Proof-of-Concept Experiment of Duty Cycle Division Multiplexing with Bit Error Rate Analysis

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Abstract: Demultiplexing concept of Duty-Cycle Division Multiplexing (DCDM) technique is tested in the back-to-back connection and after transmission over copper wire and optical fiber. Three different lengths of copper wire are tested with the total loss of 3.3, 6.6, and 9.9 dB respectively. Even though the sampling points and threshold values were not dynamic, the demultiplexing process for the case of back-to-back, and after transmission over the links with 3.3, and 6.6 dB losses, was successful without experiencing any errors. This can be witnessed when the recovered data is compared against the transmitted bits. However, the errors are recorded in the link with 9.9 dB losses, which was mainly due to the non-optimized sampling points and threshold values. In experiment over 60 km Standard Single Mode Fiber, successful transmission was demonstrated. The receiver sensitivity is calculated off-line by using bit error rate analysis. These results confirm the validity of DCDM demultiplexer structure including the sampling process and the data recovery rules.

Keywords: Optical communication system, multiplexing and demultiplexing, duty–cycle division multiplexing.

1. INTRODUCTION

The demand for high-speed internet increases exponentially by year. Multiplexing allows many users to share a transmission medium, thus reducing the total cost and complexity. Time Division Multiplexing (TDM) [1-3], Frequency Division Multiplexing (FDM) or Orthogonal FDM (OFDM) [4-6], and Code Division Multiplexing (CDM) [7-9] are among the popular alternatives. In optical fiber communications, with the introduction of Erbium-Doped Fiber Amplifier (EDFA) [10-13], Wavelength Division Multiplexing (WDM) [14-16] technology becomes feasible and emerges as the technology of choice in the telecommunication industry. By using WDM, the utilization of optical fiber capacity is increased [17, 18]. Further efforts were taken to increase the capacity utilization of optical fiber by the introduction of Polarization Division Multiplexing (PDM) [14, 15, 17-19], Duobinary (DB) [20-23], Differential Quadrature Phase Shift Keying (DQPSK) [17, 24, 25], and Quadrature Amplitude Modulation (QAM) [14, 15, 26].

Recently, Duty-Cycle Division Multiplexing (DCDM) is proposed as an alternative multiplexing and demultiplexing technique to increase the channel utilization of WDM system [27-33]. In this multiplexing technique, different return-to-zero (RZ) duty-cycles is signed for differentiate channels. The multiplexed signals in DCDM provide one rising edge transition per symbol, which is located at the beginning of the symbol. In addition, the spectrum of DCDM signal have one impulse per multiplexing user, where one of them with the lower frequency is located at the frequency equal to the symbol rate [27-29]. Due to these properties, DCDM provides a simpler clock recovery process and lets the data recovery process to be performed at the symbol rate. From theoretical and simulation studies, it has been shown that DCDM has narrower spectral width, thereby, better tolerance to chromatic dispersion in comparison to RZ signal [27, 28]. However, to date, there is no experimental work reported verifying DCDM concept. Therefore, it is the interest of this paper to perform a Proof-of-Concept (PoC) experiment to validate the DCDM working principle with the main focus on demultiplexing and the data recovery. To the best of our knowledge, this is the first time that the concept of DCDM is experimentally tested and reported.

2. EXPERIMENTAL SETUP

Fig. (**1a**) shows the experimental setup for 3-channel DCDM system. At the transmitter, signals S1, S2, and S3 representing Channel 1, Channel 2, and Channel 3, respectively, were generated by using Microcontroller-A at 1 kb/s per user. As shown in Fig. (**1b**), for multiplexing three channels, there are eight (2^3) possible combination of bits, which

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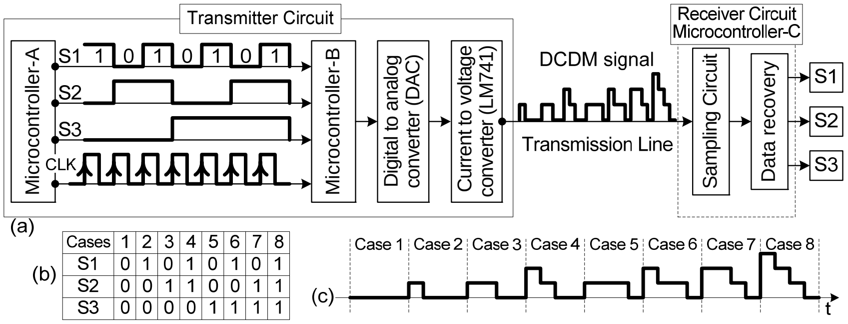

Cases	1	2	3	4	5	6	7	8
S1	0	1	0	1	0	1	0	1
S2	0	0	1	1	0	0	1	1
S3	0	0	0	0	1	1	1	1

Fig. (1a). Experimental setup for 3-channel DCDM system, (**b**) eight possible combinations of bits for multiplexing 3 channels, and (**c**) eight possible DCDM multiplexed patterns.

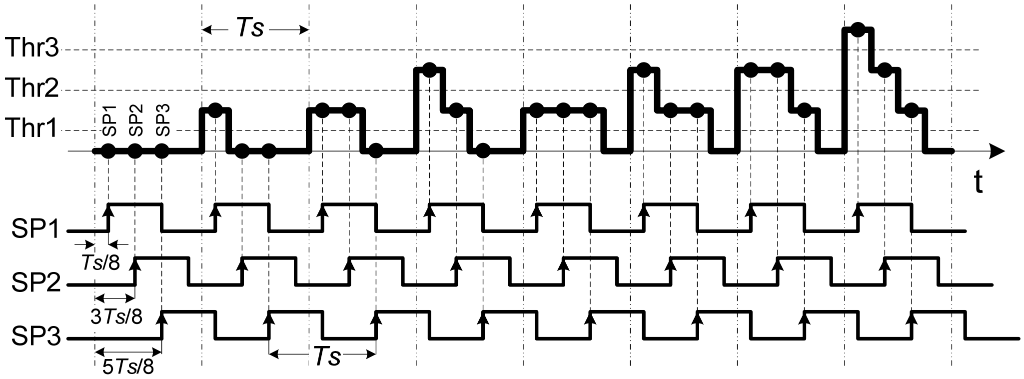

Fig. (2). Schematic of sampling process using three samplers operating at the symbol rate.

seven of them (Case 2 to 8), are considered in this experiment. Case 1, which all users sending bit zero, is not considered in this prototype due to the hardware limitation. For this purpose, S1, S2, and S3 have fixed pre-coded bit-streams of 1010101, 0110011 and 0001111, respectively.

One bit stream per channel from Microcontroller-A will be sent into the Microcontroller-B, whenever the clock is in the high state. Microcontroller-B generates DCDM multiplexed patterns/symbols (as shown in Fig. (**1c**)), based on the incoming bits (according to Fig. (**1b**)). For example, when Microcontroller-B received bit 1 from Channel 1, 2, and 3 (Case 8 in Fig. (**1b**)), it will generate a step-down shape signal as shown in Case 8 of Fig. (**1c**). The multiplexed signal is then passed through the Digital-to-Analog Converter (DAC) followed by a current-to-voltage converter. After this stage, DCDM symbol, which each contains 3 bits per symbol (equal to 3 kb/s), are ready for transmission. The base band multiplexed signal is first transmitted over back-to-back connection and then through a copper wire with 3.3, 6.6 and 9.9 dB losses. In these setups, the baseband signals are not modulated onto any carrier. At the receiver side, Microcontroller-C is designed according to the demultiplexing structure discussed in the reference [30]. In this microcontroller, as illustrated in Fig. (**2**), three different samplers (SP), SP1, SP2 and SP3, which operate at the frequency equal to the symbol rate (1 kHz), are utilized taking three samples per symbol. The three samplers are designed such a way that the first sampler, (SP1), samples the first slots by a delay of $T_s/8$ s (or 0.125 ms); the second sampler, (SP2), samples the second slots with the delay of $3T_s/8$ s (0.375 ms); and the third sampler, (SP3), samples the third slots with the delay of $5T_s/8$ s (or 0.625 ms), from the beginning of the symbol as shown in Fig. (**2**), where T_s is the symbol duration. Sample is not taken from the fourth slots, since it is the guard slot without carrying any information. Each sampling point is then compared against three threshold (Thr) values, Thr1, Thr2, and Thr3, as shown in Fig. (**2**). The DCDM signals are then recovered by employing the recovery rules reported in the references [27, 28, 30]. Due to the processing time, the recovered signals experienced 1-bit delay (1 ms). The sampling points and the threshold values are embedded into Microcontroller-C referring to the fixed bit rate (1 kb/s) and the fixed output voltage signal from Microcontroller-B.

In another experiment as shown in Fig. (**3**), the multiplexed signals are externally modulated using an analog Intensity Modulator (IM) onto an optical carrier, which is generated by a Distributed Feedback (DFB) Laser Diode (LD) oscillating at 1550 nm. The modulated signal is then boosted by employing a short length of Erbium Doped Fiber (EDF). The signal is then transmitted over 60 km standard single mode fiber (SSMF), (with dispersion coefficient of 17 ps/(nm.· km) and attenuation of 0.19 dB/km), followed by three Dispersion Compensation Fiber (DCF) modules with the total attenuation and dispersion of around 8 dB and 1020 ps/nm, respectively. A variable optical attenuator is also added after the DCF modules to control the received power for the purpose of sensitivity measurement. Then the signal is passed through an optical Tunable Band Pass Filter (TBPF) followed by a p-i-n photo diode (PD). In this experiment, there is no preamplifier before the optical BPF, due to unavailability of EDF/EDFA. The demodulated signals after the photodetector are captured from the oscilloscope and analyzed in off-line. Due to unavailability of electrical low-pass filter (LPF), the output signal from the pho-

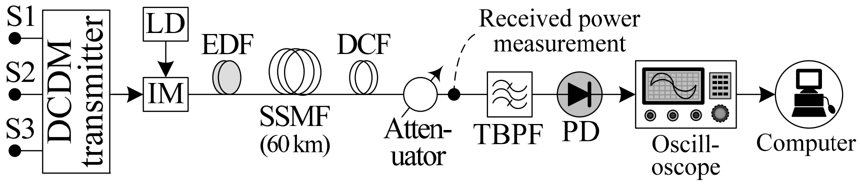

Fig. (3). Setup with SSMF.

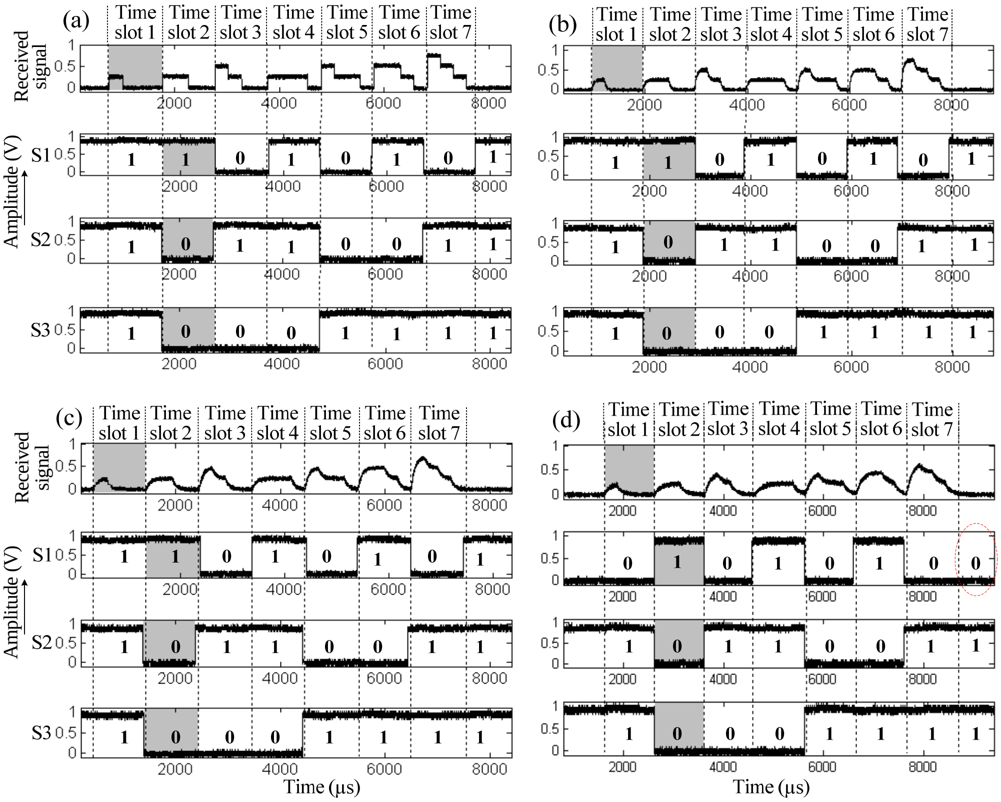

Fig. (4). Examples of received signals and the recovered data captured from oscilloscope for the case of (**a**) back-to-back connection, (**b**), (**c**), and (**d**) over the link with 3.3, 6.6, and 9.9 dB losses, respectively.

todetector is directly used for performance analysis. Bit Error Rate (BER) of the received signal is then estimated using the bit error rate analysis presented in the reference [30].

3. RESULT AND DISCUSSION

Three channels each running at 1 kb/s are multiplexed using DCDM in electrical domain using microcontroller. The 3 kb/s baseband multiplexed signals are then transmitted over multiple lengths of copper wire without modulating over any carrier. The received signals are then demultiplexed according to the recovery rules that are embedded into the Microcontroller-C (Fig. **1**). DCDM demultiplexer concept and the data recovery rules are first tested in the back-to-back connection. As example, Fig. (**4a**) (the top signal), shows seven patterns of DCDM received signals for the back-to-back connection that is captured from the oscilloscope. The eye diagram in this case is presented in Fig. (**5a**), which is generated in the off-line. The received signal is then demultiplexed using the Microcontroller-C with one bit delay and extracted from oscilloscope as shown in Fig. (**4a**), where the signal S1, S2, and S3 represent the regenerated signals for the Channel 1, 2, and 3, respectively. In this experiment, as the eye diagram implies, there is no attenuation and delay to affect the transmitted signal. From the received signals, it is observed that all the transmitted signals are recovered back correctly without any error count from the regenerated signals. This result confirms the validity of DCDM demultiplexer and recovery rules.

In addition to the back-to-back connection, DCDM signals are transmitted over several meters of copper wire to validate DCDM demultiplexer and recovery rules when the impairments such as attenuation and delay are exist in the medium. In this case, DCDM baseband signals are transmitted over 100, 200, and 300 m copper wires with total loss of around 3.3, 6.6., and 9.9 dB, respectively. As example, seven patterns of DCDM received signals for the case of 100, 200, and 300 m copper wire are captured from oscilloscope and presented in top of the Fig. (**4b**, **c**), and (**d**), respectively. The eye diagrams for the case of 100, 200, and 300 m copper wire are shown in Figs. (**5b**, **c**), and (**d**), respectively. As the eye diagrams and the received signals shown, the effect of attenuation and delay become stronger at the higher copper

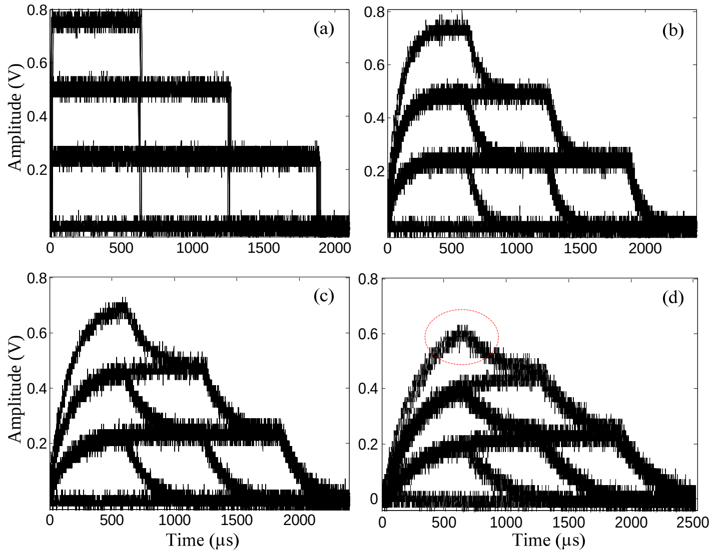

Fig. (5). Eye diagram of DCDM signal for the case of (**a**) back-to-back connection, (**b**), (**c**), and (**d**) over the link with 3.3, 6.6, and 9.9 dB losses, respectively.

wire length. The received signals are then demultiplexed and recovered back as example of them for the case of 100, 200, and 300 m are shown in Figs. (**4b**, **c**), and (d), respectively. The result from the regenerated signals shows that all the transmitted signals for the case of 100 and 200 m are recovered correctly without any errors occurred. However, in the case of 300 m, a fixed error, which is one bit error per every seven symbols (or every 21 bits), is observed for Channel 1 (channel with the shortest duty-cycle), as highlighted by a circle in Fig. (**4d**). This error is mainly due to the non-optimization of the sampling point and the threshold values. As mentioned earlier, in this experiment, the sampling points and the threshold values are fixed in the Microcontroller–C. This is why, the signal related to the Channel 1 experienced error (out from the threshold (Thr3) value), which is located at the higher amplitude (as highlighted with a circle in Fig. (**5d**). This problem can be improved by optimizing the sampling point and threshold values. Nevertheless, these results validate the concept of DCDM. Even though the signal experienced loss and delay, to certain extent, the original signal can still be recovered.

Another observation from this experiment is the non error propagation within the symbol. This means that even though some part of the received symbols is in error, the data for other channels can still be recovered correctly. One property of DCDM signals is that any error occurred in the first slot (the slot with the shortest pulse width), will not affect on the other channels. Also, any error occurred on the second slot, will not affect on Channel 3. However, any error occurred in the second and third slot will directly affect on Channel 1, and 2, respectively.

In addition to the copper wire, DCDM multiplexed signal is modulated over an optical carrier and transmitted through 60 km SSMF as the setup shown in Fig. (**3**). As explained earlier, one attenuator is used in the link to change the system received power. The received signals are then extracted from the oscilloscope and analyzed in off-line for every point of the received power. Fig. (**6**) shows the BER as a function of received power for three-channel DCDM system (receiver sensitivity) without preamplifier. Performance of the system is almost linearly reduced by increasing the attenuation of the system. In general, performance of Channel 1 (S1), which has the shortest pulse width, is worst that the other channels. On the other hand, performance of Channel 3 (S3), which has the longest duty-cycle, is the best. With reference to BER 10^{-9}, Channel 1, 2, and 3 required received power of around –21.8, –22.5, and –24.5 dBm, respectively. This result is similar to the simulation results reported the in references [28, 30], which the channel with the shortest and the longest pulse width performs as the worst and the best channels, respectively (the exact value differs due to different bitrate). Performance of the system is expected to be improved by employing preamplifier, and electrical LPF to eliminate photodetector noise. In addition, the difference between performance of different channels can be reduced by optimizing the signal level spacing in adjacent levels as reported in the reference [34].

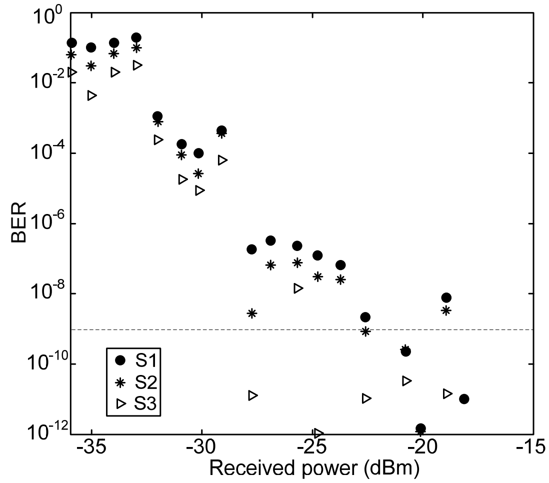

Fig. (6). Receiver sensitivity of 3-channel DCDM system after transmission over 60 km SSMF.

4. CONCLUSION

The proof-of-concept experiment of DCDM has been successfully demonstrated, which shows the feasibility of its demultiplexing concept and the recovery rules. Even though, the system was not in the optimized form, the received signal that experienced channel impairments is successfully recovered. One may argue that the bitrate used in this experiment does not reflect the system ability to support high capacity transmission. However, as the objective is only to prove the viability of DCDM concept, it is considered achieved. The success of this technique will open a new research paradigm in optical communication systems history. Transmission of 3-channel DCDM over single wavelength proves that using this technique, WDM channel utilization can be increased by several folds. This technique will become a new alternative to fulfill the future telecommunication network requirement to support high speed operation.

CONFLICT OF INTEREST

None declared.

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