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A novel architecture of single-arm duobinary direct modulation format for optical communication

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Recent trend have shown that the growth of internet traffic has accentuated the aggravating lag of access network capacity and most widely deployed broadband solutions are unable to provide enough bandwidth for the emerging services. A new technology is required that is inexpensive, simple, scalable, and capable of handling above mentioned fundamental constraints in high-speed communication systems. The optical duobinary coding is an effective method in high-speed transmission systems to increase the dispersion tolerance, to improve the spectral efficiency, and to reduce the sensitivity of non-linear effects. Therefore, a novel and simple (alternative) duobinary precoder is presented in this paper using standard logic ICs for the configuration of duobinary single-arm direct modulation transmitter. The performance of the proposed single-arm duobinary direct modulation format is evaluated by comparing the bit-error-rate (BER), eye diagram, and Q value with different bit rates. The obtained results show satisfactory performance and good agreement with the simulated results.

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1. Introduction

For the past decades, the long haul communication systems have grabbed lots of researchers' attention where the telecommunication backbone has experienced substantial growth; however, little has changed in the access network. The remarkable growth of internet traffic has emphasized the aggravating lag of access network capacity as reported in [1]. The "last mile" still remains as the bottle-neck between the high-capacity local area networks (LANs) and the backbone network. Currently, the most commonly deployed broadband solutions are digital subscriber line (DSL) and cable modem (CM) networks. Although they are an improvement over 56kbps modems, they are unable to provide enough bandwidth for the emerging services, such as IP telephony, video on demand (VoD), interactive gaming, or two-way video-conferencing. A new technology is required that is capable of delivering bundled voice, data, and video services to an end-user subscriber over a single network.

Thus, in order to get full access to the wide range of services mentioned above; a cost effective full access network opticalization [2][3], so-called, fiber-to-the-home (FTTH) system appears to be the best candidate for the next generation access network. This access network technology is developed rapidly throughout the world. The researcher, Mark Main [2] predicted that there will be more than 9 million of FTTH/FTTP (fiber-to-the-premises) connections in Japan by year 2009-2010. Based on the prediction, the FTTP by household penetration in Hong Kong increased from 27% (in the year 2004) to 34% at the end of year 2009 [2].

Recently, there are several key technologies that have brought the researchers attention to do research on high spectral efficiency, high-capacity routed transport networks [4], and suitable modulation formats for the network system. Modulation formats are used to trade off the noise resilience, fiber propagation characteristics, and resilience to narrowband optical filtering due to multiple passes through OADMs (optical add/drop multiplexer). Therefore, the motivation of this study is to look at the performance of the short haul communication network, especially the access network by using the proposed single-arm duobinary direct modulation format.

Recent studies [5]-[15] also show that the duobinary modulation format is superior compared to other two conventional modulation formats [i.e., RZ (Return-to-Zero) and NRZ (Non-Return-to-Zero)] in long haul communication. The NRZ was the dominant modulation format for the past few decades due to its simplicity and low cost. However, NRZ is not suitable to implement in long-haul communication due to its low dispersion tolerance. In this study, a novel single-arm duobinary modulation format is proposed and investigated to see whether it can replace the NRZ modulation format as the most suitable and cost effective modulation format in the short-haul communication link. The above mentioned modulation format will be constructed and simulated using OptSim™ (optical simulation or in the layman's term, OptSim™ is a high-end optical system simulator developed by ARTIS Software Corporation). The operating wavelength of the fiber is at 1550nm. In summary, this study only concentrates on how to construct the modulation format on physical layer and evaluates the performance of the proposed modulation format.

The organization of this paper is as follows: Section 1 highlights the motivation and scope of this study. Section 2 describes the experimental setup and the methodology employed to conduct the simulation for this study. The performance parameters accounted in this simulation are also discussed here. Section 3 discusses the simulation results and analysis. Finally, Section 4 provides the concluding remarks.

2. Method

In this section, a simple and cost effective technique is demonstrated to generate the single-arm duobinary direct modulation format through the use of VCSEL (Vertical-Cavity Surface-Emitting Laser).

2.1 Proposed duobinary precoder

The proposal of a simple realization of the duobinary precoder is shown in Fig. 1. The functionality of the precoder can be established by connecting an inverter and an AND-gate, followed by a toggle flip-flop (T-FF) and therefore, using standard ICs. No external feedback is required, since the recursion is an integral function of the T-FF. Consequently, this precoder structure using only feed-forward building blocks avoids all problems with implementation and adjustment. Besides, an upgrade to higher bit rates or single-chip integration can be done straightforwardly.

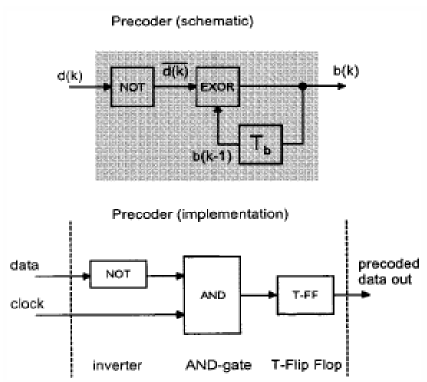


Fig. 1. Simple realization of duobinary precoder.

2.2 Single-arm duobinary direct modulation format setup

The proposed setup shown in Fig. 2 is constructed using the components available in OptSim^{TM} library. The logical components implementation, i.e., NOT gate, AND gate, CLOCK, and T-FF take the same configuration of duobinary precoder as shown in Fig. 1. In this paper, single-arm duobinary precoder is used for the configuration of transmitter with the reduced complexity using standard single-arm Mach–Zender Modulator (MZM) implementation. This single-arm duobinary external modulation is realized using a single duobinary filter, single driver amplifier, and the single-arm MZM with internal push-pull configuration. However, the single-arm duobinary precoder is utilized in this setup to construct a novel single-arm duobinary direct modulation format for the optical transmission system, which implicates the actual innovation in this study.

In the schematic setup for the single-arm duobinary direct modulation format shown in Fig. 2, data source from the pseudo-random bit sequences (PRBS) generator is fetched to the single-arm duobinary precoder. The duobinary signal is then passed through the NRZ driver in order to convert the logical signals into equivalent electrical signals. These signals will pass through the low pass Bessel filter before the signals are used to modulate the VCSEL. The optical signal from VCSEL will couple to the fiber for transmission. The received optical signal will be detected by the photo-detector before sending for further processing.

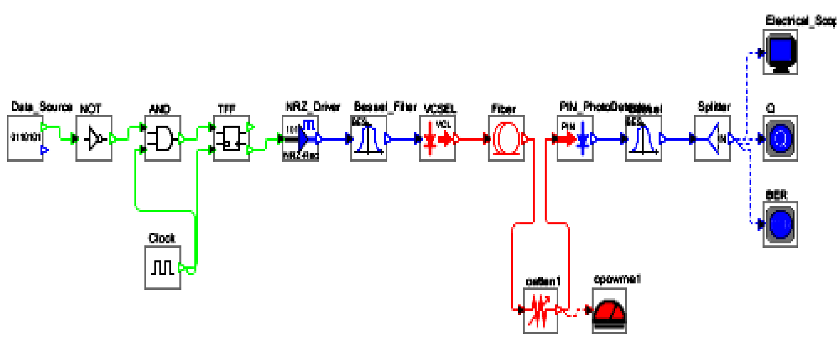


Fig. 2. Schematic setup for single-arm duobinary direct modulation format.

2.3 Modeling

In this paper, the transmitter and receiver parameters are optimized to ensure the realistic simulation in the optical transmission system. For example, the transmission of 1Gbps bit rate of the single-arm duobinary direct modulation format requires different levels of NRZ driver level compared to 2.5Gbps and 5Gbps bit rates for the optimum performance. Moreover, the performance of this single-arm duobinary direct modulation format is monitored by comparing the bit-error-rate (BER), eye diagram, and Q value at the receiver end for different bit rates. One way of comparing the performance is through the analysis of the maximum data rates supported by a regeneration-free transmission distance. The regeneration-free transmission distance is defined as the distance that can be bridged without the need of retransmitting the digital data along the traveling path. This is particularly important for analysis of passive optical network. The target performance is set to BER = 10^{-9} as this value is the typical error rate for the optical fiber telecommunication [5].

2.3.1 System model and parameter

In order to ensure that the single-arm duobinary direct modulation operates at its optimum stage, back-to-back system optimization is performed. During this back-to-back system optimization, fiber is not connected in the system setup. As mentioned, the transmission of 1Gbps bit rate of single-arm duobinary direct modulation format requires different levels of NRZ driver level in comparison with 2.5Gbps and 5Gbps bit rates. Thus, in order to perform optimization, the NRZ driver level is the only parameter that is allowed to be adjusted during the transmission of different bit rates. In other word, a particular NRZ driver level might give the best performance for 1Gbps bit rate; however, if this NRZ driver level is still maintained for the simulation of 2.5Gbps bit rate, it tends to produce the un-satisfying results. This goes true for the simulation of 5Gbps bit rate. Thus, in order to optimize the performance for different bit rates, the level of NRZ driver should be adjusted accordingly to produce a good output.

The back-to-back optimization is done by setting a fixed bit rate, for example, 1Gbps, and the value of NRZ driver level is swept through a range of value. The performance of the system is judged or evaluated by the optimum output of the given values. Thus, through the simulation of different bit rates, i.e., 1Gbps, 2.5Gbps, and 5Gbps, the following Table 1 is obtained.

Table 1.Optimized NRZ driver level for different bit rates.

Bit Rate / Driver level	Low level	High level
1Gbps	0.0005	0.18
2.5Gbps	0.0005	0.09
5Gbps	0.009	0.05

Table 1 shows the different NRZ driver levels for different bit rates for the optimum system performance. Thus, by ensuring the NRZ driver level, the system is designed to operate at the optimum condition.

Other than the NRZ driver levels, which differ for different bit rates, however, the rest of the component parameters of the single-arm duobinary direct modulation format are fixed at different bit rates. Thus, this system is working at wavelength of 1550nm for the laser source VCSEL. Furthermore, for this modulation format, an electrical filter, fifth-order low pass Bessel filter is used with -3 dB bandwidth BW_{TX} of 10GHz at the transmitter and fifth-order low pass Bessel filter is used with -3 dB bandwidth BW_{RX} of 10GHz after the photo-detector. Thus, the optimized value of filters' bandwidth is 10GHz and fifth-order low pass filter is used for both the transmitter and the receiver. To obtain the optimized bandwidth of the transmitter and receiver filter in this single-arm duobinary modulation format optical link, the transmitter and receiver is connected back-to-back with no fiber in between; rather an optical attenuator is inserted between the transmitter and the receiver. By ranging the order of the poles of the Bessel filter, as well as ranging the -3dB bandwidth of the filter, the optimized value can be determined. Besides the transmitter and the receiver filter bandwidth parameters, the 0dBm is chosen as the optical power for the laser source VCSEL, since higher optical power might cause the nonlinearity effect in fiber transmission system. Same optical power is applied in this modulation format for the different transmitted bit rates. The system uses standard single mode fiber (SSMF) as the transmission medium for all the different types of transmitted bit rate. For the fiber components used, the parameters are listed in Table 2 below.

Table 2. Parameters of SSMF and fiber model in OptSim^{TM}.

Type of Fiber	Standard SMF
Attenuation	0.2 dB/km
Zero Dispersion Wavelength	1515.43128 nm
Dispersion Slope at 1550nm	0.10797[ps/nm^2/km]
Dispersion at 1550nm	17 [ps/nm/km]
Reference Frequency	193.4 THz

For the receiver of this single-arm duobinary modulation format, the PIN photo-detector is chosen due to its benefits. The parameters of the PIN photodiode are shown in Table 3.

Table 3. Parameters of PIN Photodiode receiver model in OptSim^{TM}.

Type of Receiver	PIN Photodiode
Reference Wavelength	1550nm
Reference Frequency	193.41449 THz
Quantum Efficiency	0.7
Responsivity (at reference frequency)	0.8751 A/W
Dark Current	0.1 nA

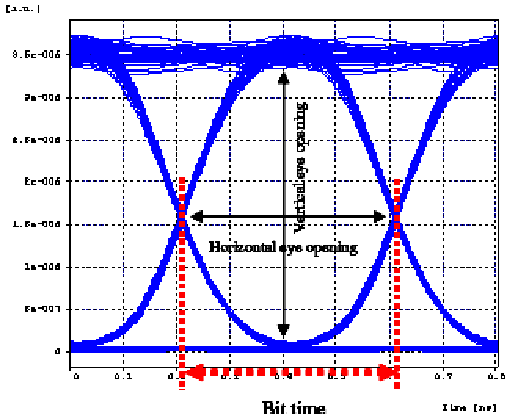
Lastly, measuring equipments i.e., BER estimator, Q estimator, electrical scope, optical power meter, and spectrum analyzer are used to gauge the performance of the proposed system. It can be noted that, there is no involvement of any amplifier or regenerator in the proposed optical system. As such, the proposed system is known as passive optical network, where there are no active components involved in the optical system, such as amplifier, and etc.

2.3.2 Performance parameter

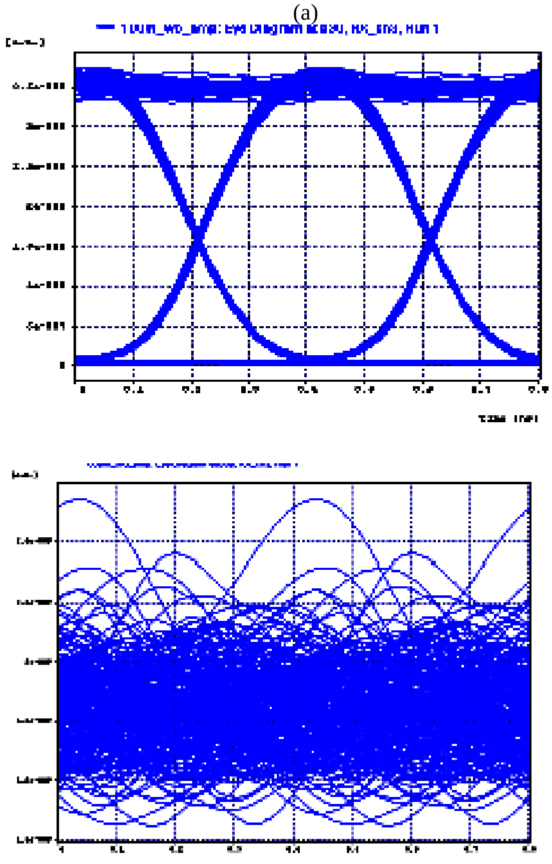
The following parameters are observed at the output of the simulated optical link. i.e., eye diagram, Q factor, and BER.

2.3.2.1 Eye diagram analysis

One popular way to assess the performance of the digital fiber-optic links is to superimpose a series of pulses on an oscilloscope display. This is called eye diagram analysis, because it produces the eye-shaped pattern as shown in Fig. 3 (a). The oscilloscope traces each received pulse on the screen. If there is no noise, each trace would follow exactly the same line, overlaying other pulses.



(a)



(b)

Fig. 3. (a) Eye diagram; (b) Eye diagram of perfectly received signal (up) and severely distorted received signal (down).

The eye diagram measures the repeatability of pulses that reaches the instrument. The better the transmission quality and the more uniform the received pulses, the more the eye will appear. If the eye starts to close, leaving less clear space in the center, it indicates that transmissions are prone to error, because it becomes hard to tell the high points of the signal (the top of the eye) from the low points (the bottom of the eye). With reference to Fig. 3 (a), the eye diagram can be interpreted as follows:

- *The vertical eye-opening*- this indicates the signal's level difference between the bit "1" and "0". If the difference is greater, then the bit "1" and "0" can be distinguished easily. If the eye-opening is small, it indicates, there is signal distortion or the signal is affected by the noise.
- *The horizontal eye-opening*- this measures the jitter in the signal. The jitter is a slightly variation in the digital signal with respect to reference time, which makes the signal diffuse.
- The signal line thickness at the top and bottom of the eye diagram is proportional to the noise and distortion appeared in the receiver output.
- The transitions between the top and bottom of the eye diagram depict the rise and fall of the signal.
- *Size of the opening*- this generally indicates, how easily the signal can be recovered. The larger the size of eye- opening, the easier the signal can be recovered by the receiver. As a result, the observer can see the quality of the received signal by observing the eye diagram.

Fig. 3(b) shows the eye diagram of an electrical signal, a superimposition of an analog signal. The up diagram is the eye diagram of a good quality received signal, whereas the down diagram displays the severely distorted received signal. The units used in the diagram of OptSim^{TM} are arbitrary units (a.u.) for the Y-axis and nanoseconds (ns) for the X-axis.

2.3.2.2 BER estimator

The BER measurements compare the digital input and the output signals to assess what fraction, if the bits are received incorrectly. It offers a quantitative measurement of signal quality [13]. In practice, a data-generator (PRBS) generates a randomized bit pattern, which is transmitted through the system. The total number of bits transmitted are counted and compared with the total number of bits received at the receiver end. The errors occur when the signal bit interpreted by the receiver does not match the transmitted signal. The more wrong bits make the transmission quality worse. A typical target for telecommunication and data transmission is 10^{-12} and 10^{-9} for video or voice transmission. The BER is related to Q factor as follows:

$$BER \approx \frac{1}{2} efrc\left(\frac{Q}{\sqrt{2}}\right) \qquad (1)$$

The above equation (1) is accurate when: (i) no pattern noise is considered, (ii) receiver sensitivity is not very close to the quantum limit where a true Poisson-quantum detection statistic is valid [9 photons/bit], (ii) receiver electrical noise is Gaussian, and (iv) Inter-symbol interference (ISI) is negligible.

2.3.2.3 Q factor

The Q factor is calculated by using the mean values and standard deviations of the signal samples as follows:

$$Q = \frac{m_1 - m_0}{\sigma_1 + \sigma_0} \tag{2}$$

where m_1, m_0, σ_1, and σ_0 are the mean values and standard deviations, respectively of the signal samples when a "1" or a "0" is received. Under the Gaussian approximation, the bit error probability $P(e)$ is given by:

$$P(e) = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{3}$$

3. Results and discussion

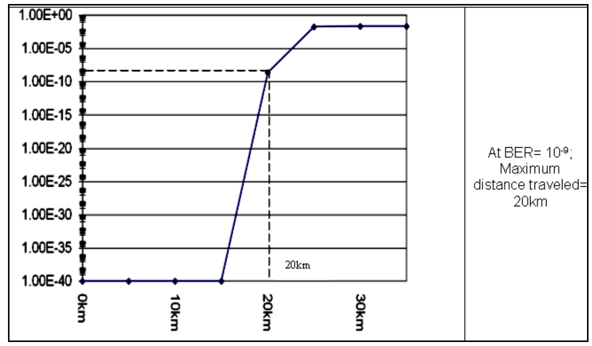
The simulations for single-arm duobinary modulation format optical link are performed with different bit rates of 1Gbps, 2.5Gbps, and 5Gbps of length from 0km to 35km using the iteration method in OptSim^{TM} and are compared using the BER, Q, and eye diagrams to judge the performance of each bit rate used.

3.1 Bit rate of 1Gbps

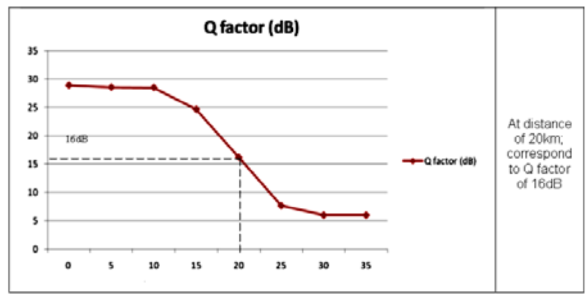
The figure of BER versus distance transmitted for bit rate of 1Gbps for single-arm duobinary modulation format is shown in Fig. 4(a). At the desired BER of 10^{-9}, which is the minimum BER that the system has to achieve, it corresponds to 20km of transmission. The transmitted signal is severely distorted after 20km of distance and it shall not comply to be used in the proposed communication link. The threshold value of BER for all the modulation formats is set to 1×10^{-9} as this BER value is the typical error rate for most of the optical fiber communication systems [5]. As a result, the transmission distance which exceeds the BER limit, is considered unacceptable in the proposed access network system.

The figure of Q factor versus distance traveled is also shown in Fig. 4(b). From the figure of BER versus transmission distance, the maximum achievable distance is 20km. This corresponds to Q factor of 16dB in Fig. 4(b).

The figure of BER versus receiver sensitivity is presented in Fig. 5. From the figure, the obtained minimum receiver sensitivity is -43dBm. The power level that reaches the PIN photodiode lower than -43dBm is not acceptable. Figure 5 is plotted by disconnecting the fiber component and adding an attenuator before the PIN photodiode. The attenuation value of the attenuator is varied accordingly. The attenuation value is iterated for a range of value in the simulation, typically from 20dB to 50dB. Thus, the figure of receiver sensitivity is obtained by plotting the BER versus the received power at the power meter.



(a)



(b)

Fig. 4. For 1Gbps bit rate (a) BER versus distance (km); (b) Q factor (dB) versus distance (km).

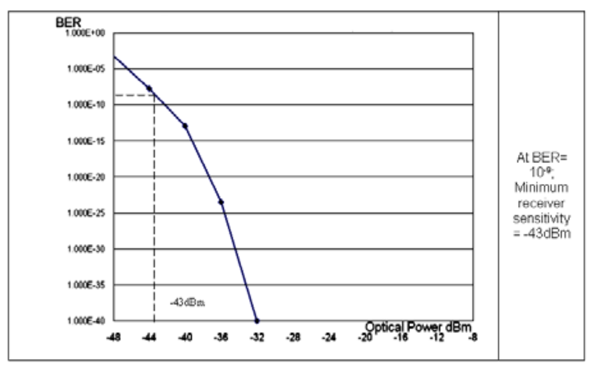


Fig. 5. BER versus receiver power sensitivity (dBm) for 1Gbps.

An iteration of variation wavelength from 1549.5nm to 1550.5nm is also performed with each increment of 0.1nm. The simulation results show that the single-arm duobinary direct modulation format is capable of transmitting in different wavelengths. Since this modulation setup is meant for a particular wavelength, in this case, 1550nm is using as the reference wavelength for transmission. Thus, by varying the transmitted wavelengths through this system, it proves that the proposed method is capable to perform in wavelength division multiplexing (WDM) system. The WDM system is important as this will increase the channel capacity and the cost efficiency of the optical network.

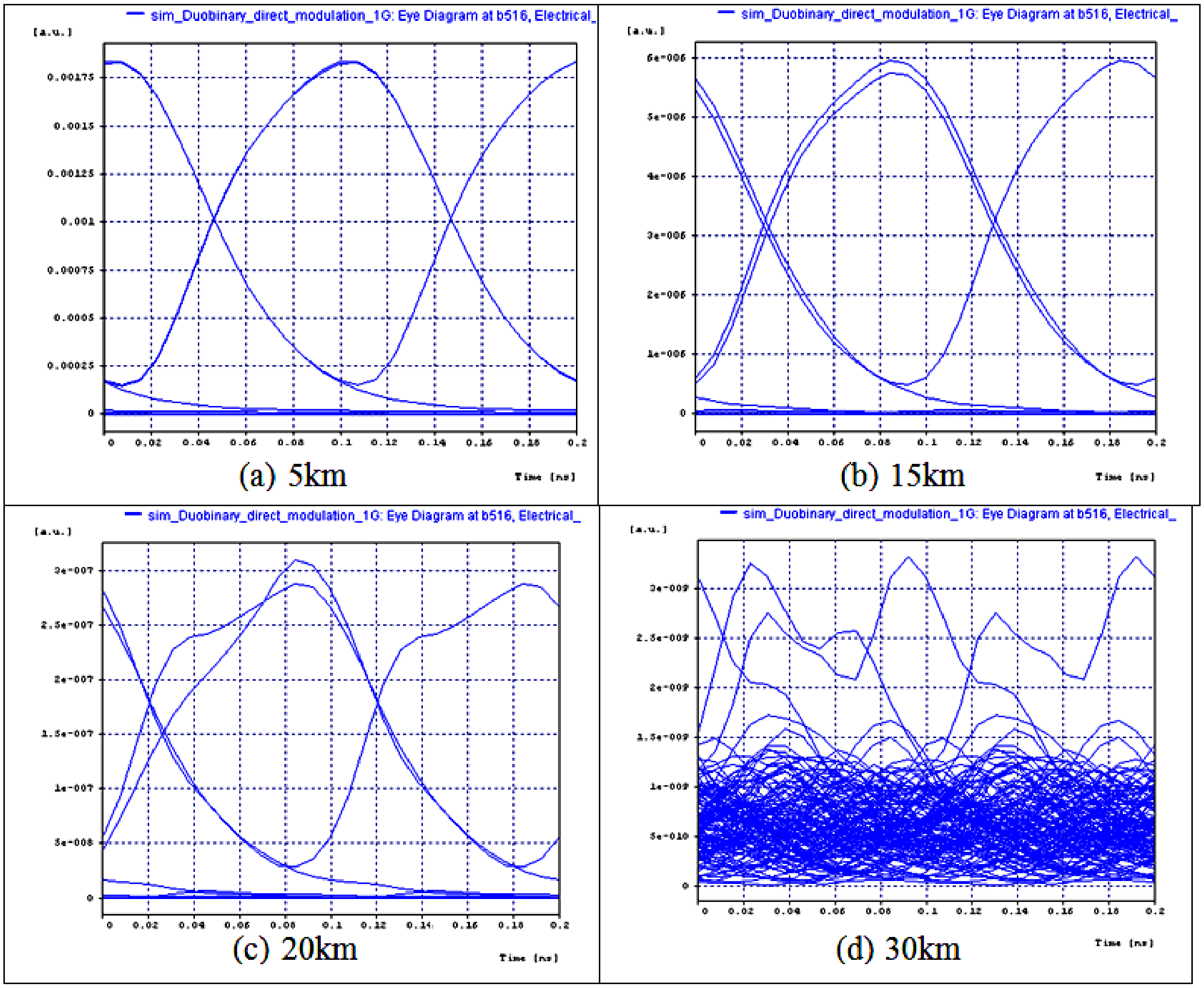


Fig. 6. Eye diagram with 1Gbps bit rate at (a) 5km; (b) 15km; (c) 20km; (d) 30km.

The eye diagram of 1Gbps bit rate single-arm duobinary direct modulation format is shown in Fig. 6. Fig. 6 shows the received signal of the eye diagram of 1Gbps single-arm direct modulation format at 5km, 15km, 20km, and 30km. At 5km and 15km of transmission distance, the eye-opening is wide and easy to distinguish. At 20km, the eye diagram of the single-arm direct modulation format shows indistinct pattern, however, the eye-opening still can be distinguished. At 30km, eye-opening is severely distorted and difficult to be distinguished. Thus, from the eye diagram analysis, the performance of an optical network system can also be justified.

3.2. Bit rates of 2.5Gbps and 5Gbps

The same analysis has been performed on bit rates of 2.5Gbps and 5Gbps single-arm duobinary direct modulation format.

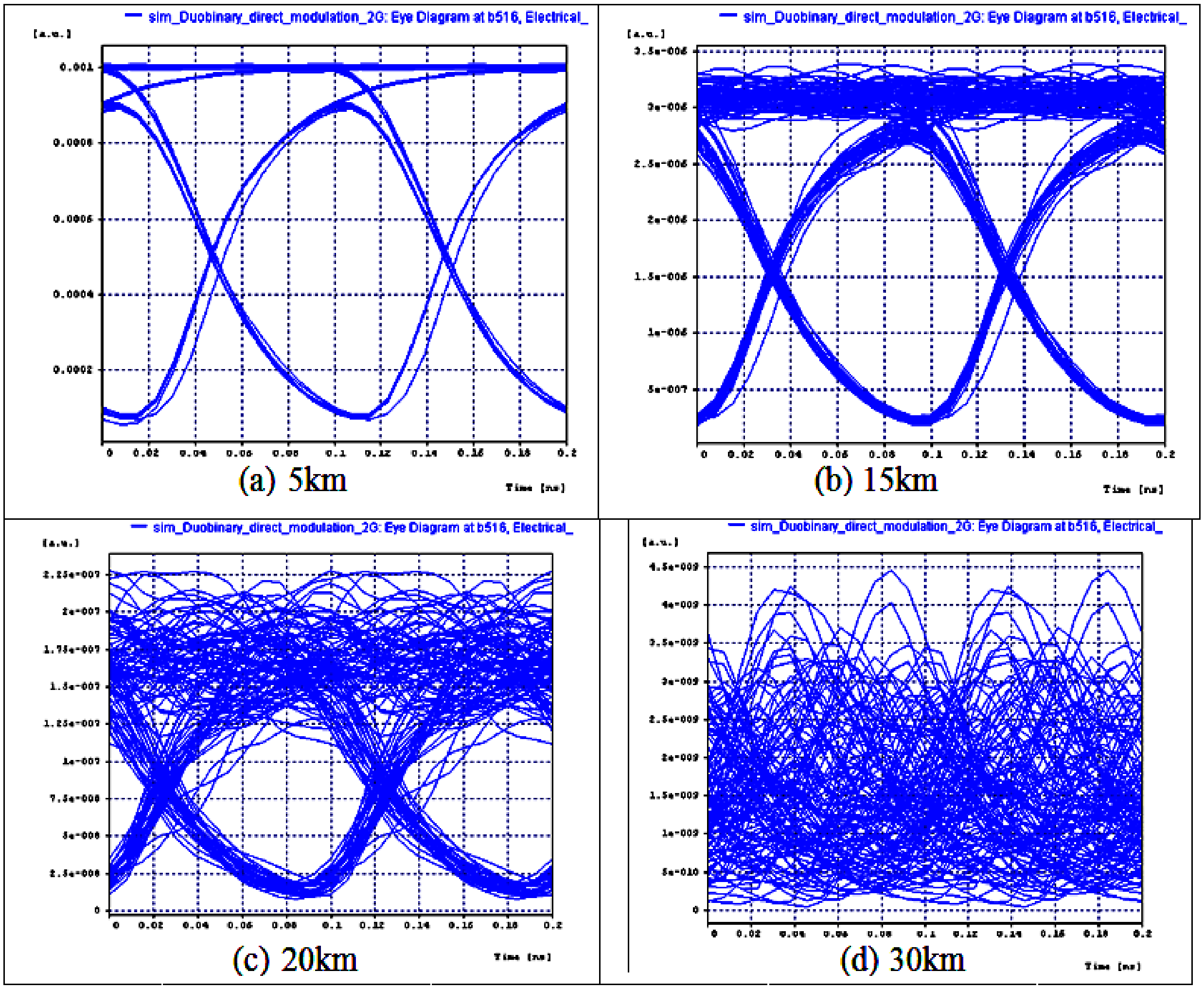


Fig. 7. Eye diagram with 2.5Gbps bit rate at (a) 5km; (b) 15km; (c) 20km; (d) 30km.

Fig. 7 shows the eye diagram of the received signal of 2.5Gbps single-arm direct modulation format at 5km, 15km, 20km, and 30km. At 5km of transmission distance, the eye- opening is wide and easy to distinguish. At 15km, the eye diagram of this single-arm direct modulation format is still clearly depicted; however, noise is noticeable at the upper levels of the eye diagram. At 20km, the eye-opening starts showing indistinct pattern. At 30km, eye- opening is severely distorted and difficult to be distinguished.

Fig. 8 shows the eye diagram of the received signal for 5Gbps single-arm direct modulation format at 5km, 15km, 20km, and 30km. At 5km of transmission distance, the eye- opening is wide and easy to distinguish. At 15km, the eye diagram of this single-arm direct modulation format has severe noise, noticeable at the upper levels of the eye diagram. At 20km and 30km of transmission distance, the eye- opening is severely distorted and difficult to be distinguished.

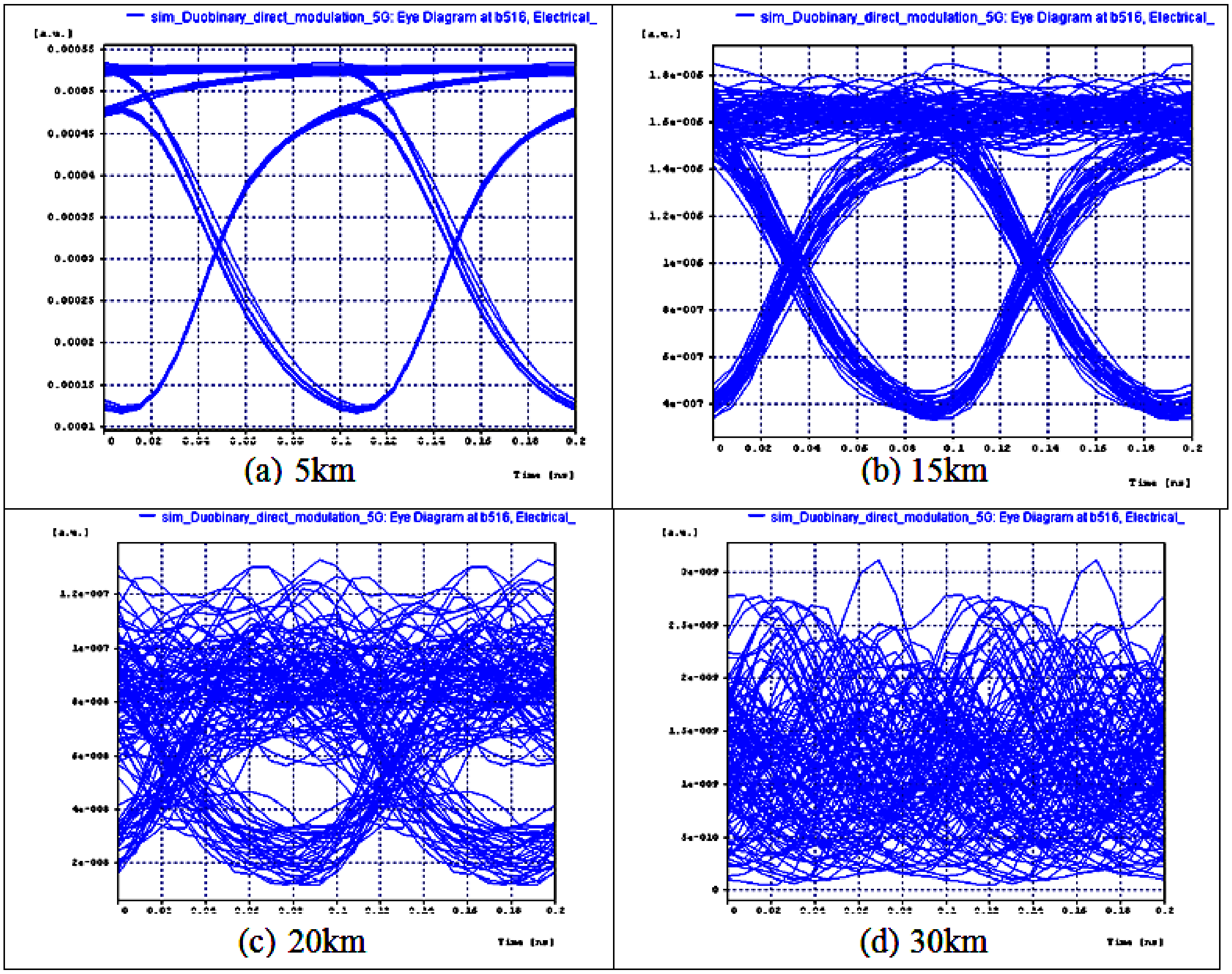


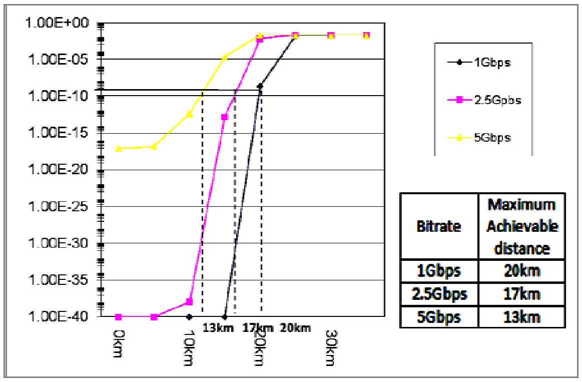
Fig. 8. Eye diagram with 5Gbps bit rate at (a) 5km; (b) 15km; (c) 20km; (d) 30km.

The figure of BER versus distance traveled for bit rates of 2.5Gbps and 5Gbps has been shown in Fig. 9(a). The simulation results of 1Gbps bit rate are included in Fig. 9(a) for the purpose of comparison with 2.5Gbps and 5Gbps. At the desired BER of 10^{-9}, which is the minimum BER that the system has to achieve, it corresponds to 20km of transmission for bit rate of 1Gbps, 17km for 2.5Gbps, and only 13km for 5Gbps. From Fig. 9(a), it can be concluded that, for 1Gbps bit rate, it can achieve the longest transmission distance of up to 20km. In other words, the higher the bit rate used, the shorter the distance that the system is capable to support.

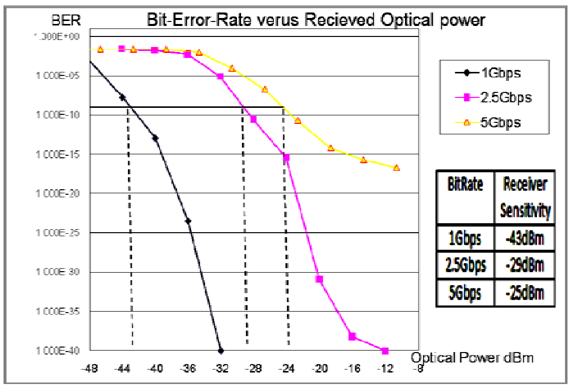
The proposed single-arm duobinary direct modulation format suggests that, the direct modulation technique can be opted with the transmission bit rate of up to 5Gbps to transmit the signal at a distance within 10km.

Besides, to transmit the signal within 20km, the bit rate of 2.5Gbps or 1Gbps can be chosen depending on the signal level that can be supported according to the above analysis.

The diagram of BER versus receiver power sensitivity is also shown in Fig. 9(b) for the bit rates of 1Gbps, 2.5Gbps, and 5Gbps. The receiver power sensitivity for bit rate of 1Gbps is presented here again for the purpose of comparison. It is observed from the figure, the minimum receiver sensitivity is -43dBm for 1Gbps. The figure also shows that the receiver power sensitivity is -29dBm for 2.5Gbps and -25dBm for 5Gbps, respectively. It proves that, at a bit rate of 1Gbps, it achieves better receiver sensitivity values of 14dB and 18dB compared to 2.5Gbps and 5Gbps, respectively. However, the bit rate of 2.5Gbps gives an improvement of only 4dB as compared to 5Gbps.



(a)



(b)

Fig. 9. For bit rates of 1Gbps, 2.5Gbps, and 5Gbps (a) BER versus distance traveled (km); (b) BER versus receiver power sensitivity (dBm).

4. Conclusions

In this paper, a novel architecture of single-arm duobinary direct modulation format is proposed. This study also highlights the selection of the main components of an optical communication system, namely, the optical source, optical fiber, and optical receiver; so as to minimize the cost for the modulation format in such optical communication system. Furthermore, for each of the selected component of the modulation format, the optimization is also performed of the component's parameters in order to produce the best performance for the optical transmission system. The high-end optical system simulator, OptSim^{TM} is used to simulate the proposed optical transmission system and to verify the proposed solution.

The obtained results prove that the proposed single-arm duobinary direct modulation format is capable to perform in WDM system. The obtained results also show that for 1Gbps bit rate, the proposed system yields the longest transmission distance of up to 20km and achieves better receiver sensitivity values of 14dB and 18dB as compared to 2.5Gbps and 5Gbps, respectively. However, the technique presented in this paper and the information obtained from the receiver power sensitivity analysis will benefit the users for future power budgeting while designing an optical communication network.

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