectively, after NRZ to RZ conversion. Combination of signals in **Figure 2d**–**f** using electrical adder generates DCDM signal as shown in **Figure 2g**. Based on this multiplexing,

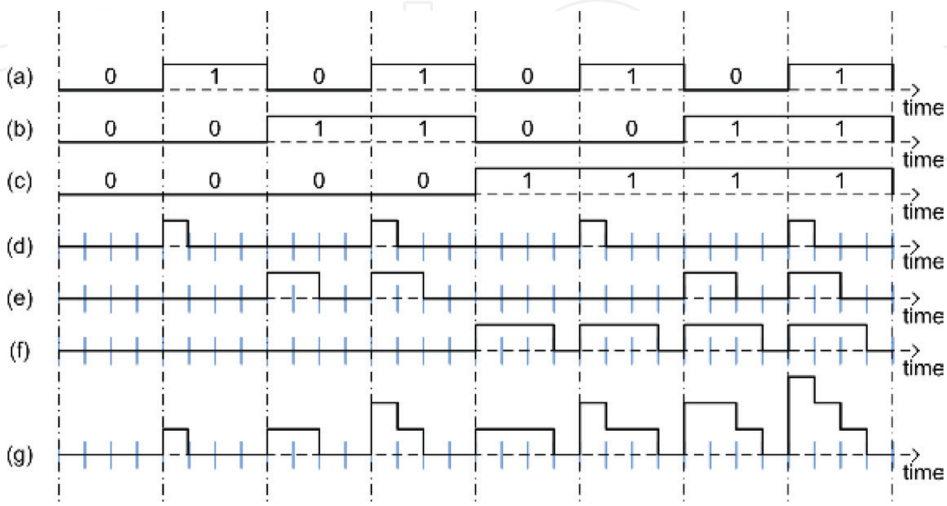

Figure 2. An example of DCDM signal.

a unique signal waveform or symbol can be obtained. There is a transition at the beginning of the DCDM symbol because RZ conversion turns the signal from high to low for bit 1 s.

4. Multi-slot amplitude coding (MSAC)

MSAC technique is a latest multiplexing concept to enhance the utilization of signal level for generating waveform or symbol compared to DCDM and ETDM [4]. In this technique, the multiplexer converts all possible combination bits of each tributary as MSAC symbol based on predefine translation rule. MSAC symbols can be obtained based on two parameters, which are the number of slots, *S* and number of signal levels, *M* as depicted in **Figure 3**. Assuming an equal duration of slot, the slot duration of MSAC symbol, *Td* is given by

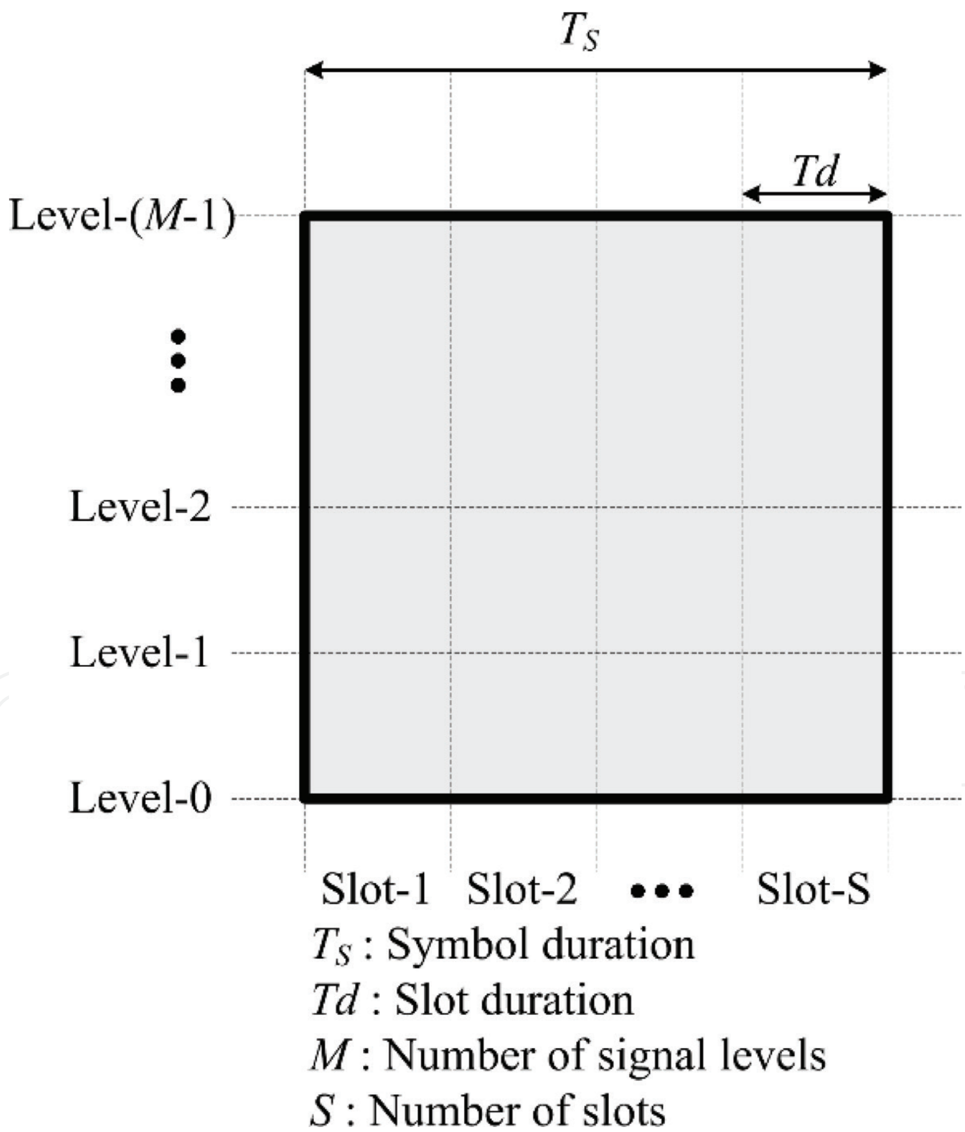

Figure 3. General format of symbol for MSAC.

$$Td = \frac{T_S}{S} \tag{3}$$

where T_S is the symbol duration. T_S is similar to the bit duration of the input tributary, T_b. Therefore,

$$T_S = T_b = \frac{1}{R} \tag{4}$$

where R is the input tributary bit rate.

For equal signal level spacing, the maximum amplitude of MSAC, A is

$$A = (M-1)\Delta \tag{5}$$

where Δ is amplitude spacing. **Figure 4** displays an example of MSAC symbol for three users. There are nine symbols ($x_1(t)$ to $x_9(t)$) for $S = 3$ and $M = 3$. Note that MSAC symbol allocates the first slot in symbol format as zero level.

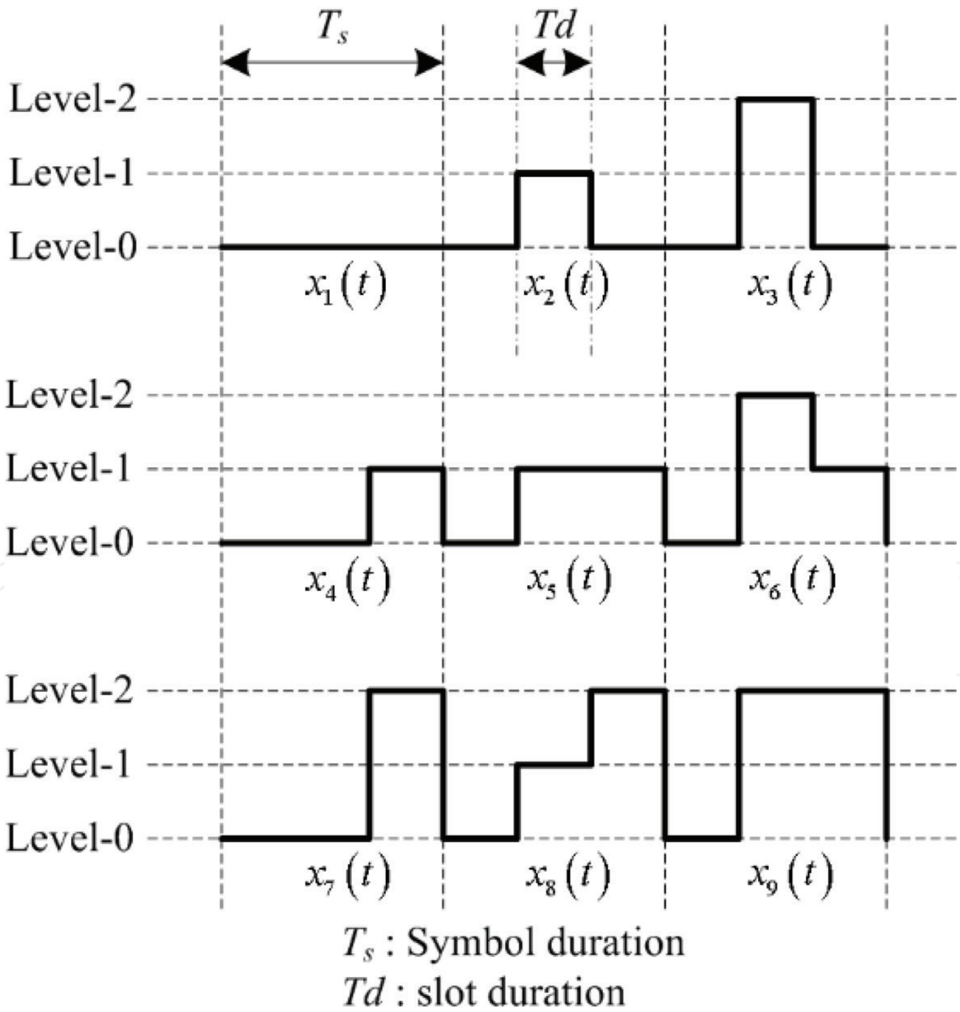

Figure 4. Example of symbol waveform for $M = 3$ and $S = 3$.

5. Optical communication system simulation using MSAC

Figure 5 shows the simulation setup for *N* tributaries MSAC in optical communication system. This setup consists of transmitter section, transmission section and receiver section. The component for the transmitter section is *N* pulse pattern generators, MSAC multiplexer, external modulator and continuous wave laser. The number of pulse pattern generator will depend on number of tributary. Each tributary consists of a pulse pattern generator for generating pseudo random binary signal (PRBS). Note that *Tr*1, *Tr*2 and *TrN* represent tributary 1, tributary 2 and tributary *N*, respectively. Each pulse pattern generator has a common clock signal in order to obtain synchronize binary data stream as input signal to the MSAC multiplexer. MSAC multiplexer model implements a conversion process based on the rule. The signal from MSAC multiplexer then modulates the light from a continuous wave laser (CW LD) at 1550 nm, using an external modulator. The optical power of CW LD is fixed at 0 dBm. The external modulator is based on an amplitude modulator (AM) model. Transmission section consists of an optical attenuator and optical fibre. The modulated optical signal is fed into an optical attenuator. In optical attenuator, the signal input electrical field for both polarizations is attenuated. This optical attenuator is used to control the amount of launch optical power from the AM. For this simulation, optical fibre is based on a single mode fibre model, and it is placed after the optical attenuator. The propagation of modulated optical signal in single mode fibre model is based on the Schrödinger equation [5]. The receiver section consists of an optical amplifier, PIN photodiode, electrical low-pass filter and clock and data recovery. An optical amplifier that acts as a pre-amplifier is placed before PIN photodiode in order to boost the signal. Note that the optical amplifier also introduces ASE noise. The received optical signal is then converted to an electrical signal using a PIN photodiode. In this simulation, the signal is corrupted with typical noises in optical system such as shot noise and thermal noise. The PIN photodiode output signal is filtered with a Gaussian low-pass filter (LPF). In order to

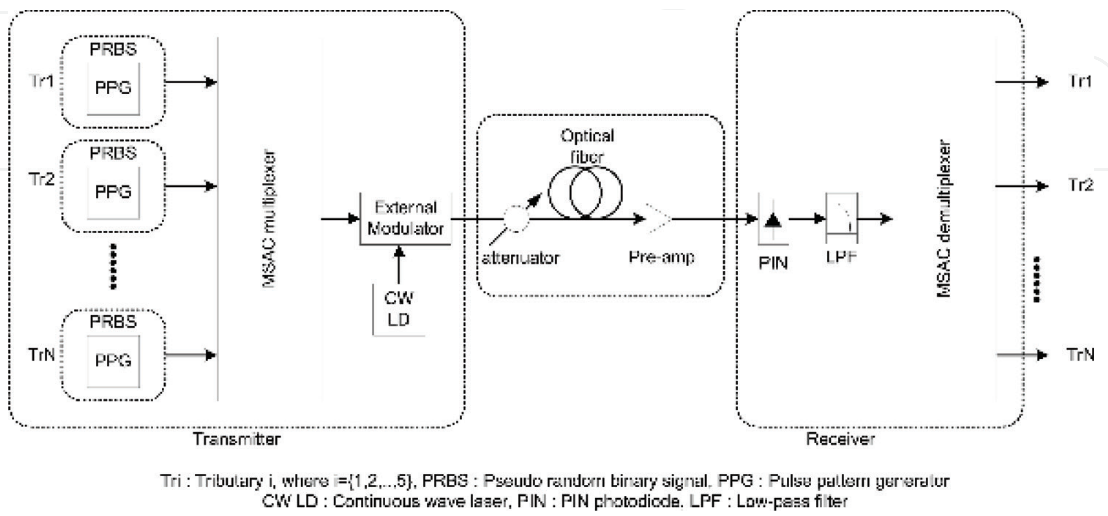

Figure 5. MSAC system setup.

http://dx.doi.org/10.5772/intechopen.68407

optimize the system performance, the cut-off frequency of filter is set at 0.75 *BW*, where BW is the first null bandwidth of baseband MSAC signal. The filtered electrical signal is fed into the clock and data recovery module to regenerate each tributary data stream. In clock and data recovery module, data recovery process is implemented using MATLAB programming based on the recovery rules of MSAC demultiplexer.

6. Results and discussion

6.1. Optical signal spectrum, spectral width and clock recovery frequency

Figure 6a–c illustrates the optical spectrum of MSAC 3 × 10, 4 × 10 and 5 × 10 Gbit/s, respectively. This spectrum has been observed at the transmitter side (after external modulator) using an optical spectrum analyser.

From this figure, simulated null-to-null spectral width of MSAC 3 × 10, 4 × 10 and 5 × 10 Gbit/s is around 60 GHz. This result shows that spectral width of MSAC remains the same even though N is increasing from 3 to 5. This is because they have similar number of slots in a symbol. In this case, number of slots is three, thus slot period is 1/(3 × 10 Gbit/s). This slot determines the width of main-lobe of optical spectrum. Therefore, increasing aggregate capacity from 30 to 50 Gbit/s using this technique will not affect the required optical bandwidth. Moreover, the modulation speed remains unchanged because of the fixed slot interval.

Another important characteristic of the optical signal spectrum is to visualize the clock information in which the frequency is similar to the symbol rate. Note that impulse or spike in optical signal spectrum means high clock frequency in the signal. As shown in **Figure 6a**, there are seven impulses in the null-to-null spectral width, where f_0 is impulse at optical carrier (1550 nm). Note that the spectral is symmetrical at f_0. Besides that the impulses appear at 10 GHz (f_1) and 20 GHz (f_2) away from f_0 on the right side of the main-lobe. The impulse at 10 GHz (f_1) can be used to recover the clock frequency by a clock recovery circuit in receiver. Note that these impulse frequencies are similar for 4 × 10 (**Figure 6b**) and 5 × 10 Gbit/s (**Figure 6c**).

6.2. Spectral efficiency

In optical communication system based on wavelength division multiplexing (WDM) technology, more than one WDM channel can be propagated in optical fibre. Each WDM channel is separated with channel spacing such as 25, 50, 100 or 200 GHz. Note that spectral efficiency in WDM optical system can be calculated based on formula in [6]. Although the simulation is based on 1550 nm or single channel wavelength, MSAC technique can be implemented over WDM system as well. In order to operate with WDM system, WDM channel spacing must be greater than the spectral width of MSAC signal in order to avoid serious interference between adjacent channels. Since the spectral width of MSAC signal is around 60 GHz, therefore 100 or 200 GHz WDM channel spacing can be used. Assuming that WDM channel spacing is 100 GHz, these are corresponding to 0.3, 0.4 and 0.5 bit/s/Hz of spectral efficiency for 3 × 10, 4 × 10 and 5 × 10 Gbit/s, respectively.

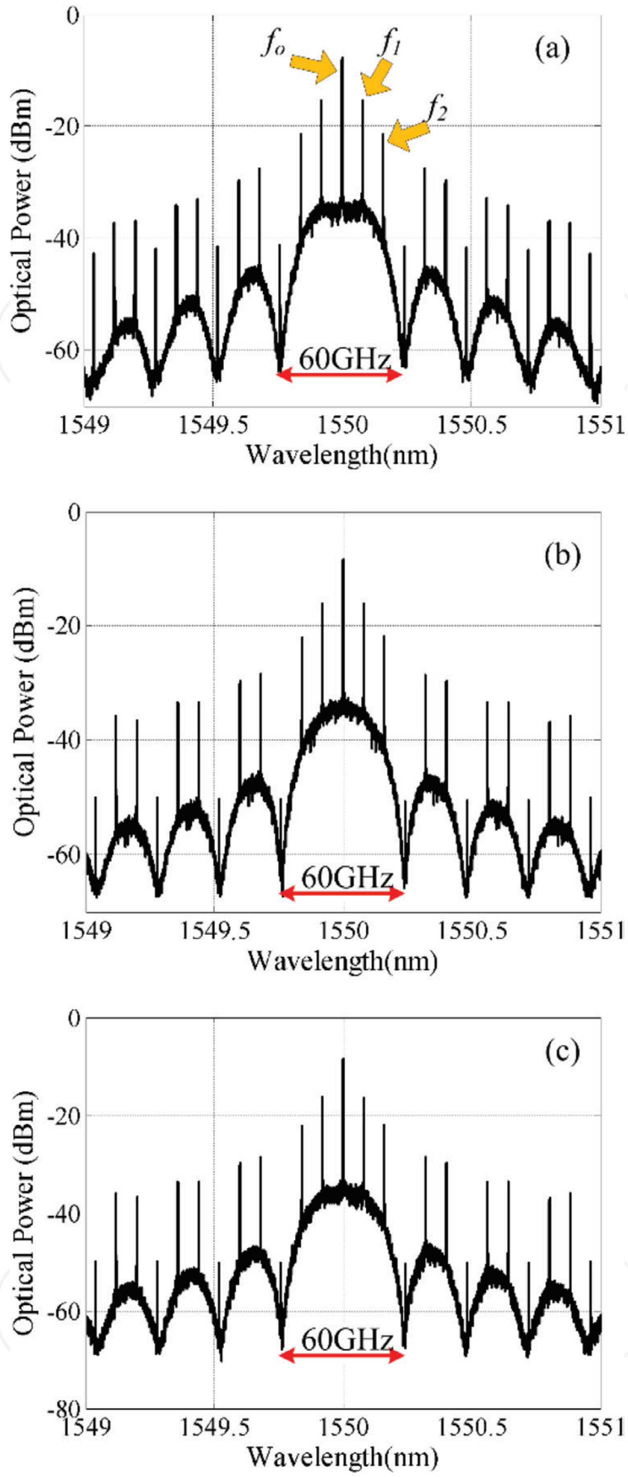

Figure 6. Optical spectrum of MSAC (a) 3 × 10, (b) 4 × 10 and (c) 5 × 10 Gbit/s.

6.3. Received optical power

Bit error rate (BER) estimation in this simulation is based on probability of error method. BER versus received optical power of MSAC at 3 × 10, 4 × 10 s and 5 × 10 Gbit/s has been plotted as in **Figure 7**. Note that this simulation is based on back-to-back setup (optical fibre is not included). As a result, the performance of MSAC system is limited by noises from optical amplifier and PIN

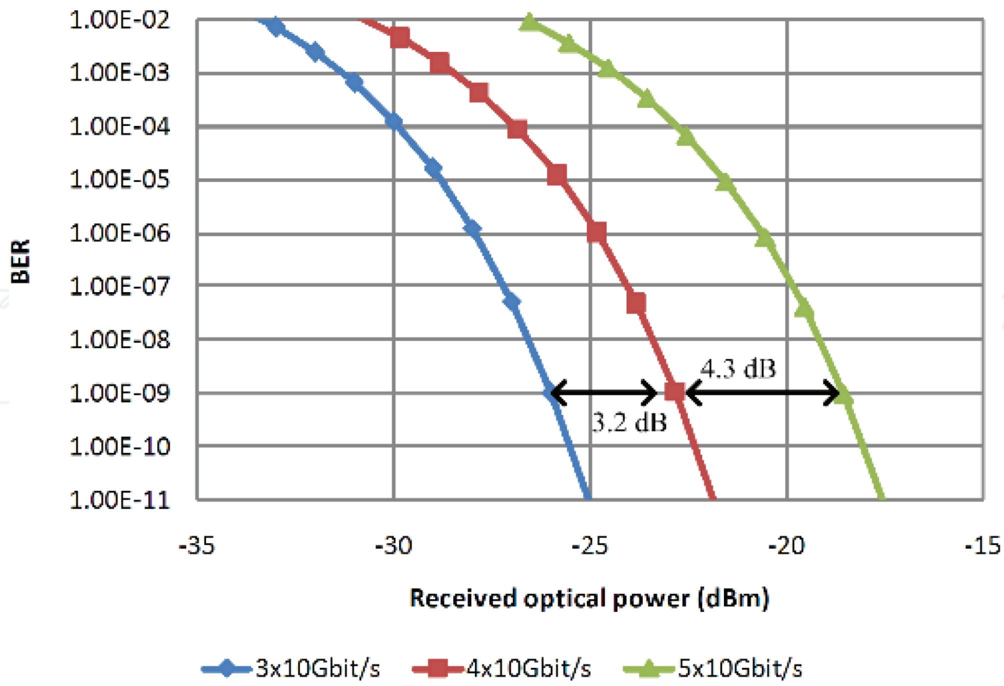

Figure 7. BER versus received optical power of 3 × 10, 4 × 10 and 5 × 10 Gbit/s MSAC.

photodiode. Inter symbol interference is minimized by setting the cut-off frequency of low-pass filter at 0.75 *BW*. From this figure, the required received optical power or receiver sensitivity of MSAC 3 × 10, 4 × 10 and 5 × 10 Gbit/s at BER of 10^{-9} is −26.0, −22.8 and −18.5 dBm, respectively.

This simulation results show that 3 × 10 Gbit/s has the lowest received optical power, whereas 5 × 10 Gbit/s has the highest received optical power. Power penalty of around 3.2 and 7.5 dB is observed for 4 × 10 and 5 × 10 Gbit/s at BER of 10^{-9}, respectively, compared to 3 × 10 Gbit/s. The reason for this penalty is due to the number of signal levels increased. MSAC 3 × 10 Gbit/s uses three signal levels; therefore, it has the lowest received optical power, whereas MSAC 5 × 10 Gbit/s uses six signal levels, thus it has the highest received optical power.

6.4. Optical signal to noise ratio (OSNR)

Figure 8 shows the BER versus OSNR of MSAC at 3 × 10, 4 × 10 and 5 × 10 Gbit/s. From this figure, the required OSNR of MSAC 3 × 10, 4 × 10 and 5 × 10 Gbit/s at BER of 10^{-9} is 25.5, 28.8 and 33.2 dB, respectively. Power penalty due to adding tributary is around 3.3 and 7.7 dB for 4 × 10 and 5 × 10 Gbit/s, respectively. As expected, MSAC system requires more OSNR in order to maintain the BER performance when tributaries increase because the number of levels increases. Note that the variation between power penalty for OSNR and received optical power is small. This indicates that received optical power and OSNR are important parameters for reliable communication.

6.5. Chromatic dispersion tolerance

Chromatic dispersion (CD) is one of the optical fibre impairment in high speed optical communication system. The CD effect in silica fibre will degrade the BER performance due to

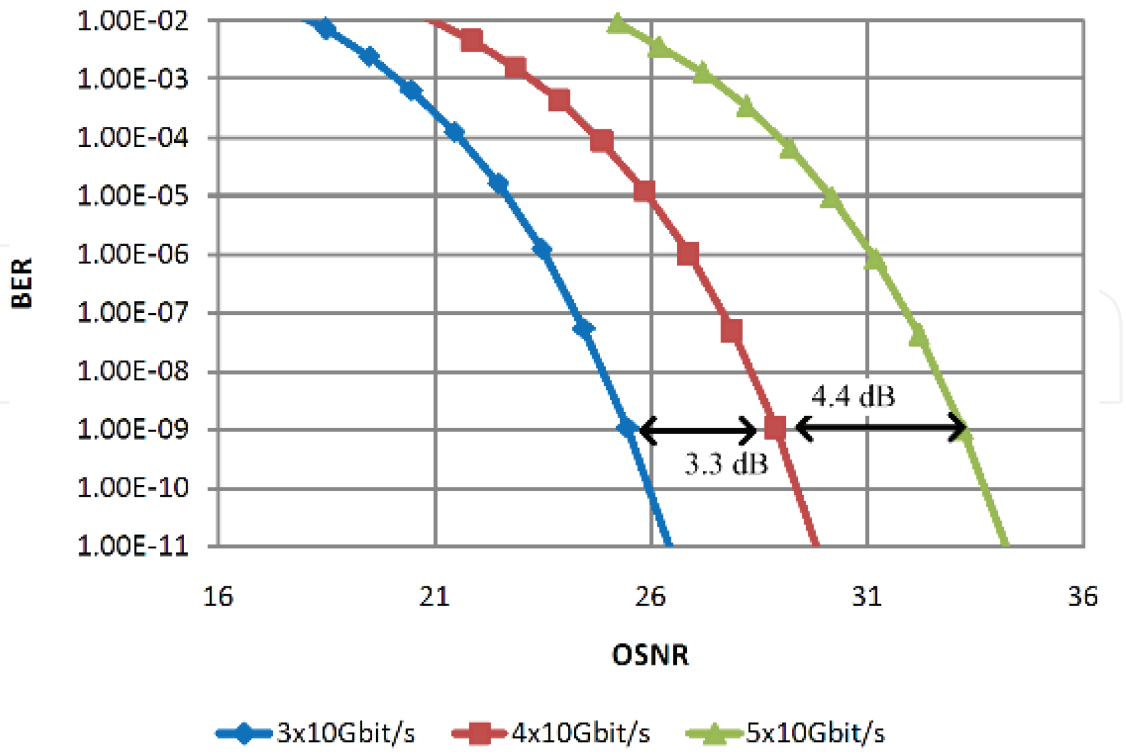

Figure 8. BER versus OSNR of 3 × 10, 4 × 10 and 5 × 10 Gbit/s MSAC.

evolution of signal shape. In order to achieve high performance quality, the accumulated CD must not exceed the allowable CD tolerance. CD tolerance is determined by estimating the amount of CD (positive and negative) at the target BER of 10^{-9}.

In order to determine the chromatic dispersion tolerance, a standard single mode fibre model is included in this simulation setup. The dispersion parameter of optical fibre model is varied from negative dispersion to positive dispersion. Other fibre impairments effect such as attenuation, self-phase modulation (SPM) and non-linear fibre effect are ignored so that the system performance is determined by fibre dispersion only.

Figure 9 depicts the BER versus dispersion of MSAC 3 × 10, 4 × 10 and 5 × 10 Gbit/s. Chromatic dispersion tolerance of MSAC 3 × 10, 4 × 10 and 5× 10 Gbit/s at BER of 10^{-9} is ±164.5, ±149.5 and ±69 ps/nm, respectively. This comparison shows that CD tolerance decreases when the number of signal levels increased. Note that optical power at the highest level for higher number of signal levels of MSAC is high compared to MSAC with small number of signal levels for BER of 10^{-9}. In terms of dispersion mechanism, pulses at higher signal level experience highest energy loss compared to signal at lower level, thus reduces the eye opening and induces a power penalty. Therefore, at similar average power, MSAC with higher number of signal levels losses its CD robustness capability.

6.6. The effect of signal level spacing

In previous work, the separation of signal level or level spacing in MSAC symbol format is equally spaced. The level spacing between level *i* and level *i*-1 is Δ. This means that level spacing

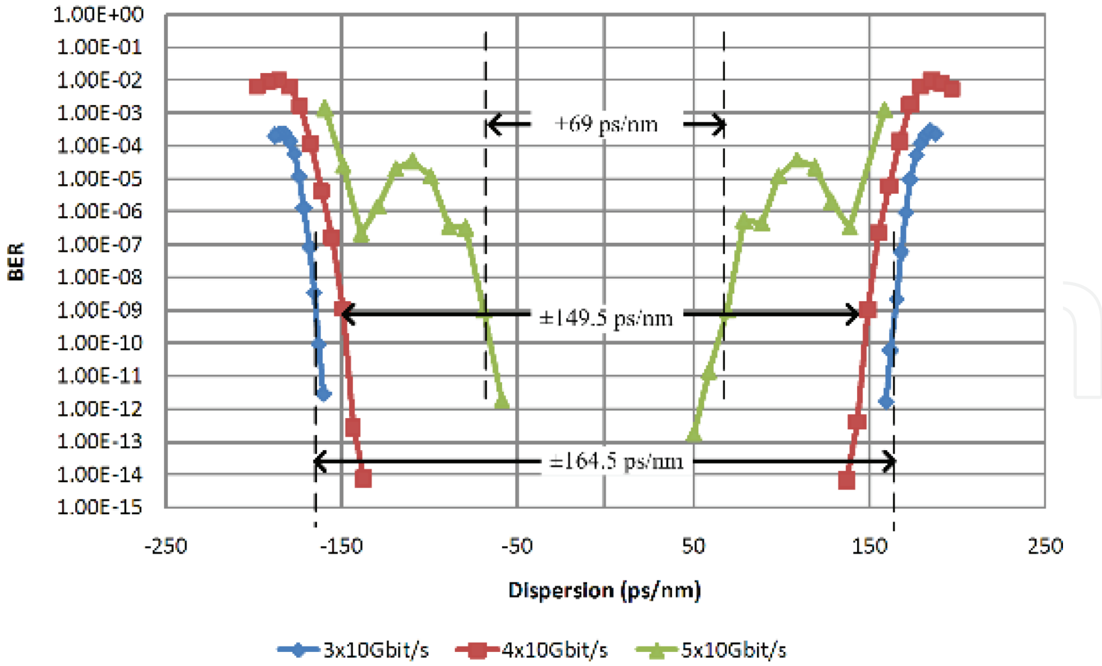

Figure 9. BER versus dispersion of 3 × 10, 4 × 10 and 5 × 10 Gbit/s MSAC.

ratio is 0, 0.5 and 1 for level 0, level 1 and level 2, respectively. This setting is, therefore, known as equal level spacing (ELS). **Figure 10** shows the BER of MSAC against normalized signal spacing of level 1 between 0.1 and 0.6. The optimum level spacing (OLS) is observed at normalized signal spacing of level 1 of 0.31. As expected, higher level spacing for upper level compared to lower level spacing in order to achieve equal probability of error region for each signal level.

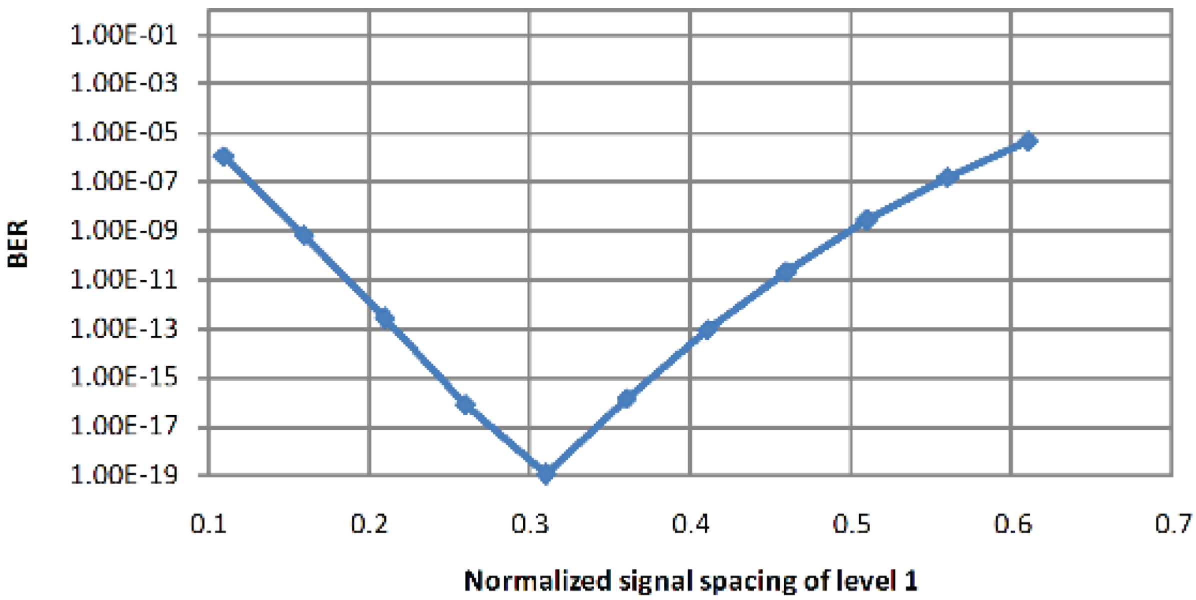

Figure 10. BER of MSAC against normalized signal spacing of level 1 between 0.1 and 0.6.

Figures 11 and **12** show the comparison between equal level spacing (ELS) and optimize level spacing (OLS) of back to back (b2b) BER performance of 3 × 10 Gbit/s MSAC system based on received optical power and OSNR, respectively. From the figure, the received optical powers of −26 and −29.5 dBm are obtained at BER of 10^{-9} for ELS and OLS, respectively. This is an improvement of 3.5 dB when OLS MSAC is adopted at receiver. In term of OSNR, ELS requires 25.5 dB, in contrast OLS requires 21.8 dB. This clearly shows that there is OSNR improvement when OLS method is applied, with improvement around 3.7 dB.

The performance in terms of dispersion tolerance for ELS and OLS method is plotted as shown in **Figure 13**. Based on that figure, ELS and OLS methods are capable of tolerating positive and negative chromatic dispersion of 329 and 311 ps/nm at BER of 10^{-9}. The reduction of 18 ps/nm is observed for OLS method compared to ELS method.

The effect of the signal level is also investigated for the MSAC system with setup of 4 × 10 Gbit/s. In general, the approach to determine the optimum level is similar for previous setup (3 × 10 Gbit/s). Since 4 × 10 Gbit/s MSAC has four signal levels, both signal levels 1 and 2 are adjusted while signal levels 0 and 3 are fixed. It is found that the optimum level spacing is achieved when the normalized signal level 1 and signal level 2 are 0.183 and 0.51, respectively.

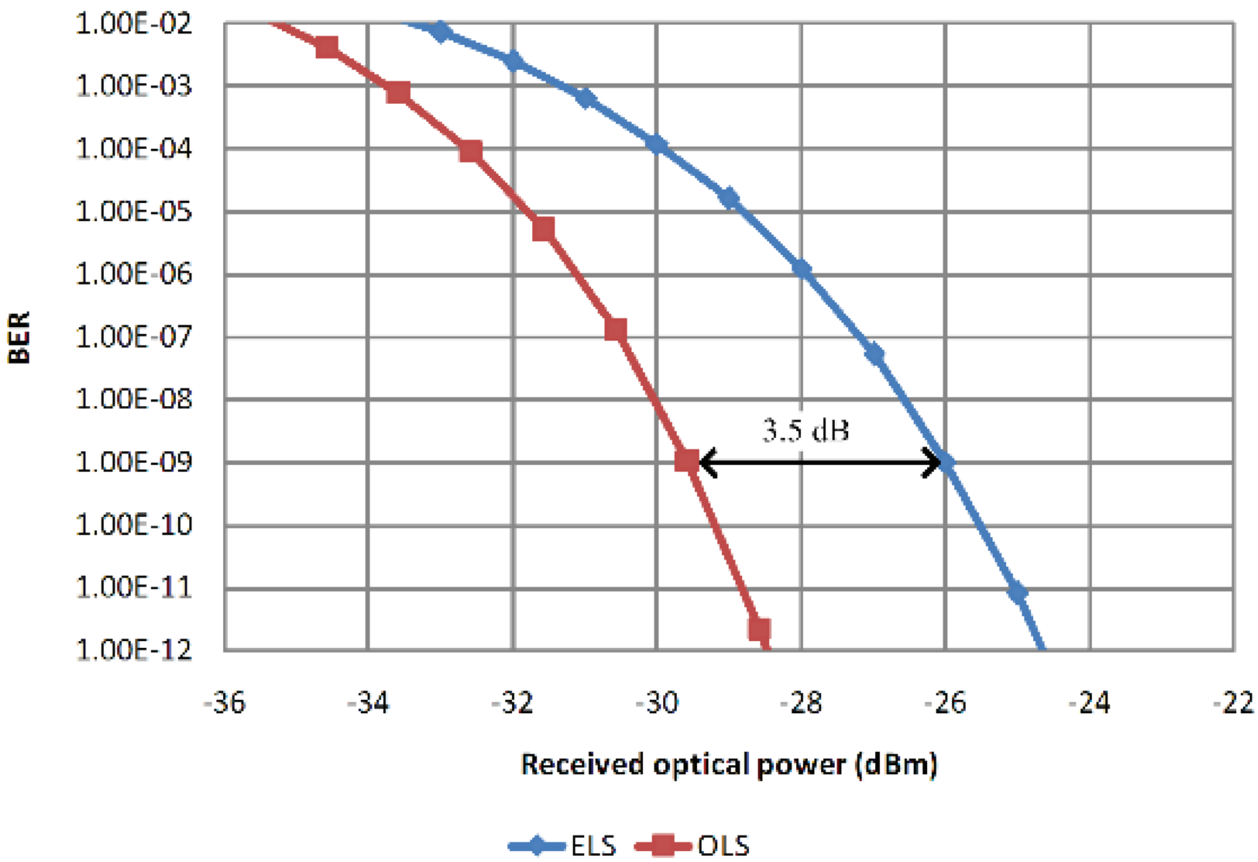

Figure 11. Received optical power comparison between ELS and OLS of b2b 3 × 10 _Gbit/s MSAC system.

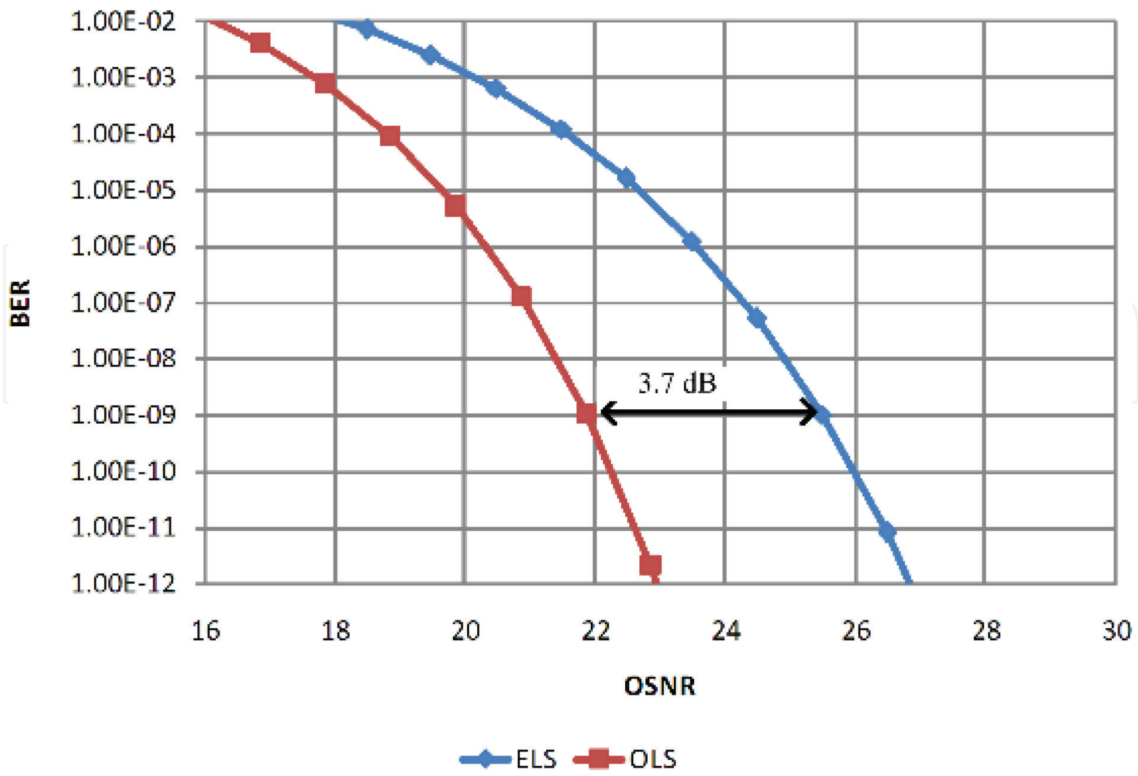

Figure 12. OSNR comparison between ELS and OLS of b2b 3 × 10 Gbit/s MSAC system.

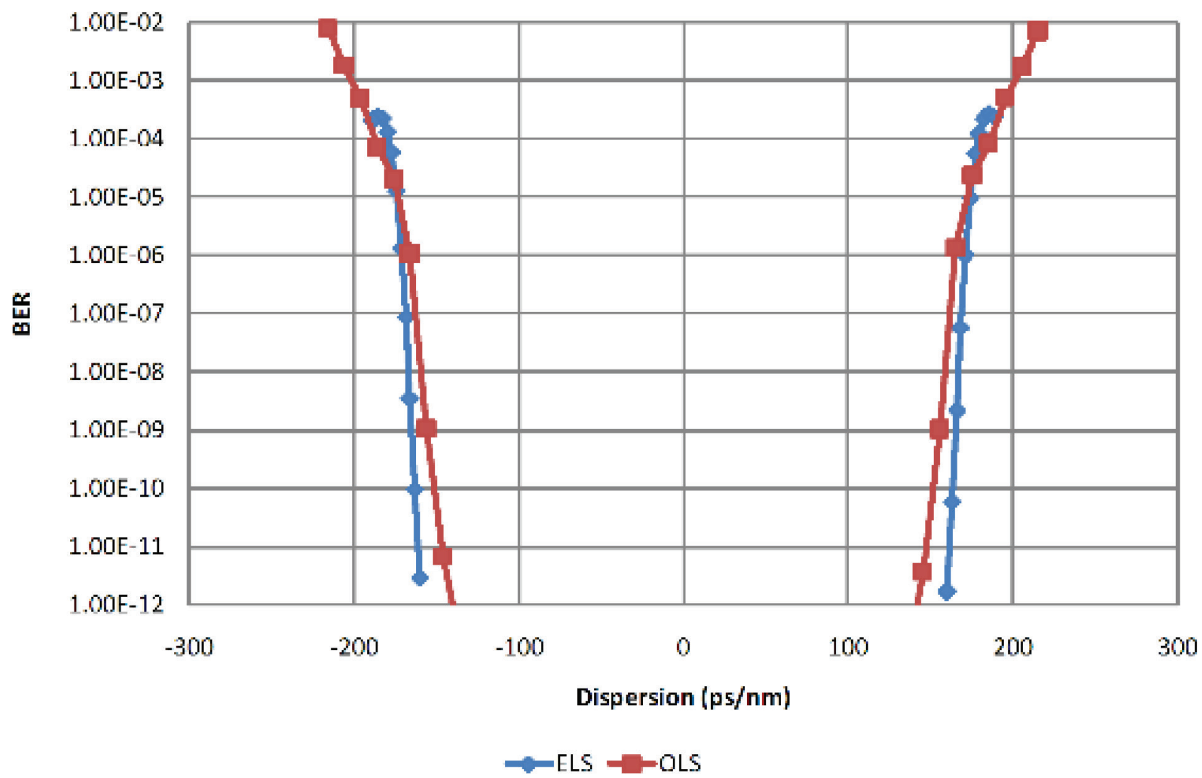

Figure 13. Dispersion tolerance comparison between ELS and OLS of b2b 3 × 10 Gbit/s MSAC system.

Figure 14 shows the comparison between ELS and OLS in terms of the received optical power for b2b 4 × 10 Gbit/s MSAC system. The received optical powers of ELS and OLS MSAC are −22.8 and −27.1 dBm, respectively, at BER of 10^{-9}. The improvement of receiver sensitivity around 4.3 dB is observed. The comparison between ELS and OLS in terms of OSNR is shown in **Figure 15**. Based on this graph, OSNR is 28.8 dB for ELS, whereas 24.5 dB for OLS. This result shows that the OSNR improvement has been achieved with similar amount for receiver sensitivity improvement. **Figure 16** shows the comparison between ELS and OLS in terms of CD tolerance. The CD tolerance is ±149.5 and ±73.1 ps/nm for ELS and OLS, respectively.

6.7. Performance comparison

The performance comparison between other electrical-based multiplexing is made according to transmission capacities, which are 30 and 40 Gbit/s. For this comparison, other versions of DCDM such as DCDM-amplitude distribution controller (DCDM-ADC), DCDM with dual drive Mach Zehnder modulator (DD-MZM), new multiplexed pattern DCDM (NMP-DCDM) and absolute polar DCDM (AP-DCDM) are included. **Table 1** shows the performance comparison between MSAC with various types of DCDM. It is very clear that MSAC with OLS has better performance compared to DCDM-ADC, DCDM with DD-MZM and NMP-DCDM. Note that level spacing for DCDM-ADC was optimized by installing a controller, whereas DCDM with DD-MZM was optimized using a dual drive Mach Zehnder modulator. MSAC with OLS offers better performance in terms of CD tolerance compared to AP-DCDM; however, the receiver sensitivity and spectral width are almost similar. Another advantage of

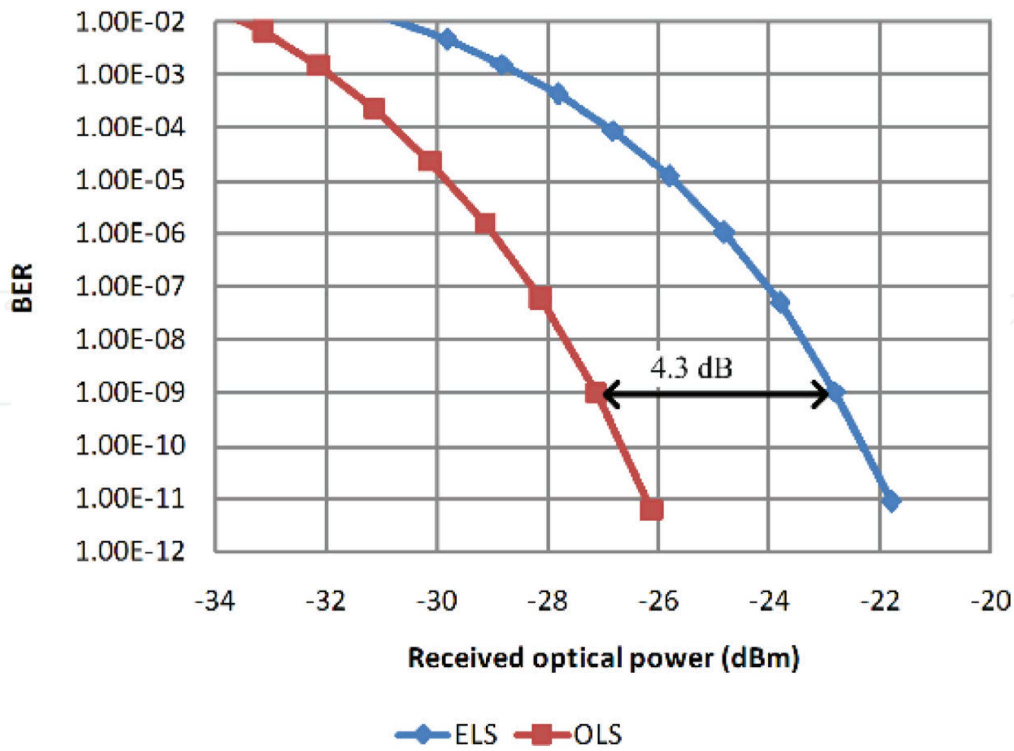

Figure 14. Received optical power comparison between ELS and OLS of b2b 4 × 10 Gbit/s MSAC system.

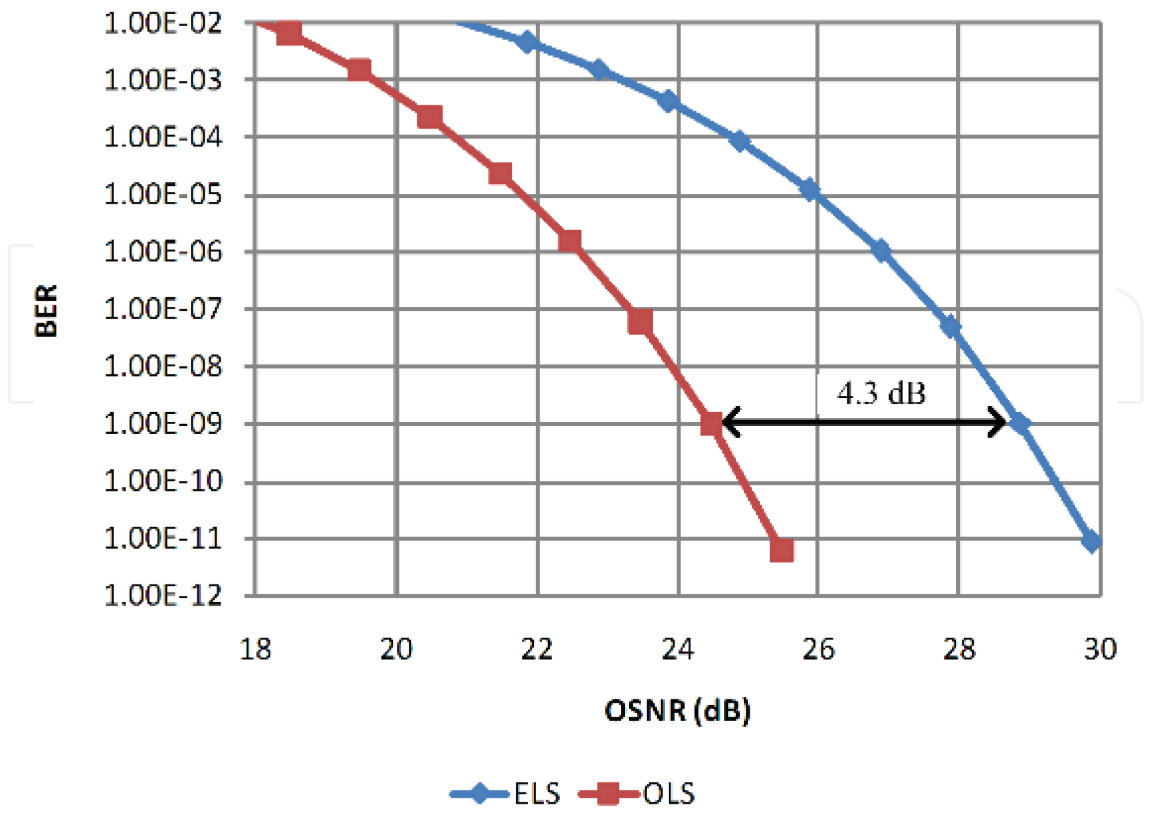

Figure 15. OSNR comparison between ELS and OLS of b2b 4 × 10 Gbit/s MSAC system.

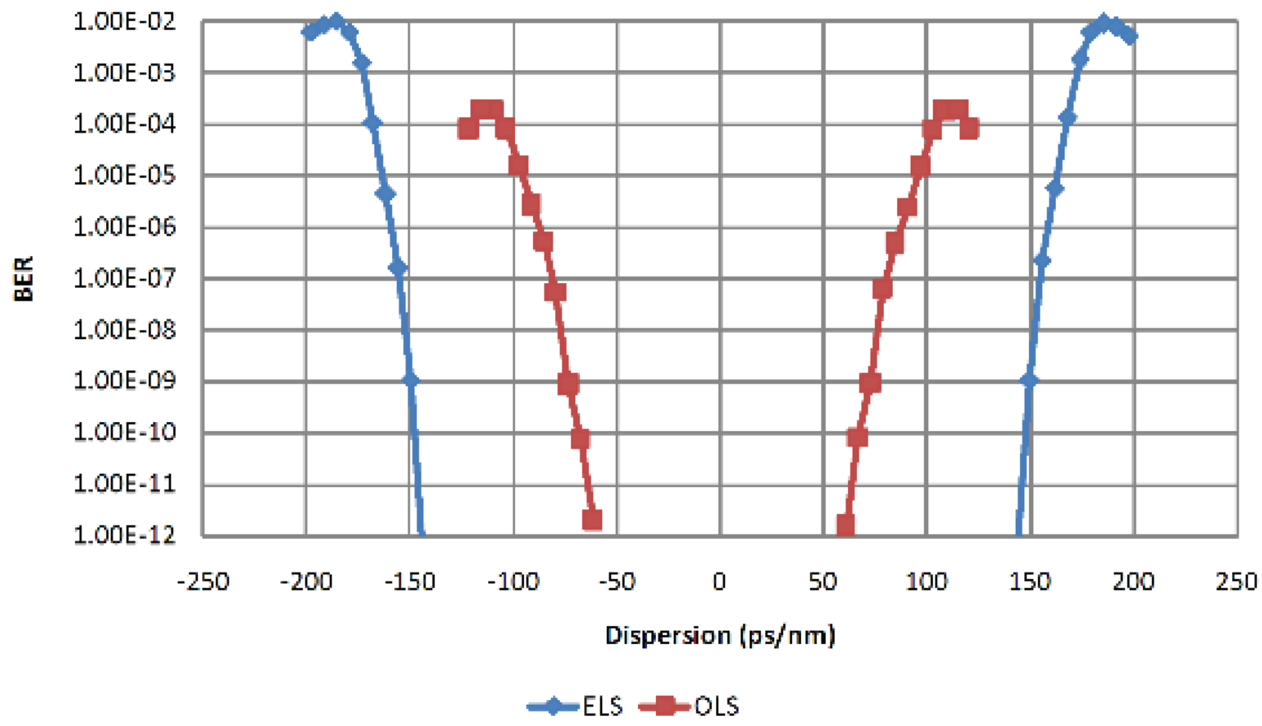

Figure 16. Dispersion tolerance comparison between ELS and OLS of b2b 4 × 10 Gbit/s MSAC system.

Technique	Guard slot	RS BER @ 10^{-9}	OSNR BER @ 10^{-9}	Spectral width (GHz)	CD tolerance (ps/nm)	
DCDM-ADC	Yes	−28.9	23.35	80	±93.5	[7]
DCDM with DD-MZM	Yes	−28.85	23.3	80	−59 to +100	[8]
AP-DCDM	No	−29	22.82	60	±109	[9]
NMP-DCDM	Yes	−28.4	23.5	–	–	[10]
MSAC with OLS	Yes	−29.5	21.8	60	±155	

Abbreviations: RS, receiver sensitivity; DCDM-ADC, DCDM amplitude distribution controller; DD-MZM, dual drive Mach Zehnder modulator; AP-DCDM, absolute polar DCDM; NMP-DCDM, new multiplexed pattern DCDM; NA, not available.

Table 1. Performance comparison between various DCDM version and MSAC for 3 × 10 Gbit/s system setup.

MSAC compared to AP-DCDM is high frequency component at symbol rate. This feature is obtained because MSAC symbols are equipped with guard slot, like DCDM or RZ, therefore, increases the transition density in the modulated signal. As a result, a complex circuit is not required for recovering clock frequency in receiver. This comparison indicates that MSAC provides significant advantages against DCDM and AP-DCDM for multiplexing high speed data stream in electrical domain.

Table 2 shows the performance comparison between DCDM-ADC, AP-DCDM and MSAC for optical transmission system with 40 Gbit/s setup. In general, the performance for all parameters for MSAC with OLS is better than DCDM-ADC. This finding is consistence with the result in **Table 1**. The performance of MSAC is also better than AP-DCDM version with guard slot. The receiver sensitivity for MSAC is inferior when comparing with the optimized level spacing AP-DCDM using DD-MZM, but it has better performance in terms of the spectral width and CD tolerance. Moreover, upgrading MSAC from 3 (3 × 10 Gbit/s) to 4 tributaries (4 × 10 Gbit/s) is achieved without extra spectral width. For ETDM, spectral width of 160 GHz

Technique	Guard slot	RS BER @ 10^{-9}	OSNR BER @ 10^{-9}	Spectral width (GHz)	CD tolerance (ps/nm)	
DCDM-ADC	Yes	−26	26.38	100	±58	[7]
AP-DCDM	Yes	−26.8	25.8	100	±62	[11]
AP-DCDM with DD-MZM	No	−31	NA	80	±68	[12]
MSAC with OLS	Yes	−27.1	24.5	60	±73.1	

NA, not available.

Table 2. Performance comparison between DCDM, AP-DCDM and MSAC for 4 × 10 Gbit/s setup.

is required for RZ format and 80 GHz for NRZ format for 40 Gbit/s system [13]. This means that ETDM is not bandwidth efficient compared to MSAC.

7. Conclusion

The evaluation of MSAC technique in fibre optic-based optical communication system has been carried out through an intensive numerical simulation. From the analysis, it is found that MSAC system performance is certainly better than DCDM-ADC, DCDM with DD-MZM and NMP-DCDM in terms of spectral width, spectral efficiency, receiver sensitivity, OSNR and CD tolerance. Besides that MSAC is also capable of achieving higher bandwidth or spectral efficiency compared to ETDM and AP-DCDM. Note that MSAC system is implemented using simple intensity modulation and direct detection scheme. As a result, the complexity of transmitter and receiver for this system is less than that of coherent scheme or optical time division multiplexing (OTDM) system. This issue is crucial for future high speed optical communication system in metropolitan region. This work has successfully demonstrated the possibility of implementing MSAC as advance multiplexing in the cost efficient high speed optical communication system for metropolitan application.

Acknowledgements

This work has been funded by the Ministry of Higher Education, Government of Malaysia under project FRGS/1/2015/TK04/UTHM/03/5.

Author details

Rahmat Talib and Mohammad Faiz Liew Abdullah*

*Address all correspondence to: faiz@uthm.edu.my

University Tun Hussein Onn Malaysia, Malaysia

References

[1] Lach E, Schuh K. Recent advances in ultrahigh bit rate ETDM transmission systems. Journal of Lightwave Technology. 2006;**23**(12):4455–4467. DOI: 10.1109/JLT.2006.886404

[2] Winzer PJ, Raybon G, Doerr CR, Duelk M, Dorrer C. 107-Gb/s optical signal generation using electronic time-division multiplexing. Journal of Lightwave Technology. 2006;**24**(8):3107–3113. DOI: 10.1109/JLT.2006.878016

[3] Mahdiraji GA, Abdullah MK, Mohammadi AM, Abas AF, Mokhtar M, Zahedi E. Duty-cycle division multiplexing (DCDM). Optics & Laser Technology. 2010;**42**(2):289–295. DOI: 10.1016/j.optlastec.2009.07.007

[4] Talib R, Abdullah MFL, Abdullah MK. Multi slot amplitude coding performance improvement with level spacing optimization. In: Conference Proceeding of the 4th International Conference on Photonics (ICP 2013); 28–30 October 2013; Melaka, Malaysia. New York: IEEE; 2013. pp. 206–208. DOI: 10.1109/ICP.2013.6687115

[5] Agrawal GP. Fiber-Optic Communication Systems. 4th ed. New York: John Wiley & Sons; 2010. DOI: 10.1002/9780470918524

[6] Winzer PJ, Gnauck AH, Doerr CR, Magarini M, Buhl LL. Spectrally efficient Long-Haul optical networking using 112-Gb/s polarization-multiplexed 16-QAM. Journal of Lightwave Technology. 2010;**28**(4): 547–556. DOI: 10.1109/JLT.2009.2031922

[7] Mahdiraji GA. Performance analysis of Duty-Cycle division multiplexing for optical fiber communication systems [thesis]. Serdang: Universiti Putra Malaysia; 2009

[8] Amouzad Mahdiraji G, Abas AF. Improving the performance of electrical duty-cycle division multiplexing with optimum signal level spacing. Optics Communications. 2012;**285**(7):1819–1824. DOI: 10.1016/j.optcom.2011.12.022

[9] Malekmohammadi A, Abdullah MK, Mahdiraji GA, Abas AF, Mokhtar M, Rasid MFA, Basir SM. Analysis of return-to-zero-on-off-keying over absolute polar duty cycle division multiplexing in dispersive transmission medium. Optoelectronics. IET. 2009;**3**(4):197–206. DOI: 10.1049/iet-opt.2008.0050

[10] Dahawü TH, Aljunid SA, Rashidi CBM, Rahman AK. Performance analysis of new multiplexed pattern for duty-cycle division multiplexing over optical communication system. In: 3rd International Conference on Electronic Design (ICED); 11–12 August 2015; Phuket. New York: IEEE; 2016. pp. 170–173. DOI: 10.1109/ICED.2016.7804630

[11] Malekmohammadi A, Mahdiraji GA, Abas AF, Abdullah MK, Mokhtar M, Rasid MFA. Realization of high capacity transmission in fiber optic communication systems using Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) technique. Optical Fiber Technology. 2009;**15**(4):337–343. DOI: 10.1016/j.yofte.2009.03.001

[12] Malekmohammadi A, Al-Mansoori MH, Mahdiraji GA, Abas AF, Abdullah MK. Performance enhancement of absolute polar duty cycle division multiplexing with dual-drive mach-zehnder-modulator in 40 Gbit/s optical fiber communication systems. Optics Communications. 2010;**283**(16):3145–3148. DOI: 10.1016/j.optcom.2010.04.026

[13] Miyamoto Y, Kataoka T, Tomizawa M, Yamane Y. 40-Gbit/s channel Technologies for optical Transport Network. Optical Fiber Technology. 2001;**7**(4):289–311. DOI: 10.1006/ofte.2001.0359