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High Speed OTDM-DWDM Bit Compressed Network for Long-Haul Communication

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***Abstract*— This paper represents an optical communication network design that incorporates both OTDM and DWDM techniques which provides up to 240 Gbit/s data transfer rate, long-haul communication distance of 2700 km with a maximum number of 384 channels in this designed architecture. Each channel has a bitrate of 625 Mbit/s that follows optical signal hierarchy OC-12, STS-12 (SONET ANSI), and STM-4 (SDH CCITT), and the design maintains standard parameters for commercially available channel grids at 100 GHz spacing. The communication is done by Single Mode Fiber (SMF) of 50 km and Dispersion Compensating Fiber (DCF) of 10 km followed by one optical amplifier gain in each span. Bit error rate (BER) remains significantly low while transmission distance for only OTDM is 18000 km at a BER < 10^{-12}, and for the hybrid OTDM-DWDM it is 2700 km at a BER < 10^{-16}. Both values are measured under 128 bits sequence length. Three compression stages are used for 8 channels each in order to minimize the gap between bits, and to utilize the space for more channels within a specific time window.**

Keywords*— *DWDM; high-speed networks; optical time division multiplexing; OTDM-DWDM; packet-interleaved bit compression

I. Introduction

Fiber optic technology has grown tremendously over the years all around the world. Fiber also shows up in research institutions, colleges and universities, as well as in the aerospace, biomedical, and chemical industries. In this modern generation, the main crisis that fiber optic communication system is facing is the need of higher data rates, higher bandwidth and high speed data transfer. The need of transferring large amount of data, gigabyte sized files, and recently invented 4k 60Hz high resolution videos require higher bitrates to minimize the time duration of file transfer worldwide.

The existing technologies for the ever-growing fiber optics communication uses a combination of multiplexing techniques with Wavelength Division Multiplexing (WDM) and some backbone techniques such as Orthogonal Frequency Division Multiplexing (OFDM) [1], Optical Time Division Multiplexing (OTDM) [2], Optical Code Division Multiplexing (OCDM) [3], Space Division Multiplexing (SDM) [4], and Orbital Angular Momentum (OAM) [5] etc. However, there are more existing technologies, and are still under development. The major problem is the need of higher bandwidth and obtaining the desired data rate to as maximum as possible. This paper represents a new proposed technique that incorporates OTDM and DWDM together [2], [6], [7]. Both of these multiplexing techniques have very high bitrate capabilities, can control and occupy a lot of channels individually under the transmission window of 1.55 µm. Transmission distance for fiber optic communication system is another major fact in the existing WDM technique [8]. WDM system has covered a distance of 500 km [9], 515 km [10], 632 km [11], and 700 km [12] in several proposed techniques by other researchers. On the other hand, OTDM is a powerful and scalable technique to investigate high-speed data transmission systems, related signal processing and monitoring technologies at serial data rates beyond the bandwidth limitation of optoelectronics [13], [14].

The proposed technique in this paper has achieved bitrate of 240 Gbit/s with the combination of OTDM-DWDM technique within 1.55 µm transmission window for 2700 km long-haul communication. A total of 48 channels are transmitted using OTDM for each WDM input, then 8 channels of WDM are multiplexed at the transmission end for making a total of 384 channels. At the receiver end, all 8 channels of WDM are demultiplexed along with 48 channels of OTDM from each output terminal, making sure that all 384 user channels are demodulated successfully. The bitrate is set to 625 Mbit/s for each channel that provides up to 240 Gbit/s in total communication.

II. Principle Operation

The entire system starts with modulation of OTDM and multiplex in WDM at the transmission side, and then demultiplex of WDM and demodulation of OTDM at the receiver side, respectively. The very first part is modulating 8 individual channels with three compression stages in OTDM. Afterwards, same set of channels are created to make 48 channels in total and multiplexed with calculated time delay in

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order to best fit all other channels in between the empty time slots created by compression stages. In this network architecture, adapting to compression stage helps to accommodate more and more channels because it provides free time slots by compressing bit interval [15], [16]. Thus, a complete transmission side is designed that goes into a specific wavelength (1550.12 nm) of the WDM system. In the same way other 48 channels from OTDM are connected as input for another wavelengths (1550.92 nm). In WDM, 8 channels are taken as input for making a total of 384 channels from OTDM into WDM multiplexer side.

At the beginning of the receiver, there is a WDM demultiplexer with 8 channels of output that goes into demodulating the rest 48 OTDM channels in each WDM channel with synchronized time delay [13], [17]. Therefore, all 384 channels goes to respective recipients. In between the transmitter and receiver, there are segments each having a Single Mode Fiber (SMF) of 50 km followed by a Dispersion Compensating Fiber (DCF) of 10 km. An optical amplifier is used for optical power gain after every 60 km of the span.

A. *Abbreviations and Acronyms*

WDM = Wavelength division multiplexing
DWDM = Dense wavelength division multiplexing
OTDM = Optical time division multiplexing
OFDM = Orthogonal frequency division multiplexing
OCDM = Optical code division multiplexing
SDM = Space division multiplexing
OAM = Orbital angular momentum
PRBS = Pseudo Random Bit Sequence
FEC = Forward Error Correction
Ych×Z = Y number of input channel(s) and Z number of output(s)
Z×Ych = Z number of input(s) and Y number of output channel(s)

III. Network Setup

The design of OTDM-DWDM network consists of two techniques, one is the OTDM, and the other is DWDM. OTDM modulation and demodulation, along with DWDM mux and demux are simulated separately for best optimization. In the process, both techniques are adjusted for better OSNR, merged together at the final stage, and further tuned for efficient output.

A. *OTDM Signal*

The OTDM modulation consists of 48 channels, in six sets of 8 channels. Each channel are muxed at 625 Mbit/s bitrate, and passed through compression stage followed by calculated time delay. Channel bit rate follows OC-12 standards [18]. While adding channels into each power combiner component, maximum 2 dB loss has been counted as design margin just because in real time scenario any of the components may show power surge due to temperature, rough or ambient weather condition etc. But in demodulation side, maximum 1 dB loss has been counted for each power splitter component. Laser power of every channel is set to 5 dBm with linewidth of 10 kHz.

A channel is designed using one CW laser diode, a Pseudo Random Bit Sequence generator with a bit rate of 625 Mbit/s, a Return-to-Zero pulse generator, then all three components are connected to an amplitude modulator followed by an optical time delay as shown in Fig. 1:-

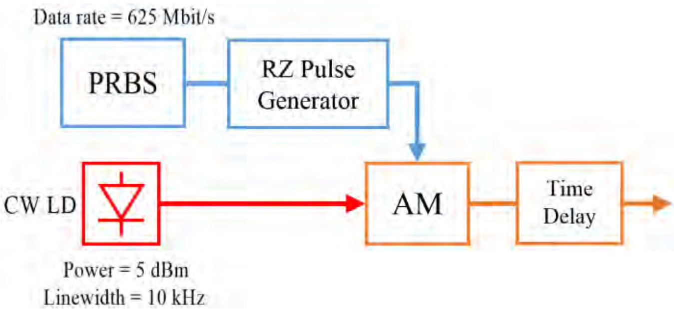


Fig. 1. Design of a single channel. A PRBS generating 625 Mbps data is coupled with 5 dBm CW Laser using amplitude modulator, whereas time delay fixes redundancies with other channels of similar structure. *(Legend: PRBS = Pseudo-Random Bit Sequence, RZ = Return-to-Zero, CW LD = Continuous Wave Laser Diode, AM = Amplitude Modulator)*

Finally all sets are combined at the end of transmission side as shown in Fig. 2:-

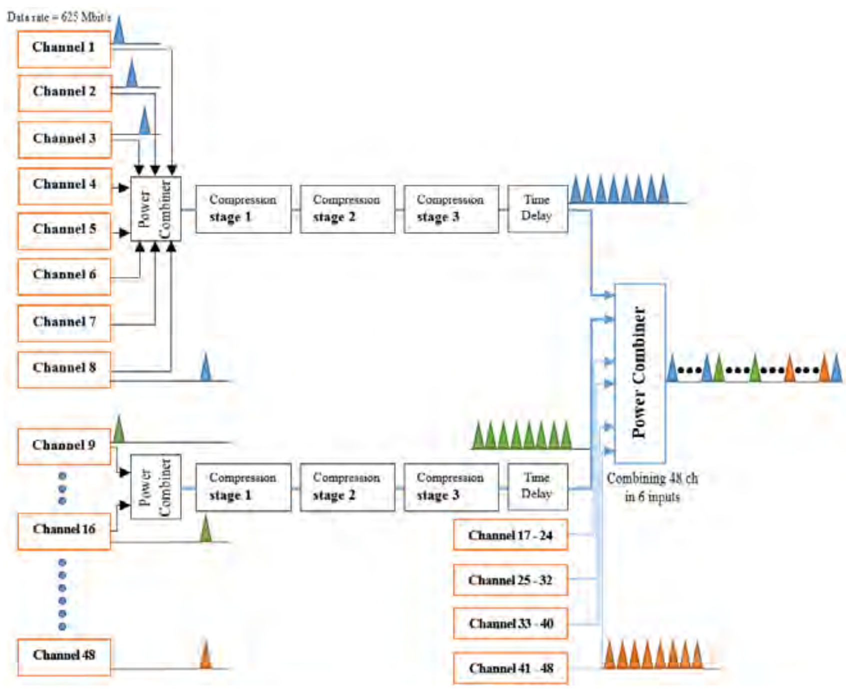


Fig. 2. OTDM transmitter sub-system, six individual 8ch×1 power combiner accumulates eight channels each, making a total of 48 user channels into one 6ch×1 power combiner.

At the receiving side, a power splitter takes out 6 outputs to another six splitters where each splitter divides into 8 outputs in order to demodulate each channel from the transmission end. Demodulation starts with a clock generator, a Return-to-Zero pulse generator, an electrical time delay component that goes into one terminal of the amplitude modulator while the other terminal is connected to one of the splitters. Demodulation of each and every channel is successfully achieved at synchronized time delay. The other five splitters also demodulates 8 channels each that makes 48 channel outputs as shown in Fig. 3:-

finalize the process of demodulation. In between the WDM MUX and DEMUX there are fiber expanding about 2700 km in segments of 60 km that have SMF of 50 km, DCF of 10 km, and one optical amplifier for regaining dissipated power at the end of each segment. The whole setup is shown in Fig. 4.

IV. Result and Analysis

The design for both OTDM and hybrid OTDM-DWDM are done successfully and mapped accurately. Nevertheless, absolute timing precision is implicated so that there is no loss in message bits.

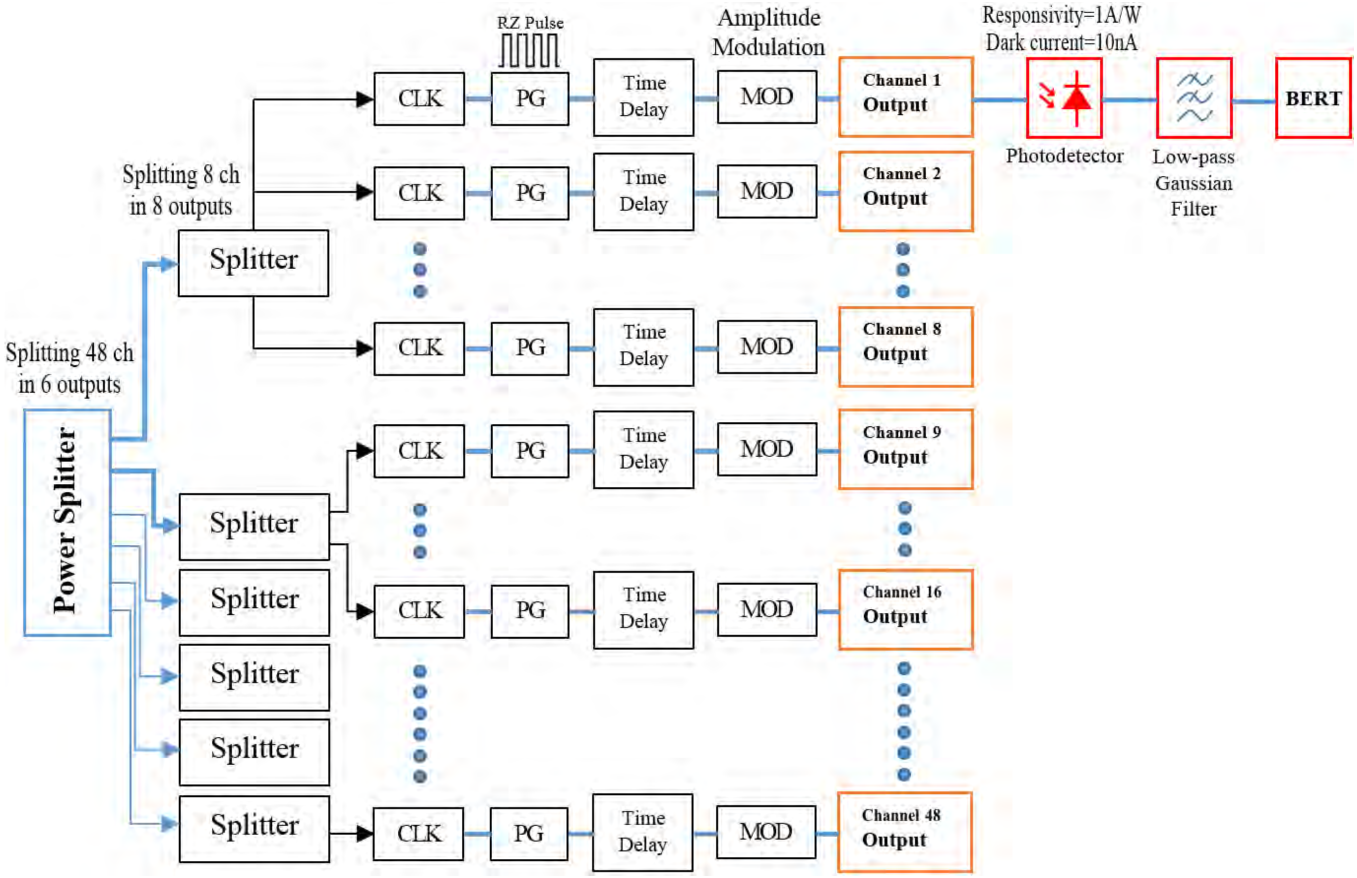


Fig. 3. OTDM receiver sub-system, one 1×6ch splitter takes out 48 channels into six individual 1×8ch power splitters, each splitter contains messages from corresponding channel which are retrieved at calculated time delay from each output of the splitter. (Legend: CLK = clock, PG = pulse generator, MOD = modulation, BERT = Bit Error Ratio Tester)

B. DWDM Signal

For DWDM system, at the transmission end, 8 channel WDM MUX is used to take 384 channels as input. Each input has 48 channels from OTDM. The proposed technique is designed using 1550.12, 1550.92, 1551.72, 1552.52, 1553.33, 1554.13, 1554.94, and 1555.75 nm following the ITU-T G.694.1 (02/2012) standard 0.8 nm DWDM channel spacing grid [19].

For DEMUX, at the receiving end, each channel from 8 outputs of WDM takes out 48 channels from OTDM in order to

A. OTDM Network

For designing the OTDM, accurate time calculation allows to best fit the 48 channels into empty time frame. In order to limit SMF non-linear loss, to keep transmission power less than 0 dBm, and considering losses within devices, the power of each laser is set to 5 dBm or, 3.1628 mW only. Single user channel bitrate is 625 Mbit/s. Bit sequence generator has no leading or trailing zeros. For 625 Mbit/s bitrate and 128 bits sequence length, transmission side data structure has been observed in Fig. 5.

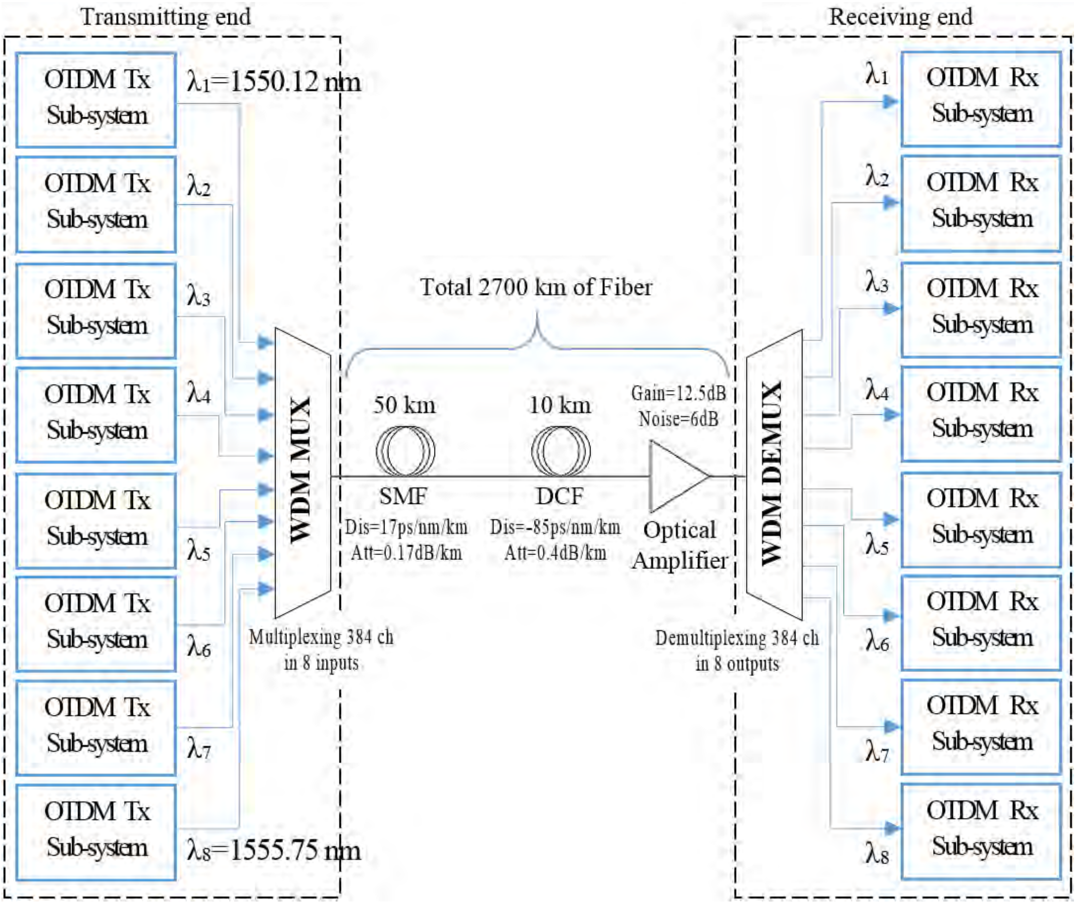
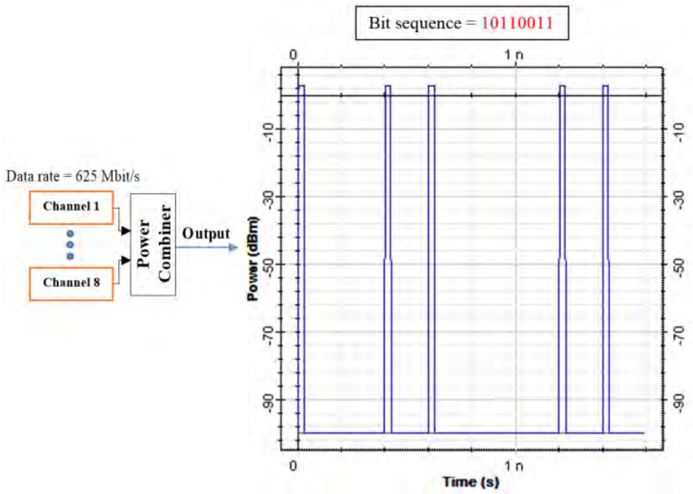
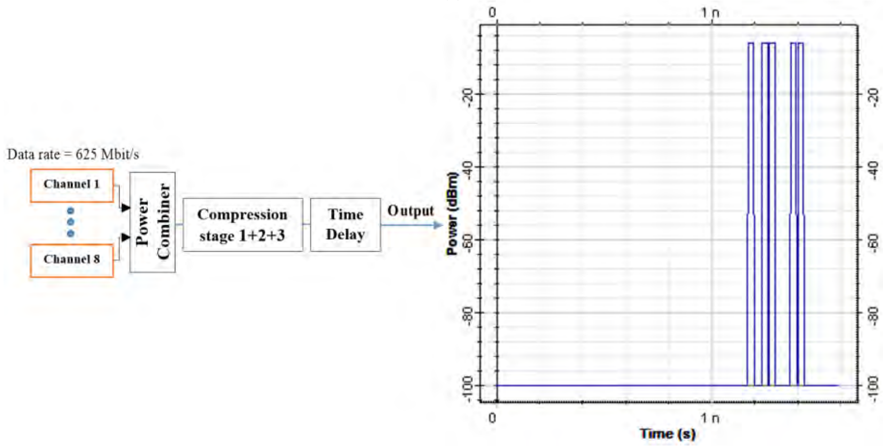


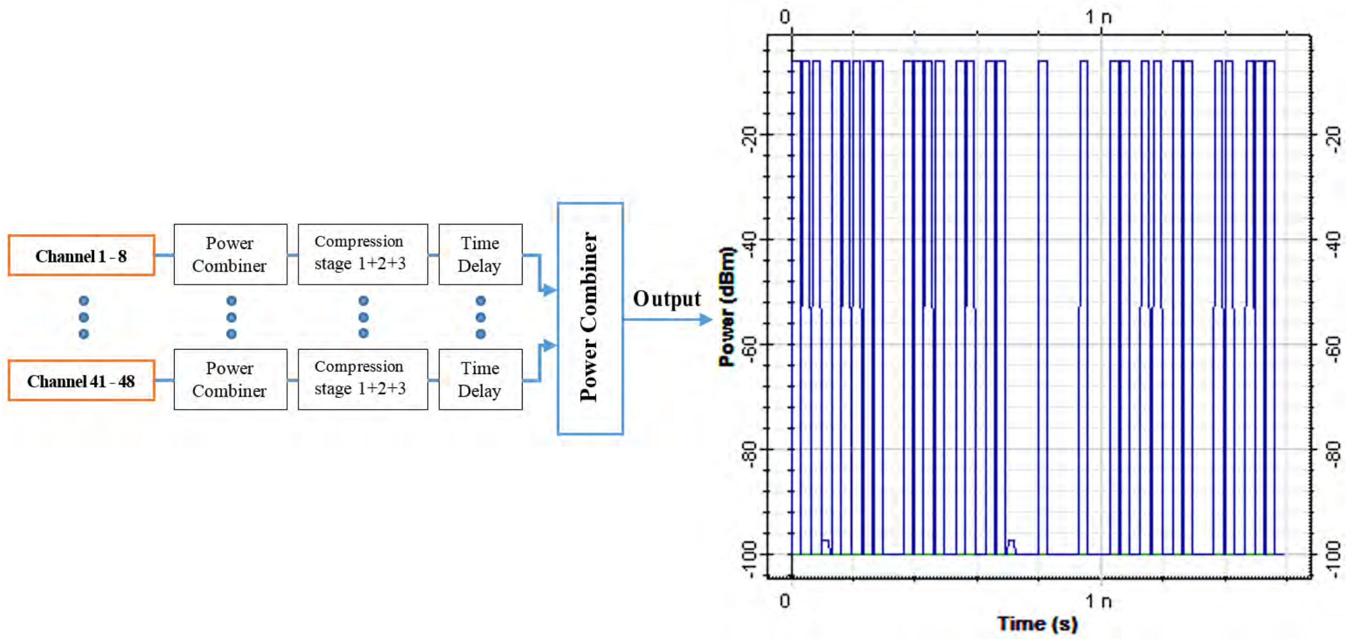
Fig. 4. OTDM-DWDM system, total 384 channels are transferred throughput 240 Gbit/s data rate that has 2700 kilometers long-haul transmission capability. (Legend: SMF = Single Mode Fiber, DCF = Dispersion Compensating Fiber)



5 (a)



5 (b)



5 (c)

Fig. 5. a) OTDM transmission of 8 channels before compression, bit sequence is manually defined 10110011, b) OTDM transmission of 8 channels after compression, same bit sequence is now taking very small amount of space and creating empty time slots for accommodating more message bits, c) OTDM transmission of 48 channels after compression and delayed time adjustment, this figure shows that ultra-high speed data transmission is achieved at the transmission end.

B. BER Result of OTDM

At 1550.12 nm, the bit error rate (BER) seen through 3R generator at channel 1 stays well under 10^{-12} at a transmission distance of 18000 km in OTDM for 128 bits sequence length. Maximum Q-factor is 6.78312, minimum BER is 1.15617×10^{-12}, corresponding eye-diagram shown in Fig. 6:-

Fig. 6 shows eye diagram for return-to-zero pulse generator in OTDM signal. RZ signals do not have any crossing points in eye diagram because pulses are returning back to zero (0) after each bit. Jitter is measured at the 50% level of either falling or rising edge of the eye, this is also known as the RMS jitter.

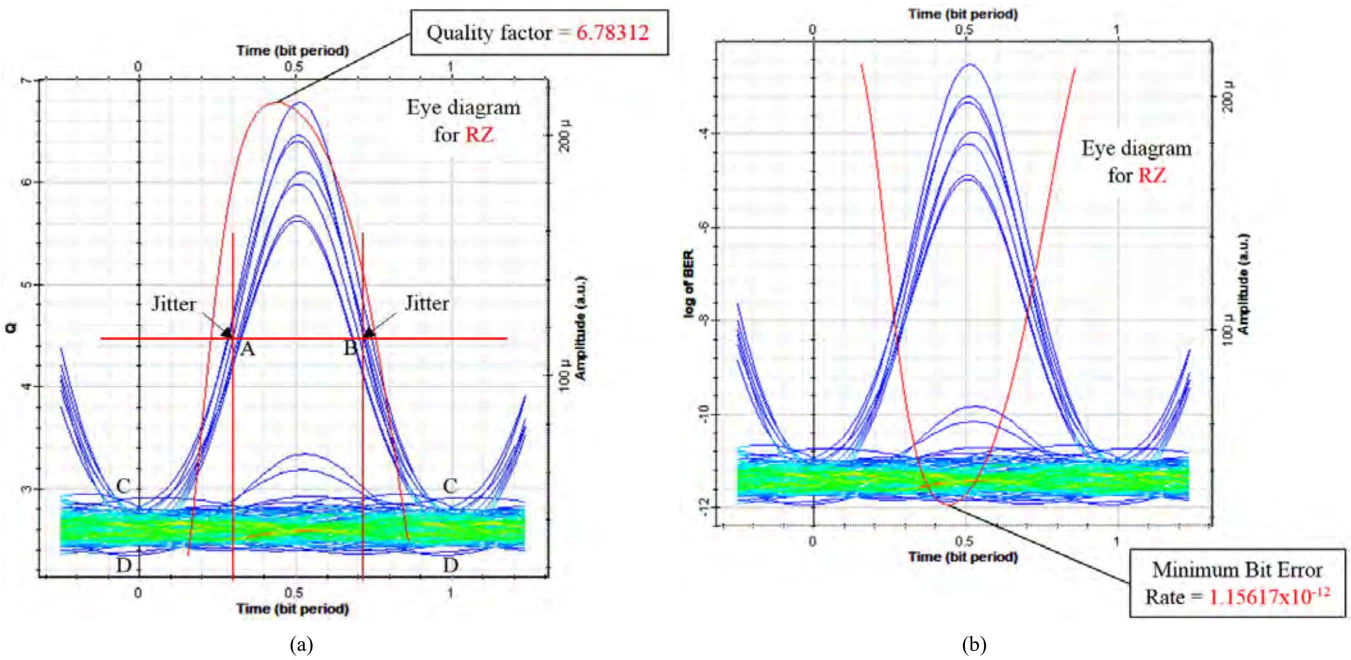


Fig. 6. a) Q-factor at ch-1 marked by the red curve is 6.78312, b) Min. BER at ch-1 marked by the red curve is 1.15617×10^{-12}.

In order to measure BER and Q-factor at the receiver terminal, PRBS are used as clock generator, and low pass Gaussian filter is connected after Avalanche Photo Diode (APD) that has a cut-off frequency of (0.75 x Bitrate), depth of 100 dB, and 1st order filter. APD photo-detector has a responsivity of 1 A/W, 10 nA dark current, thermal noise of $1x10^{-22}$ W/Hz. The values are taken without any forward error correction (FEC).

The proposed technique in this paper allows 18000 km transmission at 1550.12 nm with BER of $1.15617x10^{-12}$ using 48 channels with PRBS, the odds of signal dispersion, shifting of data bits are also accounted for. Any change in laser power can greatly deteriorate transmission quality, some values taken from the simulation at channel 1 are included in Table 1, and a graph showing log(BER) and transmission distance limitation due to different magnitude of laser power are represented in Fig. 7:-

TABLE I. MEASURING BER WITH RESPECT TO TRANSMISSION DISTANCE

Laser Power (dBm)	Transmission Distance (km)			
	4980	9960	15000	18000
5	-88.1189	-30.8756	-14.7909	-11.937
4	-64.8025	-24.3698	-13.0285	-10.5681
3	-46.8056	-17.3952	-10.0836	-8.04046
	log(BER)			

GRAPH I. log(BER) vs. Transmission Distance

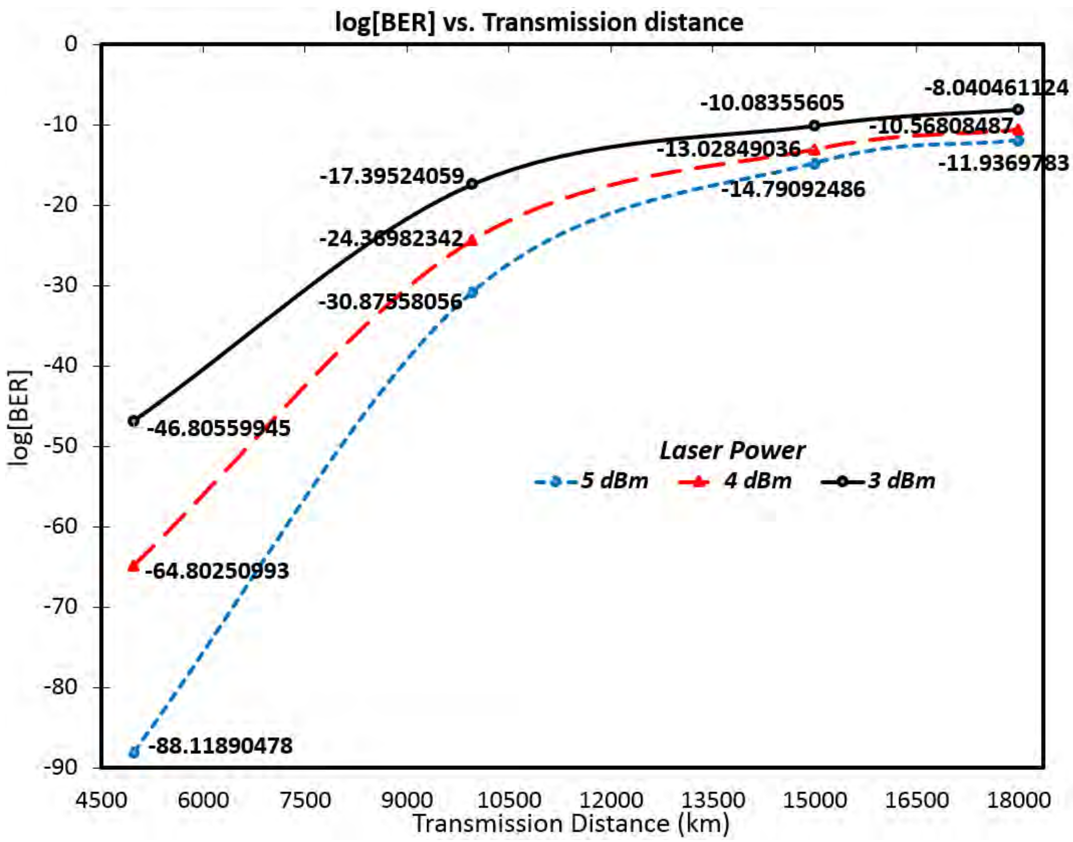


Fig. 7. log(BER) vs. transmission distance graph from ch-1 shows the effects on transmission due to laser power. Laser power at 5 dBm for all CW lasers contribute to better BER over the distance of transmission than that of 3 and 4 dBm.

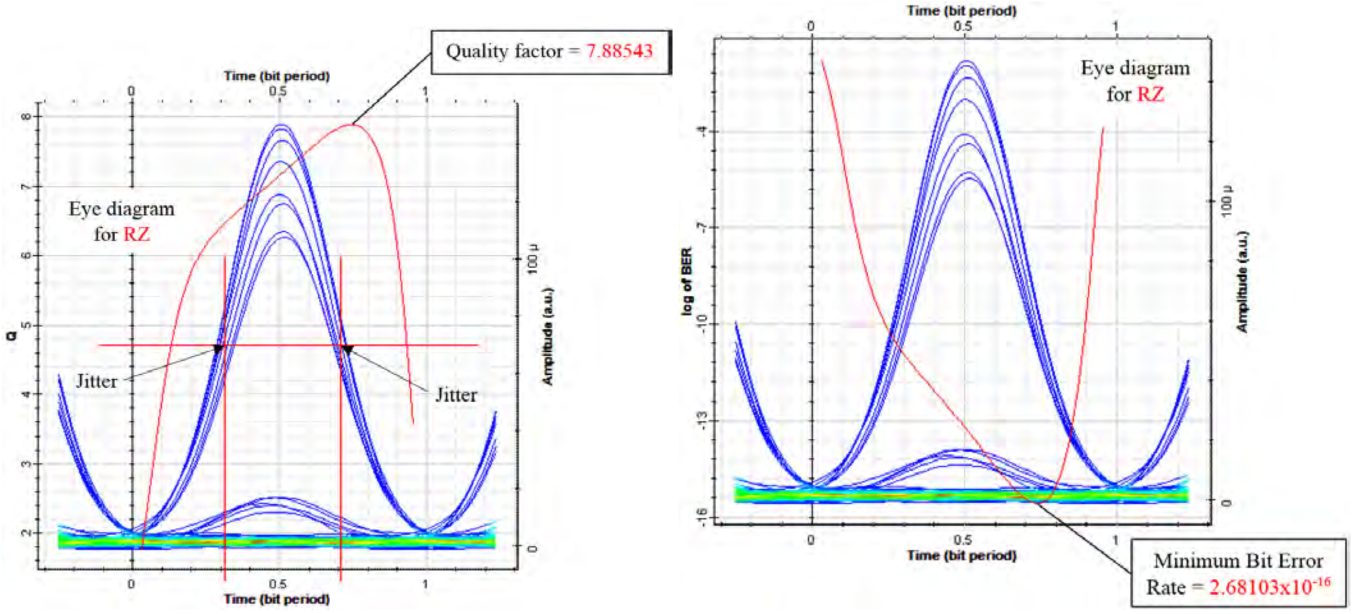
C. Hybrid OTDM-DWDM Network

For designing the hybrid OTDM-DWDM system, choosing wavelength carefully is a great factor because power attenuation and dispersion of message bits take place under different wavelengths. Network setup in this paper is done within 1.55 µm transmission window because it is the lowest attenuation window for SMF, but dispersion matters now. Changing wavelength from 1550 nm to 1560 nm will make a significant dispersion that will cause shifting in pulse train and message bit stream, resulting defective demodulation of message, degrading BER value, and limiting transmission distance as well. In order to maintain a better BER and communication distance, wavelength width ranges from 1550 nm to 1556 nm, which has minimum attenuation loss, improved amount of BER and allows maximum distance. All WDM channels designed in this network transmit the data within 1550.12, 1550.92, 1551.72, 1552.52, 1553.33, 1554.13, 1554.94, and 1555.75 nm wavelength [19].

Both MUX and DEMUX have 8 channels input and output respectively, with a noise threshold of -100 dB and 3 dB noise dynamicity. MUX is designed with a bandwidth of 0.8 nm, Bessel type filter, filter order is 2. For DEMUX, bandwidth is 0.8 nm, same Bessel type filter with an order of 2, and resampled at $3.2x10^{11}$ Hz. A Gaussian optical filter is connected at each output terminal with a bandwidth of 90 GHz so that noises can be filtered out within respective wavelengths.

D. *BER Result of OTDM-DWDM*

At 1550.12 nm, the bit error rate (BER) seen through 3R generator at channel 1 stays well under 10^{-12} at a transmission distance of 2700 km in OTDM-DWDM combined system for 128 bits sequence length. Maximum Q-factor is 7.88543, minimum BER is 2.68103×10^{-16}, and corresponding eye-diagram is presented in Fig.8:-



(a) (b)

Fig. 8. a) Q-factor at ch-1 marked by the red curve is 7.88543, b) Min. BER at ch-1 marked by the red curve is 2.68103×10^{-16}.

PRBS are used as clock generator, and low pass Gaussian filter connected after Avalanche Photo Diode has a cut-off frequency of (0.75 x Bitrate). All criteria were kept same as OTDM network. Transmission distance for OTDM-WDM combined network is reported 140 km [20], 560 km [21], 700 km [12], and 1822 km [22] by other authors. But the proposed technique in this paper allows 2700 km transmission at 1550.12 nm with BER of 2.68103×10^{-16} using 384 channels from OTDM. Moreover, the BER values are taken without any FEC, the odds of signal dispersion, shifting of data bits are also accounted for.

In DWDM, channel spacing limits transmission distance because of side modes of each wavelength, cross talk, spectrum interference etc. [23]. Therefore some results are included regarding the change in transmission distance and BER value with respect to channel spacing difference by 0.8 nm (100 GHz) and 1.6 nm (200 GHz). All the values of BER are taken from 1550.92 nm subsystem design at channel 1 for both cases, and are included in Table 2. A graph showing transmission distance and log(BER) degradation due to change in channel spacing is presented in Fig. 9.

TABLE II. MEASURING BER WITH RESPECT TO TRANSMISSION DISTANCE

Channel Spacing (nm)	**Transmission Distance (km)**			
	0	**240**	**720**	**1200**
0.8	-238.89	-25.454	-43.303	-44.489
1.6	-970.03	-3.2938	-55.584	-11.581
	log(BER)			

TABLE III. MEASURING BER WITH RESPECT TO TRANSMISSION DISTANCE

Channel Spacing (nm)	**Transmission Distance (km)**		
	1680	**2160**	**2700**
0.8	-15.805	-19.356	-14.809
1.6	-6.532	-6.3154	0
	log(BER)		

GRAPH II. log(BER) vs. Transmission Distance

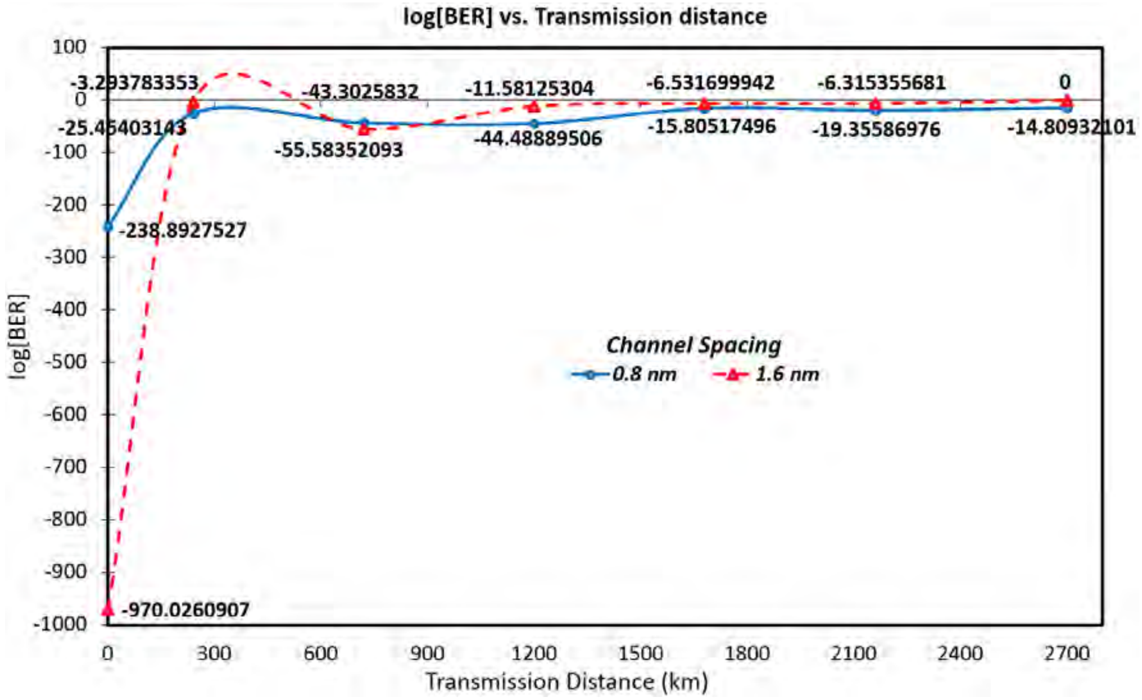


Fig. 9. log(BER) vs. transmission distance graph from ch-1 shows the significance of channel spacing that effects communication distance. From the graph, the proposed technique for 0.8 nm spacing (blue curve) has better BER than that of 1.6 nm, so less bandwidth is used in this network.

V. Conclusion

A complete simultaneous fiber optical communication system has been successfully designed, analyzed, and demonstrated by combining OTDM and DWDM network architecture at 240 Gbit/s data rate for 2700 kilometers. Moreover, the compression stages provide a room to adapt a maximum number of 384 channels into the network. Throughout the simulation, standard parameters were maintained for commercially available channel grids at 100 GHz [19], carrier capacity at OC-12 [18], only one optical amplifier within each 60 km span, minimum laser power at 5 dBm, maximum user channel under fast TDM technique, and most importantly at less system complexity. The system is efficient, accurate, and still error free while demodulating data in OTDM at a distance of 18000 km with Q-factor of 6.78312 (BER < 10^{-12}), and demultiplexing in WDM at a distance of 2700 km with Q-factor of 7.88543 (BER < 10^{-16}).

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