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Demonstration of Duty Cycle Division Multiplexing with Bit Error Rate Estimation

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Abstract— **Experimental demonstration of Duty Cycle Division Multiplexing (DCDM) is reported which validates the potential implementation of the system in communication field. We also presented the operation of bit error rate (BER) estimation algorithm, which is specially derived for DCDM. With the increase of link attenuation, the signal amplitude decreased and the pulses are distorted. BER estimation on the received signal was performed and measured against transmission distance of 100 meter until 400 meter copper wire. It is shown that the channel with the largest duty-cycle value shows the best performance. The experimental eye diagrams at several distances are also demonstrated and compared against their back-to-back counterpart.**

Keywords— **multiplexing, optical communication**

I. Introduction

In telecommunication system, to increase the network capacity and transmission medium utilization, multiple analog signals, data or channels can be combined together by a process known as multiplexing. Common predominant multiplexing techniques are Time Division Multiplexing (TDM) [1]-[2], and Frequency Division Multiplexing (FDM) [3]. The introduction of Wavelength Division Multiplexing (WDM) [6] and Polarization Division Multiplexing (PolDM) [7] in optical fiber communication systems have increased the network capacity.

Realizing the need of cost effective design for higher data rate transmission, Duty Cycle Division Multiplexing (DCDM) was introduced as a new multiplexing and demultiplexing technique that uses duty cycles to differentiate the channels [11,12]. Using this technique, it was proven by theoretical studies and simulations that the utilization of Wavelength Division Multiplexing (WDM) channel capacity can be increased significantly [12]-[13]. As PolDM can only multiplex two polarization channels, DCDM has more to offer with its ability to multiplex more than two channels. Simulation studies have also shown that DCDM can contribute towards narrower spectral width, which results in better tolerance to chromatic dispersion [13]. However, to date, there is no experimental work reported verifying the concept. Therefore, it is the interest of this paper to experimentally demonstrate the DCDM working principle and its Bit-Error-Rate (BER) estimation algorithm. This paper focuses on the demultiplexing part, which is more critical than the multiplexing process. By using multiplexed DCDM signal that is generated at the transmitter, the demultiplexing concept is experimentally validated by processing the received signal based on the DCDM demultiplexing rules. For performance evaluation, we experimentally perform the BER estimation on the received signal, which is reported for the first time to our knowledge.

II. Working principle

DCDM multiplexing and demultiplexing concepts are based on duty-cycle values, which allow more than two channels to be multiplexed in a WDM channel. The value of the duty-cycle for each user can be assigned in various ways. In this paper uniform distribution is used, mainly due to its simplicity. The duration for i_{th} user T_i is defined as

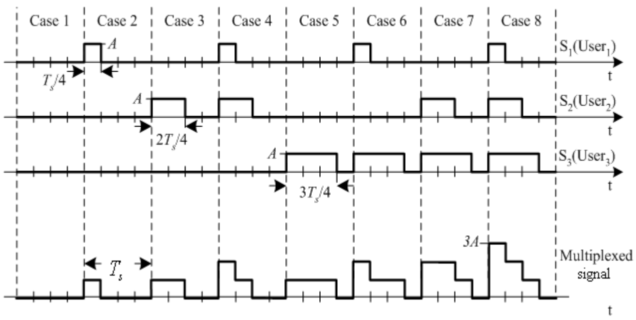
$$T_i = \left(\frac{i \times T_s}{n + 1} \right) \qquad (1)$$

where n represents the number of multiplexed users and T_s is the clock period. Fig. 1(a) shows $2n$ possible combinations of bits for n users. In this paper, in order to demonstrate the feasibility of multiplexing more than two channels with lowest complexity, we focus on 3-user system where there are 8 possible cases. For the duty-cycle value, the first, second and third user uses duration of $T_s/4$, $2T_s/4$ and $3T_s/4$ respectively to transmit bit 1s. This means User$_1$ (S_1), User$_2$ (S_2), and User$_3$ (S_3) uses 25%, 50%, and 75% of duty-cycle respectively, which are multiplexed together as shown in Fig. 1 (b). For 3-user DCDM system, the multilevel multiplexed signal has four slots within one pulse duration. If one sample per slot is taken, the 1st sample (taken from the first slot), has $n + 1$ possible levels, the second sample (taken from the second slot), has n possible levels, and the n^{th} sample (taken from the n^{th} slot) has only 2 possible levels (0 or A).

At the receiver side, the original data for each user can be demultiplexed and recovered by taking 1 sample per slot (except for the last slot which is considered as the guard band for transition purposes between two consecutive waveforms). The rules shown in Table I are used for channel demultiplexing. Each multiplexed signal in Fig. 2 is sampled at three sampling points sp_1, sp_2, and sp_3. The amplitude at each sampling point is compared against three threshold values of thr_1, thr_2 and thr_3 as shown in Fig. 2. There are 6, 4 and 2 rules for S_1, S_2, and S_3 respectively as shown in Table I. As an example, for the first rule for S_1, when both amplitudes at sampling point 1 (sp_1) and sampling point 2 (sp_2) are less than thr_1, S_1 is equal to 0, which is for Case 1. All rules for S_1 follow the values sp_1, sp_2, thr_1, thr_2, and thr_3 as shown in Fig. 2 for the decision making. For S_2, the decision for 8 cases is made based on the sp_2, sp_3, thr_1, and thr_2. Finally, for S_3 when sp_3 is less than thr_1, the regenerated amplitude is 0, which is represented by Cases 1, 2, 3, and 4. If the amplitude at sp_3 is more than thr_1, the regenerated amplitude is 1, which is for Cases 5, 6, 7, and 8.

Cases	1	2	3	4	5	6	7	8
S_1	0	1	0	1	0	1	0	1
S_2	0	0	1	1	0	0	1	1
S_3	0	0	0	0	1	1	1	1

(a)



(b)

Fig. 1 (a) 8 possible combination of bits for 3-user DCDM system, and (b) Multiplexed signal

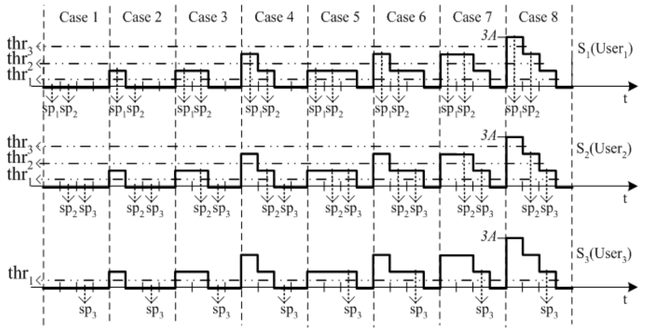


Fig. 2 Sampling points and threshold values for S_1, S_2, and S_3 for DCDM Recovery Rules

TABLE I
DCDM RECOVERY RULES

Rules for S_1 (User$_1$):							
1	If	($sp_1 < thr_1$)	&	($sp_2 < thr_1$)	then	S_1=0	Case 1
2	If	($thr_1 \leq sp_1 < thr_2$)	&	($thr_1 \leq sp_2 < thr_2$)	then	S_1=0	Case 3,5
3	If	($thr_2 \leq sp_1 < thr_3$)	&	($sp_2 \geq thr_2$)	then	S_1=0	Case 7
4	If	($thr_1 \leq sp_1 < thr_2$)	&	($sp_2 < thr_1$)	then	S_1=1	Case 2
5	If	($thr_2 \leq sp_1 < thr_3$)	&	($thr_1 \leq sp_2 < thr_2$)	then	S_1=1	Case 4,6
6	If	($sp_1 \geq thr_3$)	&	($sp_2 \geq thr_2$)	then	S_1=1	Case 8
Rules for S_2 (User$_2$):							
1	If	($sp_2 < thr_1$)	&	($sp_3 < thr_1$)	then	S_2=0	Case 1,2
2	If	($thr_1 \leq sp_2 < thr_2$)	&	($sp_3 \geq thr_1$)	then	S_2=0	Case 5,6
3	If	($thr_1 \leq sp_2 < thr_2$)	&	($sp_3 < thr_1$)	then	S_2=1	Case 3,4
4	If	($sp_2 \geq thr_2$)	&	($sp_3 \geq thr_1$)	then	S_2=1	Case 7,8
Rules for S_3 (User$_3$):							
1	If	($sp_3 < thr_1$)	then	S_3=0	Case 1,2,3,4		
2	If	($sp_3 \geq thr_1$)	then	S_3=1	Case 5,6,7,8		

III. EXPERIMENTAL SETUP

Fig. 3 (a) shows the experimental setup for 3-user DCDM system. At the transmitter, signals S_1, S_2, and S_3 representing User$_1$, User$_2$ and User$_3$ respectively were generated by using the Microcontroller A at 1 kb/s per user. S_1, S_2, and S_3 have a precoded 1010101, 0110011 and 0001111 bit-stream respectively. Even though the data rate is very low, it is sufficient for our experiment as the main objective is to prove the DCDM operation. The performance at higher bitrate will vary accordingly.

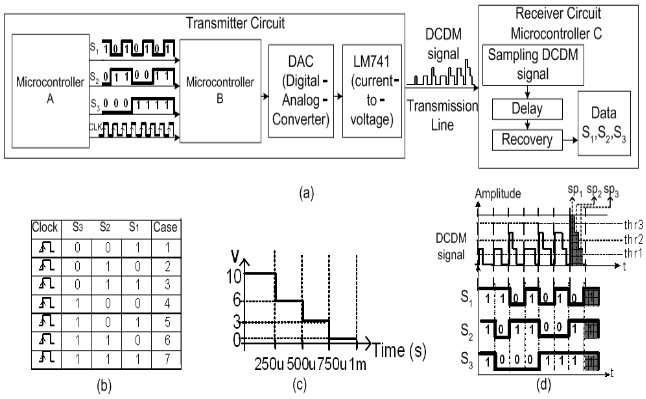


Fig. 3. Experiment setup for DCDM system. (a) Experimental setup for 3-user of DCDM system. (b) Table for Microcontroller A. (c) DCDM signal for case 7. (d) Sampling process for Microcontroller C.

Based on Fig. 3(b), whenever the clock is in high state (rising edge), the bit-stream is generated by the Microcontroller A. The signals are then sent to the Microcontroller B to generate the DCDM multiplexed signal. For example, when the Microcontroller B reads Case 7 from the Microcontroller A, it will generate a step-down shape signal as shown in Fig. 3(c). The signal is then passed through the Digital-Analog-Converter (DAC) and a current-to-voltage converter. After this stage the generated 3 bits per symbol signal is ready for transmission. The signal is first transmitted in back-to-back setup and then through a copper wire of 100 meter until 400 meter with 0.033 dB loss per meter. In this setup the baseband signal is not modulated onto any carrier. At the receiver, the Microcontroller C samples each received signal at three sampling points which are sp_1, sp_2 and sp_3. Each sampling point is compared with the three threshold values. The three threshold values which are thr_1, thr_2, and thr_3 are determined as shown in Fig. 3(d).The DCDM signal is then recovered using DCDM recovery rules [12]. The recovered signals experience 1-bit delay due to the processing time, which in our case is 1 ms.

IV. RESULTS AND DISCUSSION

Fig. 4(a) shows the data quality in back-to-back transmission line. Figs. 4(b) and (c) show the DCDM signal and recovered bit-stream after copper wire of 200 meter and 300 meter with 6.6 dB and 9.9 dB loss respectively. Comparing between Figs. 4(a), (b), and (c), the amplitude of the DCDM signal is distorted after the transmission line. The distortion increases with the attenuation.

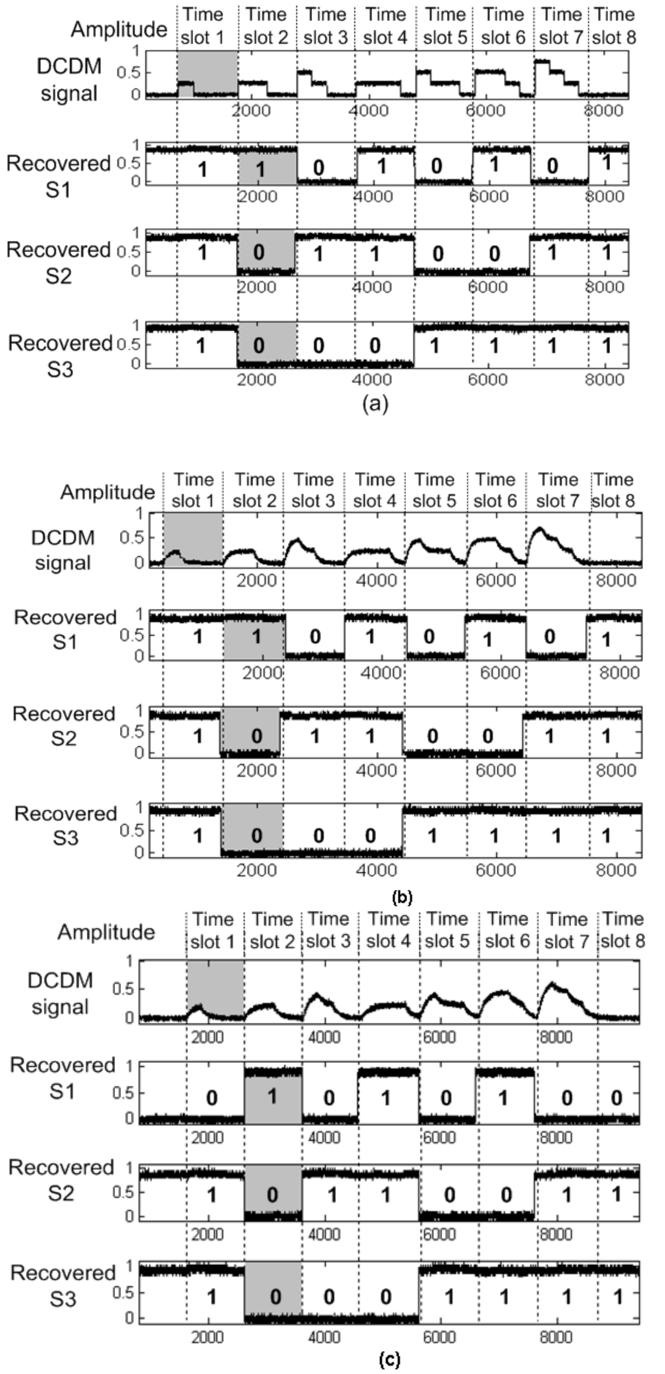


Fig. 4 Transmission and recovered data stream in back-to-back and after transmission line. (a) Back-to-back transmission. (b) 6.6 dB loss after transmission line. (c) 9.9 dB loss after transmission line.

Using the recovery rules in [12] the DCDM signal can be recovered back to S_1, S_2, and S_3. Every recovered signal experienced 1-bit delay for back-to-back and after transmission line as shown in Fig. 4. Based on this result, DCDM signal is fully recovered after transmission with 6.6 dB loss. However, with 9.9 dB of attenuation, the signal cannot fully be recovered as shown in Fig. 4(c). Thus, when the DCDM signal transmits to 100 meter and 200 meter, it is still well recovered back to original bit-stream while distance over 300 meter and more, signal cannot be fully recovered. As can be seen the S_1 data in time slot 7 in Fig. 4(c) is erroneously recovered. This error occurred after the amplitude of DCDM signal decreases, which made the signal and noise indistinguishable by the recovery circuit. Nevertheless, these results validate the concept of DCDM as the signal experienced attenuation and noise; the original signal can still be recovered. Although previous simulation work on DCDM focused on high speed of transmission, for this paper, the purpose is only to validate the DCDM demultiplexing concept. By having low transmission bitrate, the focus can be fully given to the problems in demultiplexing concept and algorithm rather than transmission impairments.

Bit error rate (BER) of 3-user DCDM system performance is showed in Fig. 5. The performance of different users is compared based on BER. Peu_1, Peu_2, and Peu_3 which are probability error rate of S_1, S_2, and S_3 respectively increased over several distance. The BER is calculated based on probability of error method using eye diagram which discussed in [12]. Peu_1 is greater than Peu_2 and Peu_3 which increases over longer distance. This is because with lowest pulse width, Peu_1 gives the lowest delay which affected the performance. It is clear that S_3 gives the better performance than S_1 and S_2 with its wider pulse width. Due to limited number of bits, the best BER is only as good as 10^{-2}. Fig. 6 shows that voltage at the receiver is reduced against longer transmission line. In this experiment, the received DCDM signal of 500 mV and above can be fully recovered. DCDM signal that lower than 500mV will experienced invalid recovered bit-stream for 300 meter copper wire as shown in Fig. 4(c).

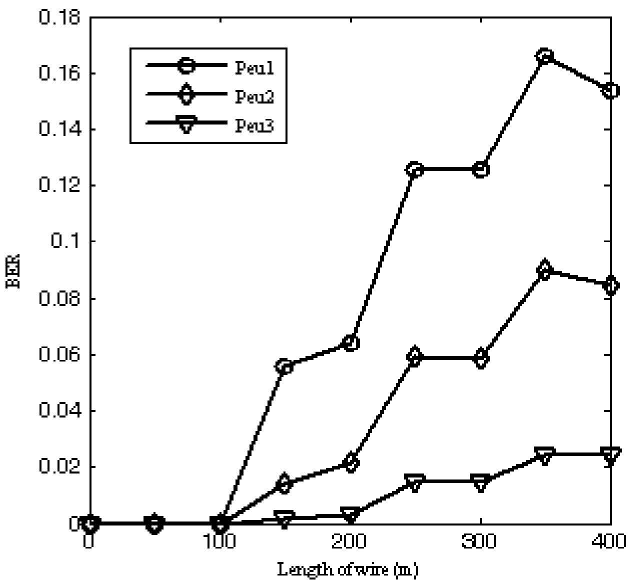


Fig. 5: BER vs. distance

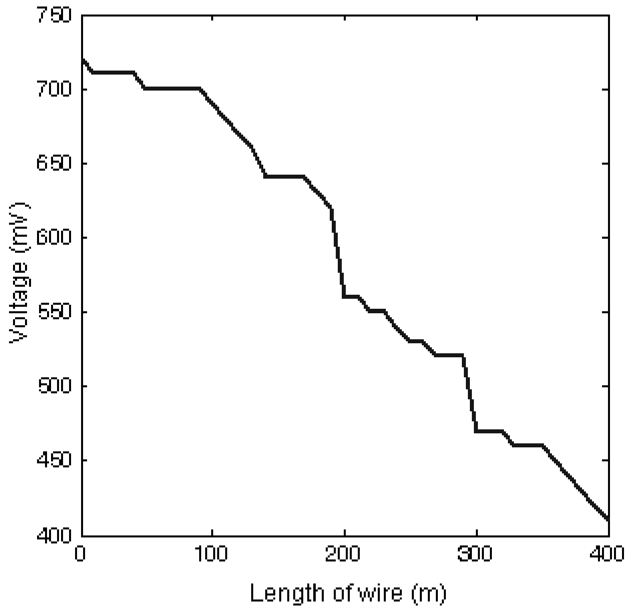


Fig. 6: Received voltage vs. Length

Figs. 7 (a), (b), (c), (d) and (e) show the eye diagram for the back-to-back and after transmission line. The eye diagram is generated off-line from the received signal due to inability of existing scope to visualize the DCDM eye diagram. Data for the received signal is extract from the scope and formed the eye diagram for back-to-back and after transmission line in the computer. The eye diagram is highly distorted after 400 m, which explain the failure to recover all bits correctly, which is previously shown in Fig. 4(c).

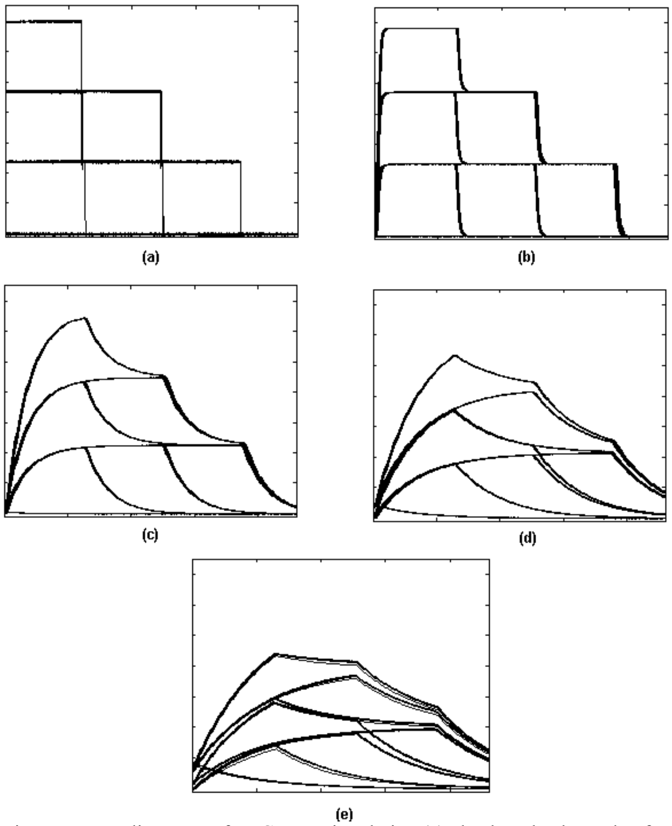


Fig. 7 Eye diagram of DCDM signal in (a) back-to-back and after transmission line of (b) 100 meter (c) 200 meter (d) 300 meter, and (e) 400 meter

V. CONCLUSIONS

Demonstration of DCDM system with bit error rate estimation is reported. This experiment shows the feasibility of implementing DCDM as alternative solution to increase optical fiber capacity utilization. Even though this small scale experiment is performed at 1 kb/s, our aim to experimentally validate the concept of DCDM and its BER estimation algorithm was successfully achieved. This experiment is significant as the first experimental trial of DCDM system.

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