Bit Error Rate Optimization in Fiber Optic Communications

S. M. Jahangir Alam, M. Rabiul Alam, Guoqing Hu, and Md. Zakirul Mehrab

***Abstract*—In telecommunication, the Bit Error Rate (BER) is an indication of how often data has to be retransmitted because of an error. The different modulation techniques scheme is suggested for improvement of BER in fiber optic communications. The developed scheme has been tested on optical fiber systems operating with a non-return-to-zero (NRZ) format at transmission rates of up to 10Gbps. Performance of improved detected signals has been evaluated by the analysis of quality factor and computed BER. Numerical simulations have shown a noticeable improvement of the system BER after implementation of the suggested processing operation on the detected electrical signals at central wavelengths in the region of 1310 nm.**

***Index Terms*—BER improvement, Modulation Techniques, Noise, Optimization, NRZ.**

I. Introduction

Optical fibers are widely used in fiber optic communications which permits transmission over longer distances and at higher bandwidths than other forms of communication. Optical transmission networks based on wavelength division multiplexing (WDM) architecture is dominating the all optical data transportation with bit rates exceeding several terabit per second rates to serve the ever increasing demand of Internet Protocol (IP) networks. Some of the main TCP/IP networking functions such as routing, add-drop multiplexing and demultiplexing and wavelength conversion, need to be functional to encapsulate the IP packet requirements into the optical layer. The linear as well as the nonlinear characteristics of the optical fiber at higher bit rates, seriously limit the data transmission performance and it is therefore becoming necessary to develop approaches to improve regeneration of transmitted data. Experimental investigations have shown a considerable progress in this direction. These were based on compensation techniques, filtering, developing optimized line coding, and further dispensation of received signal. In a communication system, the receiver side BER may be affected by transmission channel noise, interference, distortion, bit synchronization problems, attenuation, wireless multipath fading, etc. The BER can be considered as an approximate estimate of the bit error probability which is the expectation value of the BER. The approximation is accurate for a long studied time interval and a high number of bit errors.

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II. Bit Error Rate and Signal-To-Noise Ratio

A. *Bit Error Rate*

In telecommunication transmission, the bit error rate (BER) is the percentage of bits that have errors relative to the total number of bits received in a transmission. For example, a transmission might have a BER of 10^{-6}, meaning that, out of 1,000,000 bits transmitted, one bit was in error. The BER is an indication of how often data has to be retransmitted because of an error. Too high a BER may indicate that a slower data rate would actually improve overall transmission time for a given amount of transmitted data since the BER might be reduced, lowering the number of packets that had to be present. The BER may be improved by choosing a strong signal strength (unless this causes cross-talk and more bit errors), by choosing a slow and robust modulation scheme or line coding scheme, and by applying channel coding schemes such as redundant forward error correction codes [1]. The transmission BER is the number of detected bits that are incorrect before error correction, divided by the total number of transferred bits (including redundant error codes). Normally the transmission BER is larger than the information BER. The information BER is affected by the strength of the forward error correction code.

B. *Signal-To-Noise Ratio*

Signal-to-noise ratio (often abbreviated SNR or S/N) is a measure used in science and engineering to quantify how much a signal has been corrupted by noise. It is defined as the ratio of signal power to the noise power corrupting the signal. A ratio higher than 1:1 indicates more signal than noise. While SNR is commonly quoted for electrical signals, it can be applied to any form of signal (such as isotope levels in an ice core or biochemical signaling between cells). In less technical terms, signal-to-noise ratio compares the level of a desired signal (such as music) to the level of background noise. The higher the ratio, the less obtrusive the background noise is. Signal-to-noise ratio is sometimes used informally to refer to the ratio of useful information to false or irrelevant data in a conversation or exchange. For example, in online discussion forums and other online communities, off-topic posts and spam are regarded as "noise" that interferes with the "signal" of appropriate discussion. The concepts of signal-to-noise ratio and dynamic range are closely related. Dynamic range measures the ratio between the greatest undistorted signal on a channel and the smallest detectable signal, which for most purposes is the noise level. Signal-to-noise ratio measures the ratio between an arbitrary signal level (not necessarily the most powerful signal possible) and noise. Measuring signal-to-noise ratios requires the selection of a representative or reference signal. Signal-to-noise ratio is usually taken to indicate an average signal-to-noise ratio, as it is possible that (near) instantaneous signal-to-noise ratios will be considerably different. The concept can be understood as normalizing the noise level to 1 (0 dB) and measuring how far the signal 'stands out'.

C. *Digital Signal*

In a digitized measurement, the number of bits used to represent the measurement determines the maximum possible signal-to-noise ratio. This is because the minimum possible noise level is the error caused by the quantization of the signal (quantization noise). This noise level is nonlinear and signal-dependent; different calculations exist for different signal models. Quantization noise is modeled as an analog error signal summed with the signal before quantization [4]. This theoretical maximum SNR assumes a perfect input signal. If the input signal is noisy, the measurement noise may be larger than the quantization noise. Real analog-to-digital converters also have other sources of noise that further decrease the SNR compared to the theoretical maximum from the idealized quantization noise. Although noise levels in a digital system can be expressed using SNR, it is more common to use E_b/N_o the energy per bit per noise power spectral density. The modulation error ratio (MER) is a measure of the SNR in a digitally modulated signal.

III. Noise Sources, Modulation and Coding

A. *Noise Sources*

Noise is a significant issue in every communication system. In the optical world (especially in WDM) there are many sources of noise. The good news is that most of the noise sources are so small that may be ignored. In other cases the action can take to mitigate one form of noise also mitigates many others. The dominant noise sources in WDM systems are amplifier noise (ASE) and thermal noise in the receivers. However, in the design of any system it is very important to be aware of all the potential sources of noise so that they can be avoided or mitigated.

B. *Modulation*

Modulation is the process of conveying a message signal, for example, a digital bit stream or an analog audio signal, inside another signal that can be physically transmitted. Modulation of a sine waveform is used to transform a base band message signal to a pass band signal, for example, a radio frequency (RF) signal. In radio communications, cable TV systems or the public switched telephone network for instance, electrical signals can only be transferred over a limited pass band frequency spectrum, with specific (non-zero) lower and upper cutoff frequencies [6]. In optical communication, there are two major modulation techniques: Electro-Absorption modulator and Mach-Zehnder modulator.

Electro-Absorption Modulator (EAM). Electro-Absorption modulator is a semiconductor device which can be used for modulating the intensity of a laser beam via an electric voltage. A change in the absorption spectrum caused by an applied electric field, which changes the band gap energy (thus the photon energy of an absorption edge) but usually, does not involve the excitation of carriers by the electric field. The EAM is candidate for use in external modulation links in telecommunications [7]. They can be operated at very high speed; a modulation bandwidth of tens of gigahertz can be achieved, which makes these devices useful for optical fiber communication. A convenient feature is that an EAM can be integrated with distributed feedback laser diode on a single chip to form a data transmitter in the form of a photonic integrated circuit. Compared with direct modulation of the laser diode, a higher bandwidth and reduced chirp can be obtained.

Mach-Zehnder Modulator. A Mach-Zehnder modulator is a intensity modulating signal light, using a simple drive circuit for the modulating voltage. The modulator includes two waveguides with respective multiple quantum well (MQW) structures. Well layers of the MQW structures of the two optical waveguides have different thicknesses or are made from different materials so the phase of light propagating through one waveguide advances and through the other waveguide is delayed in response to the same applied voltage. The phase changed light signals are combined as an output light signal that is intensity modulated [3].

C. *Coding*

There are different types of coding are used such as Non-Return-to-Zero (NRZ), Return-to-Zero (RZ), Alternate Mark Inversion (AMI), Manchester, Differential Manchester and Multi-state Coding.

NRZ Coding. If the bit stream is to be sent as simply the presence or absence of light on the fiber (or as changes of voltage on a wire) then the simplest NRZ coding is possible. In this method a one bit is represented as the presence of light and a zero bit is represented as the absence of light. This method of coding is used for some very slow speed optical links but has been replaced by other methods for most purposes.

RZ Coding. In RZ coding the signal returns to the zero state every bit time such as, a “1” bit is represented by a “ON” laser state for only half a bit time. In a restricted bandwidth environment (such as in most electronic communications) there are two different line states required to represent a bit (at least for a “1” bit) and this type of coding is not desired.

AMI Coding. It is a synchronous clock encoding technique which uses bipolar pulses to represent logical 1 value. The alternating coding prevents the buildup of a D.C voltage level down the cable. This is considered an advantage since the cable may be used to carry a small D.C. current to power intermediate equipment such as line repeaters [5].

Manchester Coding. It is a type of digital encoding that is used in data transmission. Within the structure for Manchester encoding, the data bits in the transmission are represented by a series of states that occur in a logical sequence. This approach to data transmission is somewhat different, as many encoding methods tend to assign a high or low state of voltage to each bit and use that information as the criteria for affecting the transfer of the bits.

Differential Manchester Coding. It is a method of encoding data in which data and clock signals are combined to form a single self synchronizing data stream. It is a differential encoding, using the presence or absence of transitions to indicate logical value. This gives it several advantages over standard Manchester encoding [8].

Multi-state Coding. It is a method in the electronic systems where both signal amplitude and phase are used to create unique line states representing particular bit combinations.

IV. Error Detection and Correction Methodology

The general idea for achieving error detection and correction is to add some redundancy to a message, which receivers can use to check consistency of the delivered message and to recover data determined erroneous. Error detection and correction schemes can be either systematic or non systematic. In a systematic scheme, the transmitter sends the original data, and attaches a fixed number of check bits (or parity data), which are derived from the data bits by some deterministic algorithm. If only error detection is required, a receiver can simply apply the same algorithm to the received data bits and compare its output with the received check bits; if the values do not match, an error has occurred at some point during the transmission. In a system that uses a non systematic code, the original message is transformed into an encoded message that has at least as many bits as the original message. If the channel capacity cannot be determined or is highly varying, an error detection scheme may be combined with a system for retransmissions of erroneous data. This is known as automatic repeat request (ARQ) and is most notably used in the Internet. An alternate approach for error control is hybrid automatic repeat request (HARQ) which is a combination of ARQ and error correction coding.

A. Error Detection Scheme

Error detection is most commonly realized using a suitable hash function (or checksum algorithm). A hash function adds a fixed length tag to a message, which enables receivers to verify the delivered message by recomputing the tag and comparing it with the one provided. There exists a vast variety of different hash function designs. However, some are of particularly widespread use because of either their simplicity or their suitability for detecting certain kinds of errors (e.g., the cyclic redundancy check's performance in detecting burst errors). Random error correcting codes based on minimum distance coding can provide a suitable alternative to hash functions when a strict guarantee on the minimum number of errors to be detected is desired.

B. Error Correction Scheme

Error correction schemes are mainly three kinds: Automatic repeat request (ARQ), Error correcting code (ECC) or forward error correction (FEC) and Hybrid schemes.

Automatic Repeat Request (ARQ). Automatic repeat request is an error control method for data transmission that makes use of error detection codes, acknowledgment and/or negative acknowledgment messages, and timeouts to achieve reliable data transmission. An acknowledgment is a message sent by the receiver to indicate that it has correctly received a data frame. Usually, when the transmitter does not receive the acknowledgment before the timeout occurs (i.e., within a reasonable amount of time after sending the data frame), it retransmits the frame until it is either correctly received or the error persists beyond a predetermined number of retransmissions. Automatic repeat request is appropriate if the communication channel has varying or unknown capacity, such as is the case on the Internet. However, ARQ requires the availability of a back channel, results in possibly increased latency due to retransmissions, and requires the maintenance of buffers and timers for retransmissions, which in the case of network congestion can put a strain on the server and overall network capacity.

Error Correcting Code (ECC). An error correcting code or forward error correction (FEC) code is a system of adding redundant data, or parity data, to a message, such that it can be recovered by a receiver even when a number of errors (up to the capability of the code being used) were introduced, either during the process of transmission, or on storage. Since the receiver does not have to ask the sender for retransmission of the data, a back channel is not required in forward error correction, and it is therefore suitable for simplex communication such as broadcasting. Error correcting codes are frequently used in lower layer communication, as well as for reliable storage in media such as CDs, DVDs, hard disks, and RAM. Error correcting codes are usually distinguished between convolution codes and block codes: Convolution codes are processed on a bit-by-bit basis and Block codes are processed on a block-by-block basis.

Hybrid Schemes. Hybrid ARQ is a combination of ARQ and forward error correction. There are two basic approaches: Messages are always transmitted with FEC parity data (and error detection redundancy). A receiver decodes a message using the parity information, and requests retransmission using ARQ only if the parity data was not sufficient for successful decoding (identified through a failed integrity check). Messages are transmitted without parity data (only with error detection information). If a receiver detects an error, it requests FEC information from the transmitter using ARQ, and uses it to reconstruct the original message. The latter approach is particularly attractive on an erasure channel when using a rate less erasure code.

V. Optical Fiber

An optical fiber is a thin, flexible, transparent fiber that acts as a waveguide, or light pipe, to transmit light between the two ends of the fiber. Optical fibers are widely used in fiber optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communication. There are two basic types of fiber: Single mode and Multi mode optical fiber.

A. Single Mode Optical Fiber

Single mode optical fiber is an optical fiber in which only the lowest order bound mode can propagate at the wavelength of interest typically 1300 to 1320nm. Single mode optical fiber is used in many applications where data is sent at multi frequency, so only one cable is needed - (single mode on one single fiber). Single mode fiber gives a higher transmission rate and up to 50 times more distance than multimode.

B. Multi Mode Optical Fiber

Multi mode fiber gives high bandwidth at high speeds (10 to 100MBS - Gigabit to 275m to 2km) over medium distances. Multi mode cable has a little bit bigger diameter, with a common diameters in the 50-to-100 micron range for the light carry component.

Tight Buffered Cables. Multiple color coded 900um tight buffered fibers can be packed tightly together in a compact cable structure, an approach widely used indoors; these cables are called tight buffered cables. Tight buffered cables are used to connect outside plant cables to terminal equipment, and also for linking various devices in a premises network. Multi fiber tight buffered cables often are used for intra-building, risers, general building and plenum applications. Tight buffered cables are mostly built for indoor applications, although some tight buffered cables have been built for outdoor applications too. Elements in a tight buffered fiber optic cable: Multiple 900um tight buffered fibers (stranded around the central strength member), Central strength member (in the center of the cable), Aramid Yarn, Ripcord (for easy removal of outer jacket), Outer jacket (also called sheath, PVC is most common for indoor cables because of its flexible, fire retardant and easy extrusion characteristics).

Loose Tube Cables. Multiple (up to 12) 250um coated fibers (bare fibers) can be put inside a color coded, flexible plastic tube, which usually is filled with a gel compound that prevents moisture from seeping through the hollow tube. Buffer tubes are stranded around a dielectric or steel central member (Aramid Yarn is used as primary strength member) and an outer polyethylene jacket is extruded over the core. These cables are called loose tube cables. Loose tube structure isolates the fibers from the cable structure. This is a big advantage in handling thermal and other stresses encountered outdoors. Loose tube cables typically are used for outside plant installation in aerial, duct and direct buried applications. Elements in a loose tube fiber optic cable: Multiple 250um coated bare fibers (in loose tube), one or more loose tubes holding 250um bare fibers. Loose tubes strand around the central strength member. Moisture blocking gel is used in each loose tube for water blocking and protection of 250um fibers. Central strength member (in the center of the cable and is stranded around by loose tubes). Aramid Yarn as strength member and Ripcord (for easy removal of outer jacket). Outer jacket (polyethylene is most common for outdoor cables because of its moisture and abrasion resistant and stable over wide temperature range characteristics).

VI. Optical Signal Loss and Bit Error Rate Analysis

A. Optical Signal Loss Analysis

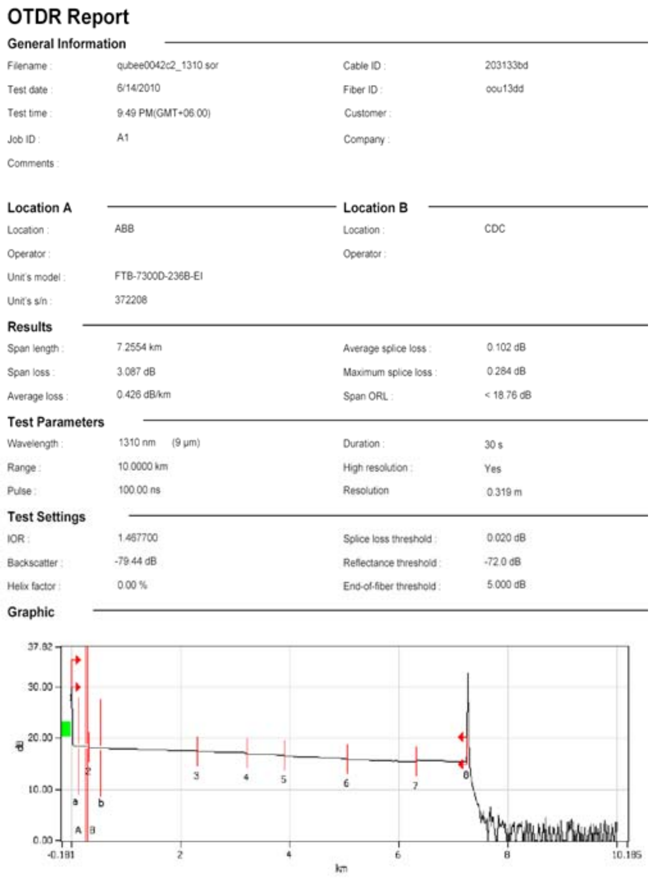
In optical fiber light is represented as signal and this signal carry individual bit. Bit error is totally dependable on signal loss. To find out the bit error in optical fiber the practical works is accomplished in Link3 to observe the signal loss in fiber optics communication. Optical Time Domain Reflectometer (OTDR) device has been used in this regard and three individual distances (1.01km, 53.045km, and 98.61km) are considered to find out the error. The example (based on a practical experience at Link3 fiber network) states the signal loss particularly. The objective of the fiber optic network is to calculate the attenuation - limited fiber length based on a power budget equation then to simulate and verify that is meets the performance objectives. The power budget equation states that the transmitted power minus the receiver sensitivity must be greater than or equal to the sum of the power losses plus the power margin:

$$P_T - S_R = AL_F + L_C + L_A + M$$

where, PT - is the transmitter, SR - is the receiver sensitivity, A - is the fiber attenuation, LF - is the fiber length, LC - is the coupling loss, LA - is the additional know losses and M - is the power margin.

B. Fiber Signal Losses Calculation

In the experiment, the fiber's length, attenuation and splice loss of a relatively short unknown optical fiber link are measured using the OTDR at 1310nm operating wavelengths. An example of OTDR generated report (shown in Fig. 1) and ODTR event table is shown in Table I.



OTDR Report

General Information

Filename :	qubee0042c2_1310.sor	Cable ID :	203133bd
Test date :	6/14/2010	Fiber ID :	ocu13dd
Test time :	9:49 PM(GMT+06:00)	Customer :	
Job ID :	A1	Company :	
Comments :			

Location A / **Location B**

Location :	ABB	Location :	CDC
Operator :		Operator :	
Unit's model :	FTB-7300D-236B-EI		
Unit's s/n :	372208		

Results

Span length :	7.2554 km	Average splice loss :	0.102 dB
Span loss :	3.087 dB	Maximum splice loss :	0.284 dB
Average loss :	0.426 dB/km	Span ORL :	< 18.76 dB

Test Parameters

Wavelength :	1310 nm (9 µm)	Duration :	30 s
Range :	10.0000 km	High resolution :	Yes
Pulse :	100.00 ns	Resolution	0.319 m

Test Settings

IOR :	1.467700	Splice loss threshold :	0.020 dB
Backscatter :	-79.44 dB	Reflectance threshold :	-72.0 dB
Helix factor :	0.00 %	End-of-fiber threshold :	5.000 dB

Graphic

Fig. 1. OTDR Generated report

TABLE I: THE OTDR'S EVENT TABLE

OTDR Report

Event Table

Type	Number	Location/Length (km)	Loss (dB)	Reflection (dB)	Attenuation (dB/km)	Cumul. (dB)
Launch Level	1	0.0000		-23.2		0.000
	Section	0.3214	0.080		0.250	0.080
Non-Reflective Fault	2	0.3214	0.284			0.364
	Section	1.9845	0.631		0.318	0.995
Non-Reflective Fault	3	2.3059	0.086			1.082
	Section	0.9039	0.280		0.310	1.362
Non-Reflective Fault	4	3.2098	0.158			1.520
	Section	0.6881	0.225		0.326	1.744
Non-Reflective Fault	5	3.8979	0.226			1.970
	Section	1.1569	0.497		0.429	2.467
Non-Reflective Fault	6	5.0548	0.172			2.639
	Section	1.2798	0.443		0.346	3.082
Positive Fault	7	6.3346	-0.317			2.765
	Section	0.9208	0.322		0.350	3.087
Reflective Fault	8	7.2554		-14.6		3.087

Marker Information

A :	0.2588 km	18.459 dB	B :	0.2895 km	18.437 dB
a :	0.1344 km	18.461 dB	b :	0.5381 km	18.038 dB
B-A:	0.0306 km	0.023 dB			

Manual Measurements

4-pt. ev. loss :	0.127 dB	A-B LSA att. :	-0.819 dB/km
A-B LSA loss :	-0.025 dB	3-pt. reflectance :	*****
2-pt. sect. att. :	0.733 dB/km	A-B ORL :	54.70 dB

From the event table (Table I) of section 2 and section 5 it is observed 0.284 dB and 0.226 dB signal loss, respectively. It has to optimize that point to minimize the signal loss in fiber optic communication. The near end zone of fiber A is fully visible before this reflection without any blinding by the front connector peak.

C. Analysis of the Bit Error Rate

The BER may be analyzed using stochastic computer simulations. If a simple transmission channel model and data source model is assumed, the BER may also be calculated analytically. In absence of available device for BER analysis, OTDR) has been used for checking the signal loss in fiber optics and the OptiSystem 9.0 for analyzing the BER. The circuit diagram of Fig. 2 has been used to do this analysis.

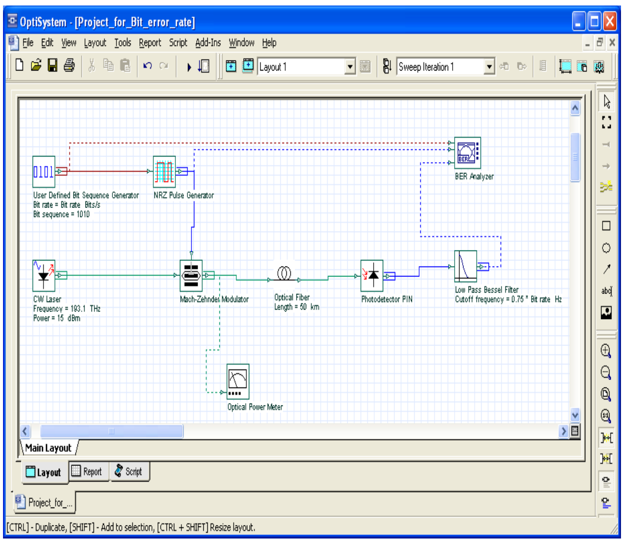


Fig. 2. The circuit digram of analyzed BER

D. The Components of the Bit Error Rate Diagram

Input bit sequence, Signal pulse generator: RZ pulse generator and NRZ Pulse generator, Modulation Technique: Mach-Zehnder and Electro-Absorption, Optical input power: 20 dB and 15 dB, cable 50 km, A low pass filter, BER analyzer. The following components of the BER diagram vary the result: Signal pulse generator, Modulation technique, Input optical Power. The results are shown in Table II and Table III and in Fig. 3 and Fig. 4.

TABLE II: 4 BITS RESULT FROM BER ANALYSIS

Input Bits	Signal Generator	Modulation Techniques	Optical Power (dB)	Min BER
1010	RZ	MZ	20	$1.85389e^{-197}$
1010	RZ	EAM	20	0
1010	NRZ	MZ	20	0
1010	NRZ	EAM	20	0
1010	RZ	MZ	15	0
1010	RZ	EAM	15	0
1010	NRZ	MZ	15	$1.28085\ e^{-203}$
1010	NRZ	EAM	15	0

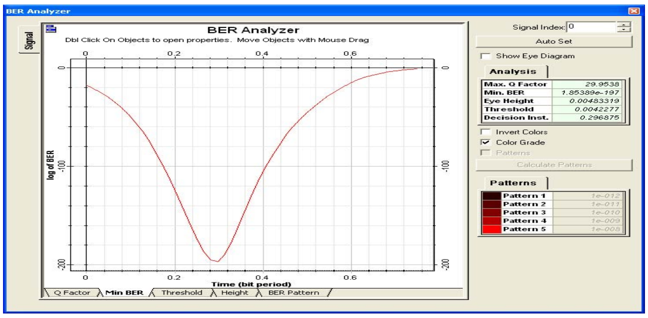


Fig. 3. Input bits: 1010, Signal Generator: RZ, Modulation Technique: Mach Zehnder, Optical Power: 20 dB, Min BER: 1.85389×e-197

TABLE III: 8 BITS RESULT FROM BER ANALYSIS

Input Bits	Signal Generator	Modulation Techniques	Optical Power (dB)	Min BER
10101100	RZ	MZ	20	$7.94587\times e^{-122}$
10101100	RZ	EAM	20	0
10101100	NRZ	MZ	20	$3.09973\times e^{-28}$
10101100	NRZ	EAM	20	$3.84761\times e^{-28}$
10101100	RZ	MZ	15	$1.86539\times e^{-59}$
10101100	RZ	EAM	15	$7.99419\times e^{-132}$
10101100	NRZ	MZ	15	$1.06647\times e^{-37}$
10101100	NRZ	EAM	15	$4.50779\times e^{-53}$

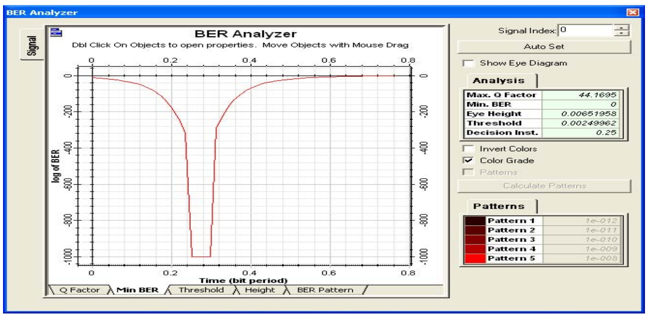


Fig. 4. Input bits: 10101100, Signal Generator: RZ, Modulation Technique: Electro Absorption, Optical Power: 20 dB, Min BER: 0

For 4 bits input (Table II), there is no bit error rate except applying Mach-Zehnder modulation technique. It is found bit error rate for both signal generators of RZ and NRZ with Mach-Zehnder modulation technique. Bit error rate found little bit smaller when applying 15 dB powers instead of 20 dB power with NRZ signal generator. For 8 bits input (Table III), all result of bit error rate is found except Electro Absorption modulation technique with RZ signal generator. Only the bit error rate is zero for RZ signal generator through Electro- Absorption modulation technique. Bit error rate is found while reducing power to 15 dB with the same condition.

VII. Conclusion

In this study, a signal post processing approach has been suggested and tested on ODTR data signals that have been transmitted through single mode transmission system. The methods proposed to calculate the true average signal loss in the fiber optic communication; the single ended measurement offers a huge advantage in terms of time, logistics, result reliability and processing effort. Numerical simulation shows a noticeable improvement of the system BER after optimization of the suggested processing operation on the detected electrical signals at central wavelengths in the region of 1310 nm. The optimum solution reduces the bit error rate by using RZ signal generator through Electro-Absorption modulation techniques. The operation of optical transmission networks will be most important features in the near future to serve the ever increasing demand of Internet Protocol (IP) networks. However, a lot of research works needs to be carried out to improve the increasing effective data transmission through these systems.

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