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Realization of high capacity transmission in fiber optic communication systems using Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) technique

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ABSTRACT

An electrical multiplexing technique, namely Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) is reported for high-speed optical fiber communication systems. It is demonstrated that 40 Gb/s (4×10 Gb/s) AP-DCDM system shows a clear advantage over conventional 40 Gb/s RZ-OOK with 50% duty cycle in terms of dispersion tolerance and spectral efficiency. At 40 Gb/s its tolerance to chromatic dispersion (CD) is 124 ps/nm and 194 ps/nm for the worst and the best user, respectively. These values are higher than that of 40 Gb/s RZ-OOK, which is around 100 ps/nm. The spectral efficiency, receiver sensitivity and OSNR for different number of channels are discussed. Comparison against other modulation formats namely duobinary, Non-Return-to-Zero (NRZ)-OOK and RZ-Differential Quadrature Phase-Shift Keying (RZ-DQPSK) at 40 Gb/s are made. It is shown that AP-DCDM has the best receiver sensitivity (−32 dBm) and better CD tolerance (±200 ps/nm) than NRZ-OOK and RZ-DQPSK. In reference to duobinary, AP-DCDM has better receiver sensitivity but worse dispersion tolerance.

1. Introduction

Multiplexing is one of the fundamental necessities in today's digital communications, which allows multiple users to share the bandwidth of the transmission medium. There are several multiplexing techniques available such as Time Division Multiplexing (TDM) [1] and Wavelength Division Multiplexing (WDM) [2,3]. Many researchers have for some time, examined multilevel signaling, e.g. AM-PSK polybinary, M-ary Amplitude-Shift-Keying (ASK) and polyquaternary as a way of improving the system performance against Chromatic Dispersion (CD) and Polarization mode dispersion (PMD) due to its reduced spectral occupancy [4]. The main issues in those techniques are degradation in receiver sensitivity due to the increased number of levels and the signal dependence on signal-spontaneous beat noise [5]. At the same time Differential Quadrature Phase-Shift Keying (DQPSK) [6] and Polarization Division Multiplexing (PDM) [7] were proposed for realizing high capacity WDM networks. However, both techniques increase the complexity of the receiver by the introduction of the temperature-stabilized Mach-Zehnder Interferometer (MZI) and fast polarization controller, respectively [7]. Pulse position modulation (PPM) is another alternative for optical communication systems. In PPM each symbol interval is partitioned into subintervals, or chips, and the transmitter sends an optical pulse during one of these chips. In this system the amplitude and width of the signal is kept constant. Position of each pulse, in relation to the position of a recurrent reference pulse is varied. In comparison to On–Off-Keying (OOK), PPM requires less optical power but higher bandwidth. Another challenge of this technique is that PPM requires both chip- and symbol-level synchronization [8].

Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) was reported for the first time in [9,10] as an alternative multiplexing technique for wireless transmission based on free space propagation model with Adaptive White Gaussian Noise (AWGN).

In this paper, AP-DCDM is modeled for optical fiber communication and characterized in dispersive optical transmission medium. AP-DCDM uses different RZ duty cycles and bipolar signaling to differentiate the channels. Subsequent users at the multiplexer input have opposite polarity, which results in unique multilevel patterns at the output of the multiplexer. As compared to unipolar input, by using bipolar signaling, the increment of the multiplexed signal amplitude with reference to the number of users is reduced. It is verified that AP-DCDM has smaller spectral width, which leads toward better spectral efficiency and dispersion tolerance than conventional RZ-OOK with 50% duty cycle. For simplicity throughout this paper, conventional RZ-OOK with 50% duty cycle is referred to as RZ-OOK. Performance of AP-DCDM in comparison to other multilevel modulation formats is also discussed.

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2. Working principle

AP-DCDM is a multiplexing technique that uses bipolar signal with different duty cycles to differentiate the channels or users. In this technique, each user transmits bit '0' with zero volts and for the case of bit one, the odd users transmit '+*A*' volts while the even users transmit '−*A*' volts. Based on the linear distribution (per user assignment) of duty cycle, the *i*th multiplexing user transmits bit 1 within T_i second, which is

$$T_i = i \times \left(\frac{T_s}{n+1}\right) \tag{1}$$

where T_s is the symbol duration and *n* is the number of users. Therefore, different users share the communication medium to transmit in the same time period and at the same carrier wavelength, but with different duty cycles. The unique duty cycle for each channel helps to regenerate data at the receiver [10]. Fig. 1 illustrates the signal multiplexing process for a four user system. In Fig. 1a, 16 possible combinations of users' data are shown, which is referred to as Case 1 to Case 16. Fig. 1b–d shows the example of duty cycle distribution for a four-user system for Case 6 to Case 11, where 20%, 40%, 60% and 80% duty cycles are used to represent User1 (U1), User2 (U2), User3 (U3) and User4 (U4), respectively. Note that the second and fourth users have opposite polarity to the first user, and similarly, the third user has opposite polarity relative to the second and fourth users. Based on the 2^n possible bits combination in Fig. 1a, each of these combinations produces a unique symbol with both positive and negative polarities (Fig. 1f). The process ends by taking the absolute value of the signal in Fig. 1f to produce absolute polar DCDM signal (Fig. 1g), which is a unique positive polarity symbol for each case. Having the knowledge of this uniqueness at the receiver side, the original data for each user can be recovered [9,10]. The unique pattern of AP-DCDM signal has multilevel amplitude. This is in contrast to PPM where position of each pulse, in relation to the position of a recurrent reference pulse, is varied while the amplitude and width of the signal are kept constant.

3. Implementation issues

Table 5 shows the requirement comparison between different modulation formats. AP-DCDM like NRZ-OOK requires only one Modulator and one photodiode (PD) for *n* number of users at the transmitter and the receiver side, respectively. This is very economical in comparison to other modulation formats such as NRZ-DPSK, which require one Delay Interferometer (DI) and two PDs at the receiver [11], or RZ-DQPSK which requires two Mach-Zehnder Modulators (MZM) at the transmitter, and two DIs together with four PDs at the receiver [11] or duobinary which require one dual-arm MZM modulator including driver amplifier for each modulator arm at the transmitter and one PD in the receiver [11]. Referring to the AP-DCDM data recovery concept, one may argue that the complexity of AP-DCDM receiver is higher than other systems. However, the complexity is due to additional electronics components and devices, the solutions of which are available in term of technology and experts [12–15]. Work on technologies aspect for 40 Gb/s Integrated Circuit (IC) has now reached the stage where cost-effective commercial products are being developed [12–14]. For the device technology, InP-based high electron mobility transistors (HEMT) ICs are a promising candidate for realizing high-speed ICs beyond 40 Gb/s [13–15]. At transmitter side, major components required by AP-DCDM such as NRZ to RZ converter [15] and full wave rectifier [13] that operates up to 50 Gb/s have been introduced in recent years. In terms of clock recovery, the electrical spectrum of 40 Gb/s AP-DCDM has a transition at every 10 GHz as depicted in Fig. 2, which makes the clock extraction from high-speed serial data stream possible.

4. Simulation setup

In this study OptiSystem and MATLAB were used to access the system performance. The performance evaluation of the system is based on Bit Error Rate (BER), which is described in Section 5. Fig. 3a shows the simulation setup. Data1, Data2, Data3 and Data4

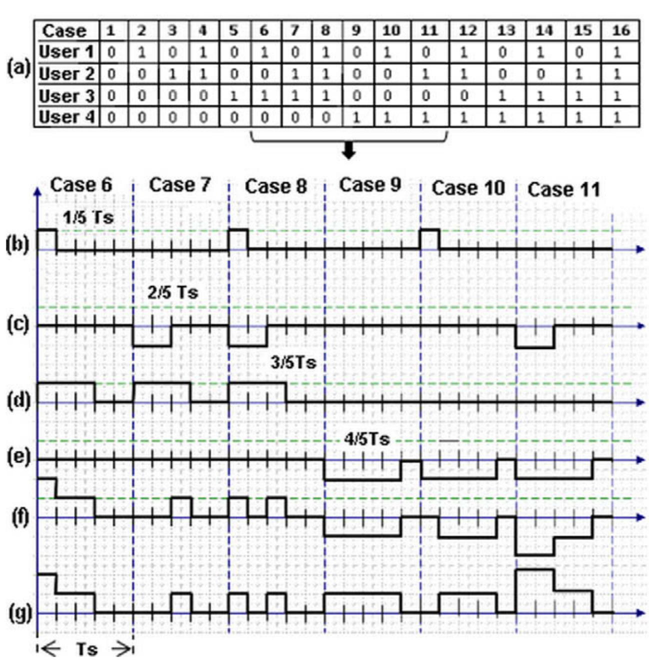

Fig. 1. (a) Sixteen possible combination of bits for four users, (b) Example of U1 data stream (Case 6 to 11), (c) Example of U2 data stream, (d) Example of U3 data stream, (e) Example of U4 data stream (f) Bipolar multiplexed signal, and (g) Absolute polar multiplexed signal.

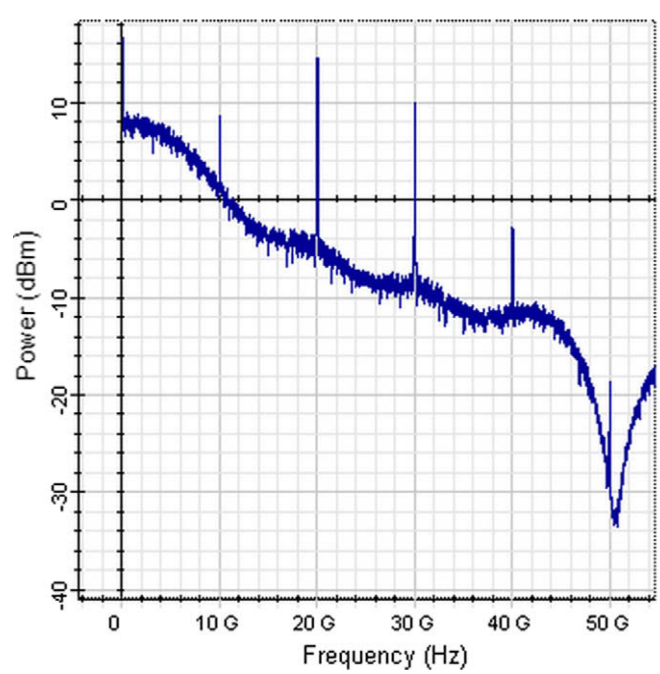

Fig. 2. Transitions at every 10 GHz which was used as frequency reference for clock recovery.

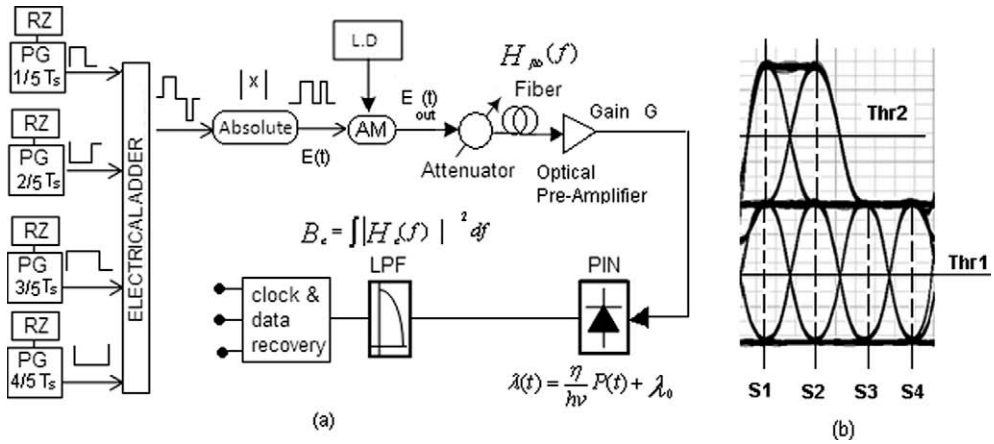

Fig. 3. (a) AP-DCDM simulation setup for multiplexing four users, (b) transmitted eye diagram including sampling points and threshold values.

each at 10 Gb/s with PRBS $2^{10}-1$ are carved with four electrical RZ pulse carvers at 1/5, 2/5, 3/5 and 4/5 T_s duty cycles, respectively. The voltages for all users at the multiplexer input are identical. All users' data are multiplexed via a power combiner (electrical adder) resulting in a bipolar signal. Subsequently, the absolute circuit is used to produce an absolute polar signal. The signals are used to modulate a laser diode (LD), which operates at 1550 nm wavelength using an amplitude modulation (AM). The eye diagram of the modulator output is shown in Fig. 3b. At the receiver side, the optical signal is detected by a photodiode and passed through a low-pass filter (LPF) and a Clock-and-Data-Recovery (CDR) unit. The bandwidth of the Gaussian low-pass filter is required to be appropriately optimized in reference to the signal pulse width. Fig. 4 shows back-to-back receiver sensitivity as a function of electrical filter bandwidth. Filter bandwidths ranging from 23 to 31 GHz yielded almost the same receiver sensitivity for 40 Gb/s AP-DCDM signal. Thus, the electrical filter bandwidth was fixed to 25 GHz in the following experiment, for eliminating the photodiode noises.

In the CDR unit, the received signal is fed into the sampling circuit. The samples are taken at four sampling points of S_1, S_2, S_3 and S_4 at the first four slots in every symbol (Fig. 3b). Outputs of the sampling circuit are fed into the decision and regeneration unit. In this unit, the sampled values are compared against two threshold values of, thr_1 and thr_2 (Fig. 3b) and the decision is performed based on the operation shown in Tables 1–4. These tables contain the regeneration rules for a four-user system that the data recovery

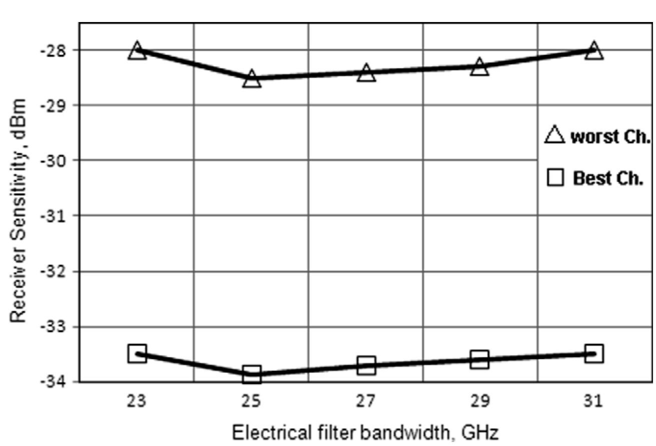

Fig. 4. Receiver sensitivity as a function of electrical filter bandwidth.

Table 1
Data recovery rules for U1.

No.	Rules		
1	if ($S_1 < thr_1$)	& ($S_2 < thr_1$)	then U1 = 0
2	if ($S_1 \geqslant thr_1$)	& ($S_2 \geqslant thr_1$)	then U1 = 0
3	if ($S_1 \geqslant thr_2$)	& ($S_2 \geqslant thr_2$)	then U1 = 0
4	if ($S_1 \geqslant thr_1$)	& ($S_2 < thr_1$)	then U1 = 1
5	if ($S_1 < thr_1$)	& ($S_2 \geqslant thr_1$)	then U1 = 1
6	if ($S_1 \geqslant thr_2$)	& ($thr_1 \leqslant S_2 \leqslant thr_2$)	then U1 = 1
7	if ($S_1 \geqslant thr_1$)	& ($S_2 \geqslant thr_2$)	then U1 = 1

unit uses to regenerate original data for each user. For example, for U1, binary 0 is regenerated when sampling values at S_1 and S_2 are less than thr_1 (Table 1 rule 1). Binary 1 is regenerated when sampled amplitude at S_1 is equal or greater than thr_1, while amplitude at S_2 is less than thr_1 (Table 1 rule 4).

5. BER estimation

As discussed in [16], a technique for BER estimation, which is also referred to as Probability of Error (PE) estimation is developed for each AP-DCDM multiplexed user, based on the data recovery rules. In the case of four users, referring to Fig. 3b the multilevel signal plus noise at the receiver input produces a multilevel analog waveform at the output of the processing circuit denoted as

$$\boldsymbol{r}_0(t) = \begin{cases} \boldsymbol{r}_{00}(t), & 0 < t < T \text{ for level } 0 \\ \boldsymbol{r}_{01}(t), & 0 < t < T \text{ for level } 1 \\ \boldsymbol{r}_{02}(t), & 0 < t < T \text{ for level } 2 \end{cases} \tag{2}$$

where $r_0(t)$ is a random variable that has continuous distribution. For simplicity throughout this paper, $r_0(t)$ is referred to as r_0. Let us assume that we can evaluate the Probability Density Functions (PDFs) for the three random variables $r_0 = r_{00}$, $r_0 = r_{01}$ and $r_0 = r_{02}$ in all four sampling points (S_1, S_2, S_3 and S_4). The PDFs are actually

Table 2
Data recovery rules for U2.

No.	Rules		
1	if ($S_2 < thr_1$)	& ($S_3 < thr_1$)	then U2 = 0
2	if ($thr_1 \leqslant S_2 \leqslant thr_2$)	& ($S_3 \geqslant thr_1$)	then U2 = 0
3	if ($S_2 \geqslant thr_2$)	& ($thr_1 \leqslant S_3 < thr_2$)	then U2 = 1
4	if ($S_2 \geqslant thr_1$)	& ($S_3 < thr_1$)	then U2 = 1
5	if ($S_2 < thr_1$)	& ($S_3 \geqslant thr_1$)	then U2 = 1

Table 3
Data recovery rules for U3.

No.	Rules		
1	if ($S_3 < thr_1$)	& ($S_4 < thr_1$)	then U3 = 0
2	if ($S_3 \geqslant thr_1$)	& ($S_4 \geqslant thr_1$)	then U3 = 0
3	if ($S_3 \geqslant thr_1$)	& ($S_4 < thr_1$)	then U3 = 1
4	if ($S_3 < thr_1$)	& ($S_4 \geqslant thr_1$)	then U3 = 1

Table 4
Data recovery rules for U4.

No.	Rules	
1	if ($S_4 < thr_1$)	then U4 = 0
2	if ($S_4 \geqslant thr_1$)	then U4 = 1

conditional PDFs since they depend, respectively, on the level 0, level 1 or level 2 being transmitted. That is, when $r_0 = r_{00}$, at the sampling point S_1, the PDF is $f(\boldsymbol{r}_0\boldsymbol{s}_1|$ Level 0 sent), and when $r_0 = r_{01}$, the PDF is $f(\boldsymbol{r}_0\boldsymbol{s}_1|$ Level 1 sent), and when $r_0 = r_{02}$, the PDF is $f(\boldsymbol{r}_0\boldsymbol{s}_1|$ Level 2 sent). In sampling point S_2, PDFs are $f(\boldsymbol{r}_0\boldsymbol{s}_2|$ Level 2 sent), $f(\boldsymbol{r}_0\boldsymbol{s}_2|$ Level 1 sent) and $f(\boldsymbol{r}_0\boldsymbol{s}_2|$ Level 0 sent) when level two, one and zero are sent, respectively. Similarly for sampling point S_3 the PDFs are $f(\boldsymbol{r}_0\boldsymbol{s}_3|$ Level 1 sent) and $f(\boldsymbol{r}_0\boldsymbol{s}_3|$ Level 0 sent) for level one and zero, respectively, and in sampling point S_4 the PDFs are $f(\boldsymbol{r}_0\boldsymbol{s}_4|$ Level 1 sent) and $f(\boldsymbol{r}_0\boldsymbol{s}_4|$ Level 0 sent) when level one and zero are sent, respectively. These conditional PDFs are shown in Fig. 5. For illustration purposes, Gaussian shapes are illustrated. In the development of the BER formula, it is assumed that the polarity of the processing circuits of the receiver is such that if only signal (no noise) were presented at the receiver input $r_0 > V_{thr2}$ when level 2 is sent; $V_{thr1} < r_0 < V_{thr2}$ when level 1 is sent; and $r_0 < V_{thr1}$ when level 0 is sent; where V_{thr1} and V_{thr2} are the thresholds (voltage) of the comparator inside the decision circuit. More details on BER calculation for AP-DCDM can be found in [16].

6. Results and discussions

Comparing the optical spectral width at the same aggregate bit rate of 40 Gb/s between RZ (50% duty cycle) without AP-DCDM and RZ over 4, 5 and 6 channels AP-DCDM shows a great spectral width reduction for the later technique. As shown in Fig. 6, considering the null–to–null bandwidth, the spectral width of 40 Gb/s RZ without AP-DCDM is around 160 GHz, which can offer a spectral efficiency of 0.25 b/s/Hz. Whereas when RZ data are carried over 4, 5 and 6 AP-DCDM channels, the spectral width is, respectively, reduced to 100 GHz (37.5% reduction with minimum spectral efficiency of 0.4 b/s/Hz), 96 GHz (40% reduction with minimum spectral efficiency of 0.41 b/s/Hz) and 93.3 GHz (around 41.69% reduction with minimum spectral efficiency of 0.42 b/s/Hz). This is because AP-DCDM divides the symbol to $n + 1$ slots (considering 1 slot for guard band), where n is the number of channels. Thus it requires a null-to-null spectral width of $2 \times [(n + 1) \times$ single channel bit rate], whereas RZ-OOK requires $2 \times (2 \times$ aggregate bit rate). This amount of saving in the spectral width is a significant achievement, which leads to better spectral efficiency and tolerance to chromatic dispersion. High signal spectrum density approaching the Nyquist limit (1/bit/s/Hz) [17] can be easily achieved in AP-DCDM over DWDM systems by considering the state of art of optical filters.

Fig. 7 shows the effect of number of channels (2, 3, 4, 5 and 6 channels) on receiver sensitivity and OSNR for the worst and best channels of AP-DCDM while the aggregate bitrate is fixed at 40 Gb/s. By increasing the number of channels from 2 to 6 the receiver sensitivity changes from −32 to −22.5 dBm for the worst channel and −32.5 to −29.5 dBm for the best channel. This degradation in receiver sensitivity is due to the increase in the number of levels

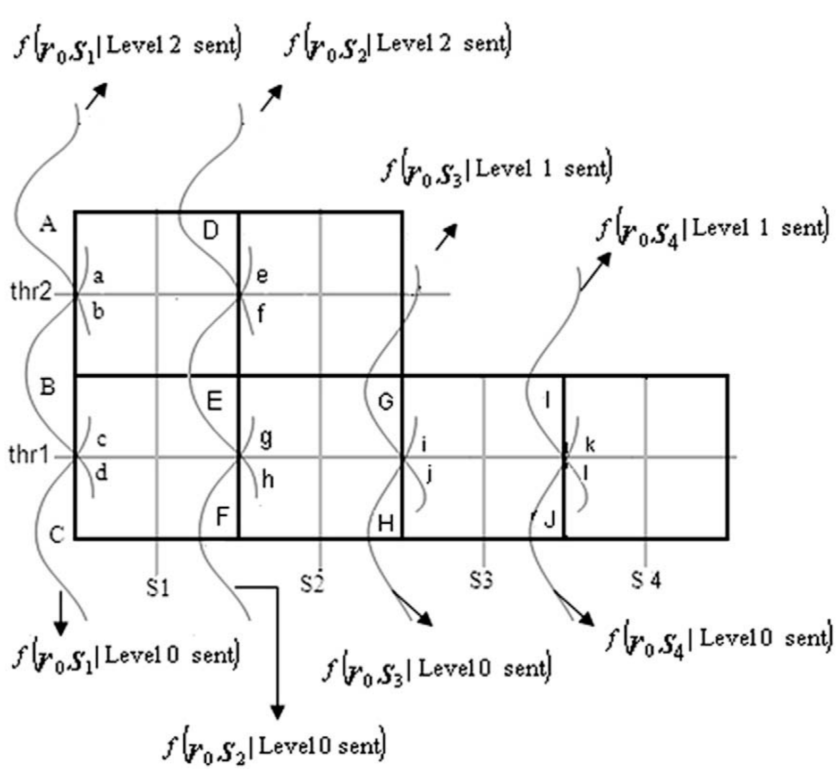

Fig. 5. Error probability for AP-DCDM.

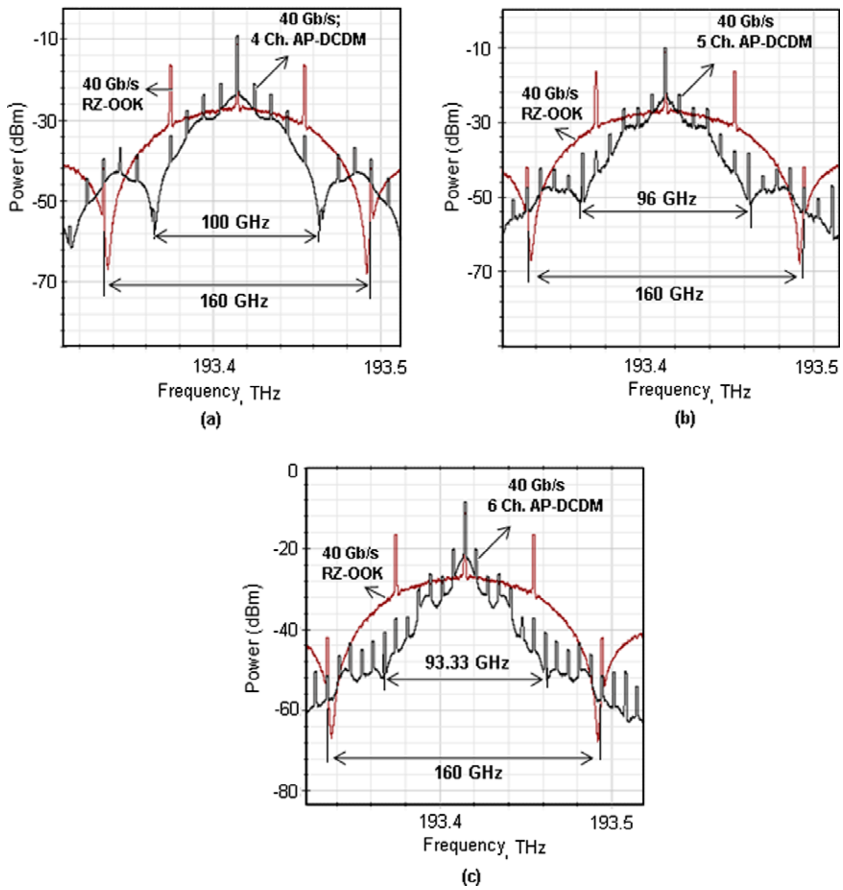

Fig. 6. Spectral width of 40 Gb/s RZ-OOK in comparison to (a) 40 Gb/s, four channels AP-DCDM, (b) 40 Gb/s, five channels AP-DCDM and (c) 40 Gb/s, six channels AP-DCDM.

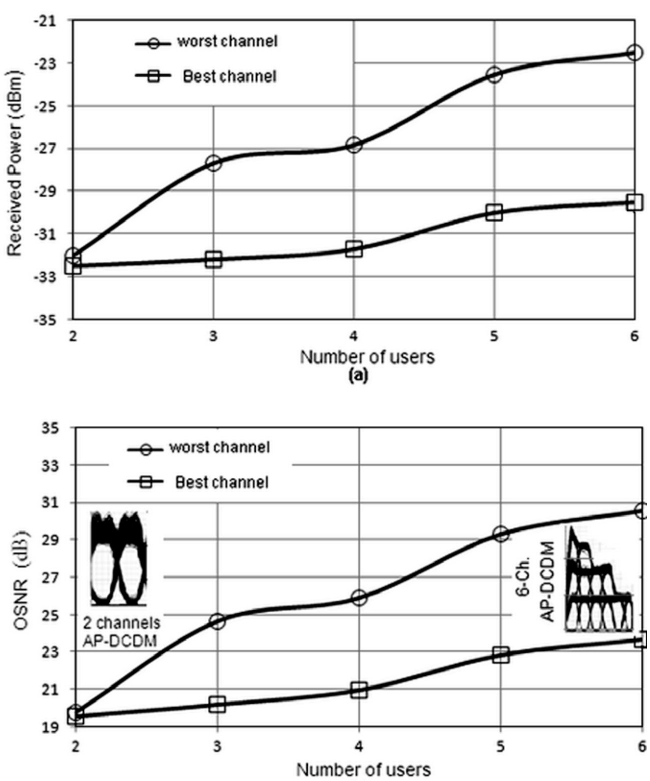

Fig. 7. Back-to-back receiver sensitivity (a) and OSNR (b) as a function of number of users at the same aggregate bitrate of 40 Gb/s and BER of 10^{-9}.

(i.e. 2 levels for 2 channels to 4 levels in 6 channels), and the fragmentation of main eyes to the smaller eyes (Fig. 7). Consequently the required OSNR also changes from 19.78 to 30.5 dB for the worst channel, and from 19.58 to 23.6 dB for the best channel. Note that in two-user system the performance of worst and best channels is very close to each other due to similar impairment experienced by both eyes as shown by the eye diagram in Fig. 7b. For comparison against NRZ-OOK we have modeled single channel 40 Gb/s NRZ-OOK transmission system. The calculated receiver sensitivity is around −29.5 dBm, which is in agreement with the reported result in [18]. Comparing the receiver sensitivity between 40 Gb/s NRZ-OOK and a worst channel AP-DCDM, the later technique shows around 2.65 dB penalty and 2.5 dB improvement for the four-user (4×10 Gb/s) and two-user (2×20 Gb/s) systems, respectively.

Fig. 8 shows the CD tolerances for 40 Gb/s RZ-OOK and 40 Gb/s (4×10 Gb/s) AP-DCDM. Using AP-DCDM, all users show almost similar behavior of positive and negative CD. U1 has the dispersion tolerance of ±67 ps/nm; U2 and U3 have the same ability to tolerate CD of ±62 ps/nm while U4 has the dispersion tolerance of ±97 ps/nm at the BER of 10^{-9}. For 40 Gb/s RZ-OOK, dispersion tolerance is around ±50 ps/nm. This result shows that 40 Gb/s RZ-OOK over AP-DCDM is more robust to dispersion in comparison to 40 Gb/s conventional RZ-OOK. This is because of the smaller spectral width of the former technique. In comparison to 40 Gb/s NRZ-OOK, the dispersion tolerance of which has been reported as 108 ps/nm (±54 ps/nm) [11], the worst and the best AP-DCDM channels show 16 and 86 ps/nm improvements, respectively.

The power penalty experienced as a result of the dispersion is shown in Fig. 9. At the BER of 10^{-9}, by increasing the dispersion from 37 to 50 ps/nm, the penalty of around 1.06 dB is experienced by the 40 Gb/s AP-DCDM as compared to 5.5 dB penalty in 40 Gb/s

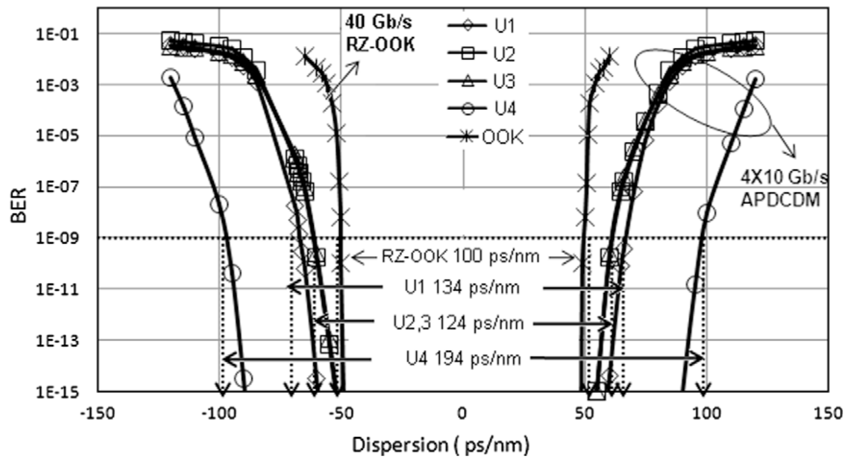

Fig. 8. Chromatic dispersion tolerance comparison between AP-DCDM and RZ-OOK at the same transmission power.

conventional RZ-OOK system. Example of eye diagrams for AP-DCDM and RZ-OOK is shown in Fig. 10. These eye diagrams correspond to BER of 10^{-9}. At a system dispersion of 50 ps/nm, both the time jitter and eye closure in the RZ-OOK case necessitate the increase in power. The performance degradation is mainly due to inter-symbol-interference (ISI). In the AP-DCDM all four eyes remain well structured as in the dispersion of 37 ps/nm case. Noting also that the thresholds, indicated as horizontal lines remain virtually unchanged in the AP-DCDM case, as opposed to the RZ-OOK case where the strong CD shifts the optimum threshold upwards [4].

7. Comparison against other techniques

In order to compare AP-DCDM system against modulation formats that carry 2 bit/symbol such as RZ-DQPSK (2×20 Gb/s) and duobinary (2×20 Gb/s), we have modeled a 2×20 Gb/s AP-DCDM system. The calculated sensitivity at BER of 10^{-9} is -32 dBm and the CD tolerance is ±200 ps/nm. Table 5 shows and compares the performance of the different modulation formats at aggregate bitrate of 40 Gb/s. Note that the experimentally obtained values for receiver sensitivity may differ a little bit from the numbers given in Table 5 due to various optical and electrical hardwares as well as different extinction ratios of modulators used in different experiments. The calculated sensitivity of NRZ-OOK at 40 Gb/s is around -29.5 dBm with CD tolerance of $\sim$ ± 54 ps/nm [11,18]. The CD tolerance of duobinary is better than that of the proposed AP-DCDM, however, it has worst performance in terms of receiver sensitivity [11,19]. The sensitivity of 40 Gb/s RZ-DQPSK is reported as -25 dBm [20] with positive CD tolerance of up to 161 ps/nm [11]. It can be concluded that two channels AP-DCDM has the best receiver sensitivity as compared to NRZ-OOK, duobinary and RZ-DQPSK. In terms of CD tolerance AP-DCDM outperforms NRZ-OOK and RZ-DQPSK, but is still inferior to duobinary.

8. Conclusion

Performance of AP-DCDM with different numbers of channels at aggregate bitrate of 40 Gb/s is evaluated. At 40 Gb/s, the results show a clear advantage of the proposed AP-DCDM technique over RZ-OOK in terms of spectral width and dispersion tolerance. Using this electrical multiplexing/demultiplexing technique, more than two users can be carried over the same WDM channel. Consequently, the capacity utilization of the WDM channels can be increased tremendously at tolerable penalty. It is concluded that at 40 Gb/s (2×20 Gb/s) AP-DCDM has better receiver sensitivity and CD tolerance than conventional NRZ-OOK and RZ-DQPSK.

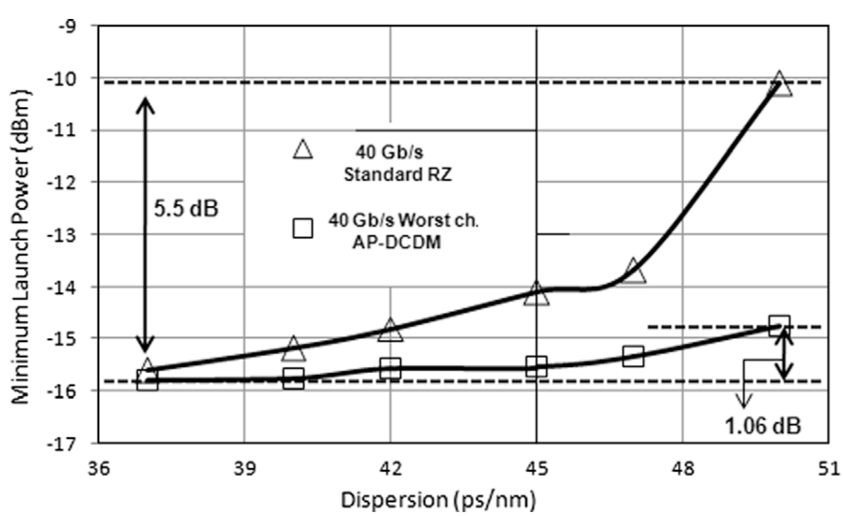

Fig. 9. Launch power against system dispersion for 40 Gb/s 50 % duty cycle RZ and 40 Gb/s AP-DCDM.

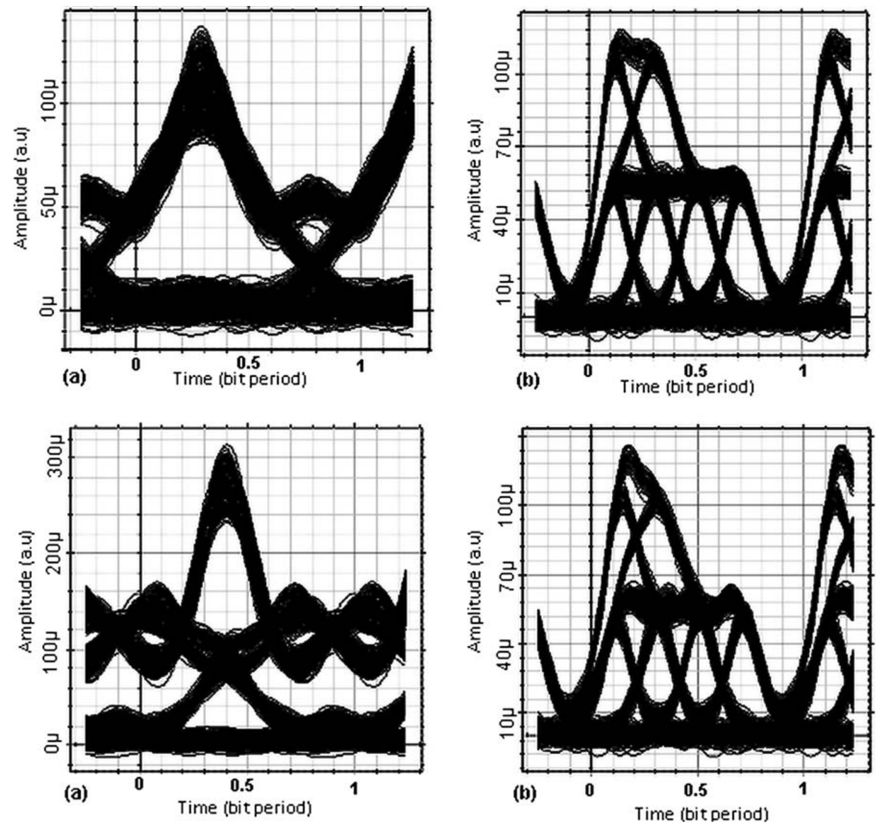

Fig. 10. Eye diagrams for 40 Gb/s systems at system dispersion of 37 ps/nm (top) and 50 ps/nm (bottom) for (a) Conventional RZ-OOK, (b) RZ-OOK over AP-DCDM.

Table 5
Comparison between different systems at 40 Gb/s.

Modulation format	TX complexity	RX complexity	Sensitivity (dBm)	Positive CD tolerance (ps/nm)	Ref.
NRZ-OOK	1-MZM	1 PD	∼−29.5	∼54 ps/nm	[18,11]
Duobinary	1 dual-arm MZM + duobinary filter + driver amplifier for each modulator arm	1 PD	−28	∼211 ps/nm	[19,11]
RZ-DQPSK	2 MZMs + 1 PC	2 DIs + 4 PDs	−25	∼161 ps/nm	[20,11]
2 Channel AP-DCDM (worst user)	1 MZM	1 PD	−32	∼200 ps/nm	–

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