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Secure Duobinary Signal Transmission in Optical Communication Networks for High Performance & Reliability

FARHAN QAMAR[1], MUHAMMAD KHAWAR ISLAM[2], SYED ZAFAR ALI SHAH[3], ROMANA FARHAN[4], MUDASSAR ALI[1]

[1]Department of Telecommunication Engineering, University of Engineering and Technology, Taxila, Taxila 47050, Pakistan
[2]Department of Electrical Engineering, Taibah University, Al Madinah Al Munawarah 41477, Saudi Arabia
[3]Department of Electrical Engineering, Air University, E-9 Islamabad, Pakistan
[4]Department of Computer Engineering, University of Engineering and Technology, Taxila, Taxila 47050, Pakistan

Corresponding author: Farhan Qamar (farhan.qamar@uettaxila.edu.pk)

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ABSTRACT A numerical study is presented in this paper based on semiconductor laser chaos generation which is being used to hide multi-level data signal, i.e., duo-binary message to take the advantage of secure environment & higher data rates at the same time. Duobinary message is generated by using the combination of duobinary precoder, duobinary generator & RZ/NRZ pulse generator. Laser rate equations are used to model chaos generation through semiconductor laser whereas message is made secured by hiding it through chaos masking scheme. Propagation of chaos hiding the multi-format message is studied for long distance communication model. Synchronization between transmitter & receiver is achieved to obtain the acceptable eye-diagrams & quality factor (Q-factor). Q-factor is function of optical signal to noise ratio (OSNR) that gives a qualitative performance of receiver. It provides the minimum SNR to obtain specific bit error rate of signal. A comparison is made with & without deployment of chaos masking scheme on RZ & NRZ duobinary optical system to observe the penalty in terms of Q-factor. In addition, response of amplifier on chaotic signal due to its nonlinearities is investigated by varying the gain of amplifier.

INDEX TERMS Duobinary modulation format, Semi-conductor lasers, Chaos synchronization, Chaos message masking, Optical amplifier, DCF (Dispersion Compensation Fiber), Long haul.

I. INTRODUCTION

Now-a-days, telecom networks are going through various technological changes to support huge data traffic. Newly developed technologies & applications such as internet services, interactive games, telemedicine, large-scale computing, IPTV etc along with existing video and voice services are making traffic enormous day by day. In this situation, the concept of multi-data formats has gained the attention of researchers to efficiently utilize the bandwidth of channel [1].

Duobinary, type of multi-level format, is a proficient optical modulation scheme which is the area of interest due to its increased spectral efficiency. It is being used to increase the channel capacity by improving the bandwidth utilization. Its simplicity of implementation, tolerance to high chromatic dispersion [2] & increased spectral efficiency [3] are some of the attractive features which can be used in long haul communication [4]. Although the concept of using duo-binary modulation scheme in long haul optical communication is already deployed [5]–[7] but the security issues explicit to these formats are still need to be studied in detail. In this paper, we analyzed & addressed the security features for the first time in multi-level format i.e. Duobinary.

Due to some important features of chaotic waveform such as noise-like time domain signal and broad spectrum, chaos communication can be used for secure communication [8]–[15]. An attacker, who can get the modulated chaotic signal, cannot interpret the information without knowing the original chaotic signal produced by the chaotic sources. Many important discoveries are made in recent years in the field of optical chaos generation [16]. Potential sources which are being used to generate chaos includes Semiconductor lasers [17]–[23], Semiconductor ring lasers [24], Erbium doped fiber ring lasers [25], [26], Vertical cavity surface emitting Lasers [27], [28], Random feedback fiber distributed lasers [29], Optoelectronic oscillators [30], [31] etc. Of these chaotic sources semiconductor lasers are most commonly used in the field of secure optical communication when high bandwidth chaos is intended. As multi-level formats are suitable for high data rates so our proposed study gives an idea to ensure the security of multi-level formats by using semiconductor chaotic lasers. Major contributions of this paper are as follow:

1. This is the first time that we combined the advantages of chaos masking & duobinary schemes (multi-level format) to take the advantage of security & high data rate at the same time.
2. Performance comparison of RZ-duobinary & NRZ-duobinary format is done when both are used in chaotic environment.
3. Amplifier response on chaotic signal due to its nonlinearities is investigated by varying the gain of amplifier according to different lengths of optical fiber.
4. Also, a complete step by step approach can be seen in our paper starting from duobinary signal generation, security feature addition, effects of channel & amplifier on chaotic signal & finally the retrieval of original message from chaos.

This paper is arranged in following sections. Section-I comprises introduction of paper. Section-II covers mathematical model, operating parameters & their values. Section-III shows proposed setup for simulations. Results & discussions are included in Section-IV. Finally, paper is concluded in Section-V.

II. MATHEMATICAL MODEL

Three schemes which are used to make signal secure are chaos masking scheme (CMS), chaos shift keying (CSK) & chaos modulation (CM). The performance comparison of these three schemes can be seen in Table 1.

TABLE 1. Performance comparison of message encoding schemes.

Ref.	Properties	CMS	CSK	CM
[32]	Easy Message Recovery	✓		
[33]	Simplicity	✓		
[34]	Noise Immunity			✓
[33]	Low Cost	✓		
[35]	Exact Message Recovery			✓
[36]	Synchronization Required	✓	✓	✓
[36]	Lowest Q-Factor		✓	

As our goal is to design low cost efficient secure system for long haul communication so CMS is chosen among the three. The basic chaotic communication model using CMS is shown in Fig. 1. In this scheme, the message $m(t)$ is simply added to the chaotic waveform $c(t)$ generated by semiconductor laser & then transmitted over channel. The transmitted chaotic waveform is similar to noise signal $n(t)$ which hides message in it. At the receiving side, the original message $m(t)$ is recovered by subtracting chaos produced by the locally

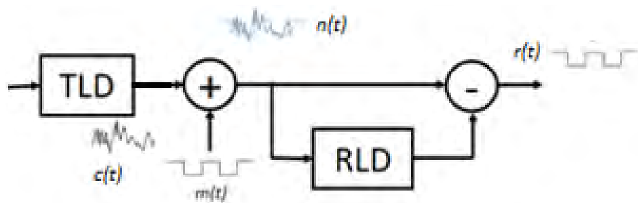


FIGURE 1. Basic CMS communication model.

available chaotic laser. Mathematically this model can be expressed as,

$$n(t) = m(t) + c(t) \tag{1}$$

$$r(t) = n(t) - c(t) \tag{2}$$

$$r(t) = [m(t) + c(t)] - c(t) \tag{3}$$

$$r(t) = m(t) \tag{4}$$

Where, $n(t)$ is transmitted signal and $r(t)$ is received signal.

The essence of secure optical communication by using chaos particularly in CMS lies in the fact that two spatially deployed chaotic lasers must be synchronized with each other [37], [38]. Synchronization of chaotic lasers is the irregular optical pulses evolution of the transmitter side laser that is well reproduced by the receiver side laser in similar fashion. In our study, this task is achieved by closely matching the parameters of these two chaotic lasers. Also, the operating conditions of both the lasers are also kept same for perfect synchronization.

Chaos produced through this model is of pulsating nature which exhibits more chaotic behavior as compared to non-pulsating chaos. The degree of chaos is measured by calculating Lyapunov exponents, which shows greater values towards positive side for the pulsating chaos [39]. As the larger values of Lyapunov exponents (towards positive side) show more instability in system so on this basis we can suggest that the generated chaos is highly unpredictable. Optical chaos generated by semiconductor laser can be represented by following laser rate equations [40]:

$$\frac{dn}{dt} = \frac{J}{ed} - G(n)\,S - \frac{n}{\tau_n} \tag{5}$$

$$\frac{dS}{dt} = G(n)\,S - \frac{S}{\tau_{ph}} + \beta_{sp}\frac{n}{\tau_r} \tag{6}$$

In eq (5), 'n' is the concentration of carrier, 'J' is the injection current density (in active layer it is electric current flowing per unit area), 'e' represents the elementary charge, 'd' is the thickness of active layer. '$G(n)$' defines the mode amplification rate due to stimulated emission & 'τ_n' is carrier lifetime.

Where as in eq (6), 'S' is photon density, 'τ_{ph}' represents photon lifetime, 'β_{sp}' defines coupling factor due to spontaneous emission & 'τ_r' is the radiative recombination lifetime due to the spontaneous emission. Eq (5) can be written as:

$$\frac{dn}{dt} = \frac{d(N/V_a)}{dt} = \frac{1}{V_a}\frac{dN}{dt} \tag{7}$$

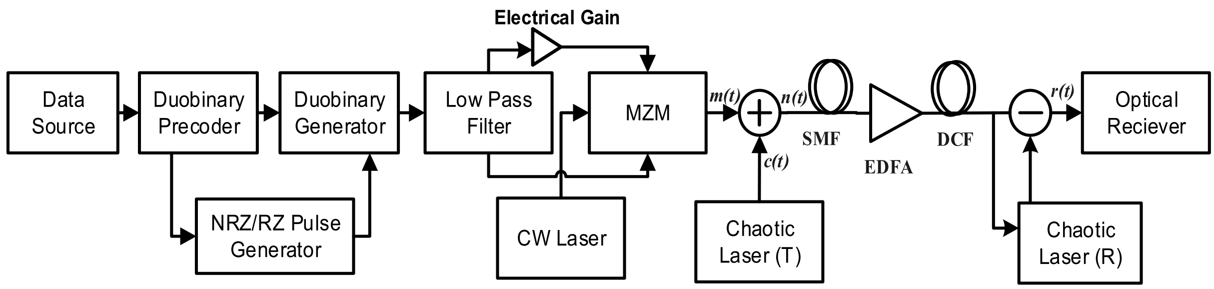


FIGURE 2. Chaotic optical communication model using duobinary format.

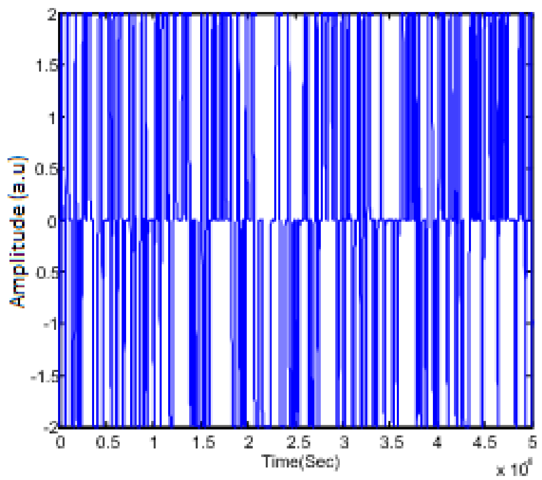


FIGURE 3. Duobinary message with data rate 10GB/s.

Where $n = N/V_a$ and 'N' is the number of carriers in active layer. 'V_a' is the volume of active layer. By solving eq (7)

$$= \frac{1}{V_a}\left[\frac{I}{e} - g(n)\,\Gamma_a N_{ph} - \frac{N}{\tau_n}\right] \tag{8}$$

In eq (8), 'I' is the injection current that is flowing through the active layer. 'N_{ph}' are the number of photons. '$g(n)$' represents the amplification rate due to the stimulated emission in the active layer.

$$= \frac{\mathrm{I}/V_a}{e} - g(n)\,\frac{V_a}{V_m}\frac{N_{ph}}{V_a} - \frac{\mathrm{N}/V_a}{\tau_n} \tag{9}$$

Where, $\Gamma_a = V_a/V_m$.

By solving eq (9)

$$= \frac{J}{ed} - g(n)\,s - \frac{n}{\tau_n} \tag{10}$$

Now, modifying eq (6)

$$\frac{ds}{dt} = \frac{d(N_{ph}/V_m)}{dt} = \frac{1}{V_m}\frac{dN_{ph}}{dt} \tag{11}$$

$$= \frac{1}{V_m}\left[g(n)\,\Gamma_a N_{ph} - \frac{N_{ph}}{\tau_{ph}} + \beta_{sp}\frac{N}{\tau_r}\right] \tag{12}$$

$$= g(n)\,\Gamma_a\frac{N_{ph}}{V_m} - \frac{N_{ph}/V_m}{\tau_{ph}} + \beta_{sp}\frac{N/V_m}{\tau_r} \tag{13}$$

$$= g(n)\,s\Gamma_a - \frac{s}{\tau_{ph}} + \Gamma_a\beta_{sp}\frac{n}{\tau_r} \tag{14}$$

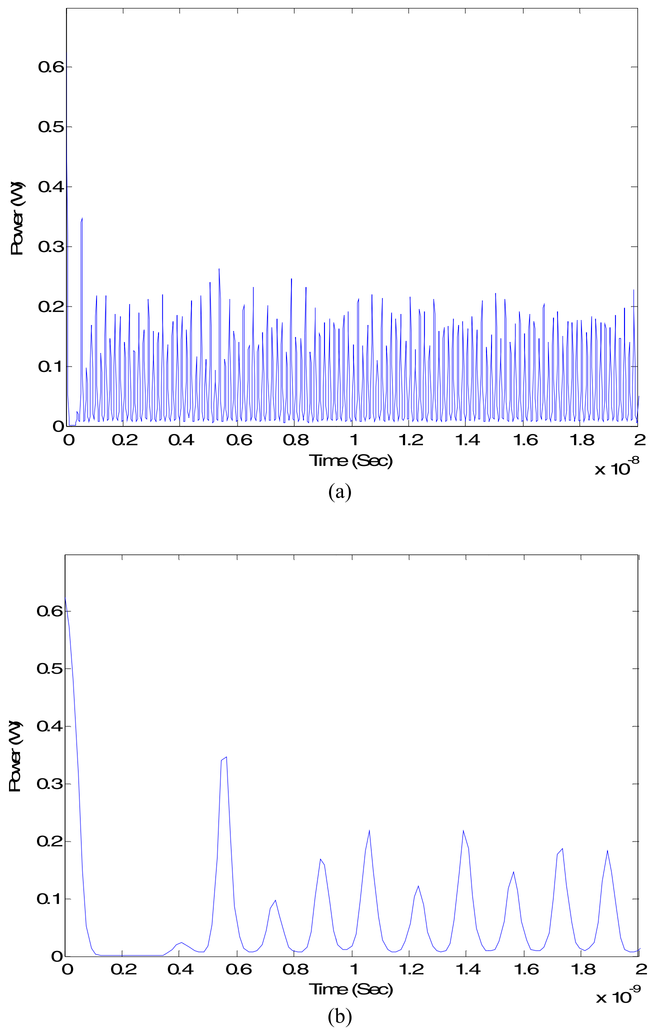
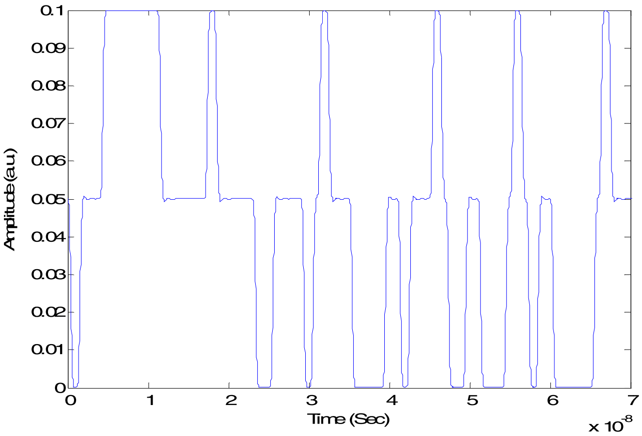


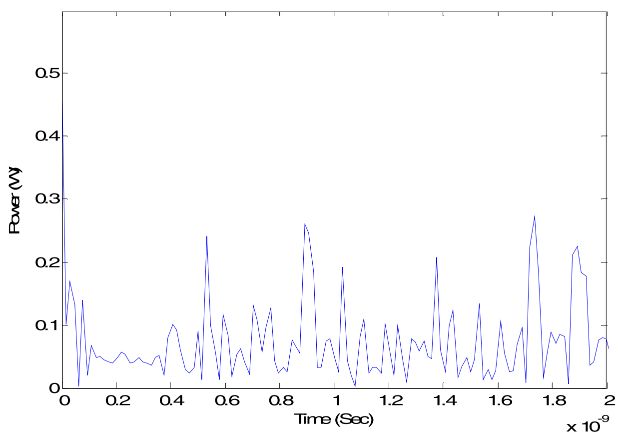
FIGURE 4. (a). Time domain plot of generated chaos. (b). Time domain plot of generated chaos on larger scale.

Eq (10) & Eq (14) are the required solved rate equations for producing chaos through semiconductor lasers. Parameters & their values which are used in this setup to control chaos are given in Table 2 and Table 3 respectively:

Duobinary modulation scheme is actually a combination of two shift keying techniques, amplitude shift keying (ASK) and phase shift keying (PSK) [2]. This scheme can transmit R bits/sec signal data rates using less than R/2 Hz of bandwidth. As the Nyquist theorem suggests that minimum

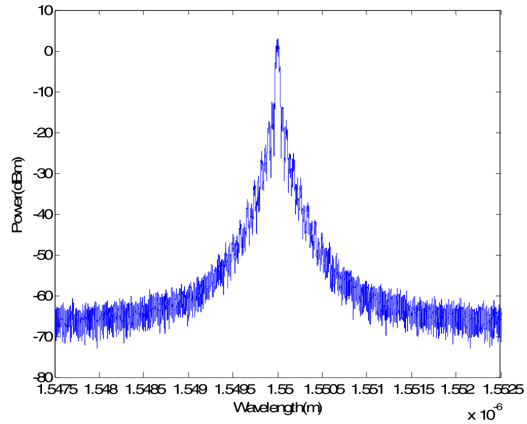


(a)



(b)

FIGURE 5. **(a). Duobinary message generated by transmitter. (b). Chaotic waveform hiding duobinary message.**



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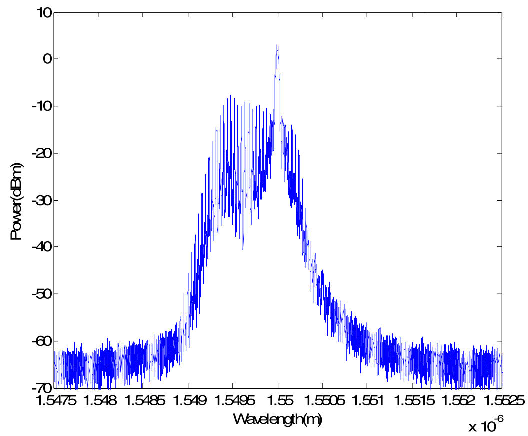


(b)

FIGURE 6. **(a). Optical spectrum of duobinary message. (b). Optical spectrum of chaos embedding duobinary message.**

TABLE 2. **Physical parameters of chaotic laser.**

Symbol	Physical Parameters	Value
N	Carrier density at transparency	$1x10^{18}$
β_{sp}	Fraction of spontaneous emission coupled into the lasing mode	$8x10^{-7}$
Γ_a	Mode confinement factor	0.4
V_a	Active Layer Volume	$1.5x10^{-10}$
τ_{ph}	Photon lifetime	$3x10^{-12}$
τ_n	Electron lifetime	$1x10^{-9}$
Λ	Linewidth Enhancement Factor	5

TABLE 3. **Operating parameters of chaotic laser.**

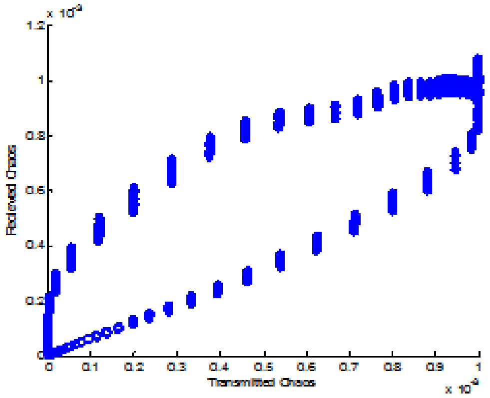
Parameter	Values
Wavelength	1550nm
Power	20dBm
Power at Bias Current	0dbm
Bias Current	30mA
Modulation Peak Current	35mA
Threshold Current	33.45mA
Threshold Power	0.145mW

bandwidth required to transmit R bits/sec is R/2 Hz with no inter-symbol interference (ISI). This shows that duobinary pulses will have the ISI but in such a way that it will be induced in controlled manner to recover the original signal.

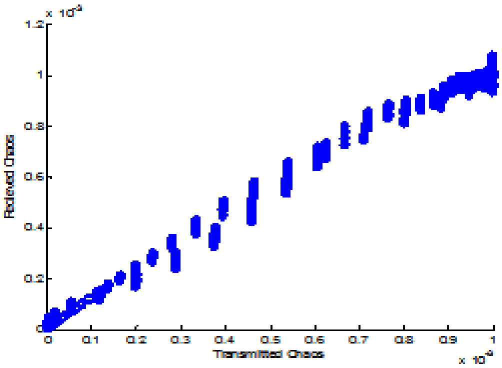
In duobinary modulation scheme the modulator drive signal can be produced by adding one bit delayed data to the present data bit which give rise to three levels i.e 0, 1, and 2. A similar effect can be achieved by using a low-pass filter to the signal having binary values. Optical duobinary modulation is obtained by 100% over-driving a Mach-Zehnder modulator with the duobinary encoded electrical signal. In this way, level 0 and 2 allow 100% transmission with opposite optical phases while level 1 allows 0% transmission. This three- level signal can be demodulated by using an optical direct detection receiver into a binary signal again. The main advantage of this correlative electrical signal encoding is that the duobinary modulated optical signals have narrower bandwidth compared to the binary NRZ modulated signals. As a result, the effect of optical fiber dispersion is reduced and thus will be feasible in long haul or ultra dense wavelength division multiplexing (WDM) systems applications.

Transmitted signal can be represented by the following equation [2].

$$x(t) = \sum_{k=-\infty}^{\infty} d_k q(t - kt), \quad d_k = 0, 1 \tag{15}$$



(a)



(b)

FIGURE 7. **(a). Transmitted vs. received chaos without synchronization. (b). Transmitted vs. received chaos after synchronization & delay matching.**

Where, d_k is data bits, q(t) is transmitted pulse, and (T = 1/R) is bit period

$$q(kT) = \begin{cases} 1 & if\ K = 0, 1 \\ 0 & otherwise \end{cases}$$

Transmitted pulse will be overlapping in time domain due to ISI, narrowing the pulse spectrum.

Now, the duobinary pulse affected by ISI can be written as,

$$x(t) = \sum_{k=-\infty}^{\infty} C_k q(t - kt) \tag{16}$$

III. PROPOSED SCHEME

The proposed scheme for chaos masking of duobinary signal is shown in Fig. 2. Duobinary generator is used to convert data into duobinary pulses coming from data source. Precoder ensures the data integrity by making it error free. Semiconductor chaotic laser is driven into chaotic mode to generate chaos. A semiconductor laser at the receiver end seeded by the transmitted chaos is driven under the same parameters to generate identical chaos for synchronization of transmitter and receiver. The duobinary signal is recovered from chaos through subtraction rule. The link consisting of SMF-28 is varied from 110 to 170 km to investigate the system performance. An erbium doped fiber amplifier (EDFA) with controllable gain and DCF of appropriate length is used for loss management and dispersion compensation of the broadened pulses. Direct detection optical receiver is used at the end to receive the signal. Table 4 shows the operating parameters of our proposed scheme.

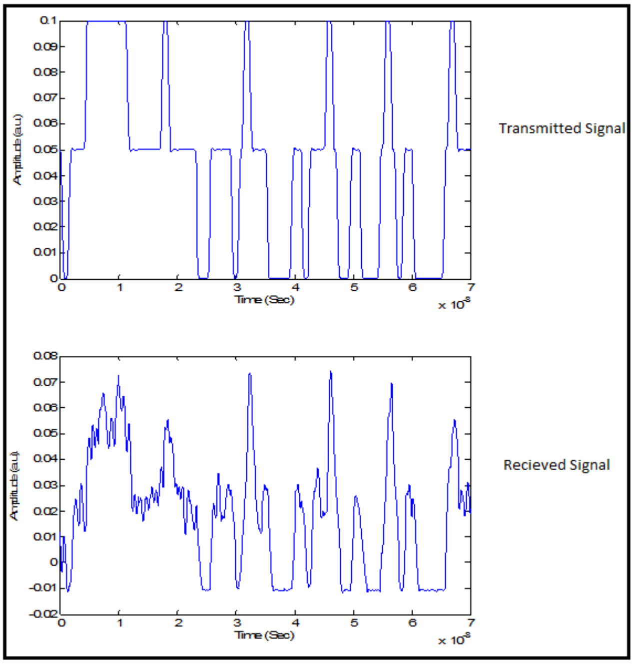


FIGURE 8. **Transmitted signal vs. received Signal.**

TABLE 4. **Operating parameters of duo-binary model.**

Parameters	Value
Data Rate	10Gb/s
Optical Fiber	110Km, 150Km, 170Km
DCF Value	-83.75ps/nm/km
DCF Lengths	22Km, 30Km, 34Km
CW Laser Wavelength	1550nm
CW Laser Power	20dBm
Optical Amplifier Gain	22-34dBm

IV. RESULTS & DISCUSSION

Simulations and analysis are made by using Optisystem 14.0 & MATLAB respectively. First of all, propagation of NRZ-duobinary format is analyzed due to its increased efficiency over RZ. The input NRZ-duobinary coded message at the rate of 10Gb/sec is shown in Fig. 3. This message is 3-level & fed to the modulator in order to convert it to the 2-level optical signal. A continuous wave (CW) laser is used for this purpose whose power is set to 20dBm and which operates at 1550nm.

At the next level this optical signal is mixed with chaotic waveform generated by chaotic laser. The chaotic waveform and their zoomed plots before mixing with duobinary

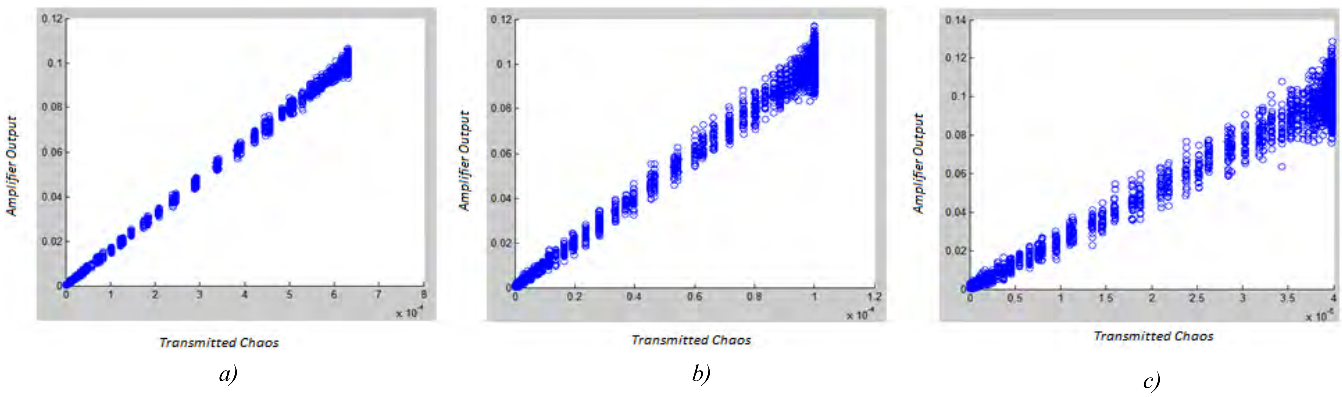


FIGURE 9. Amplifier response on chaotic waveform at different SMF lengths & corresponding gains. a) 22dB. b) 30dB. c) 34dB.

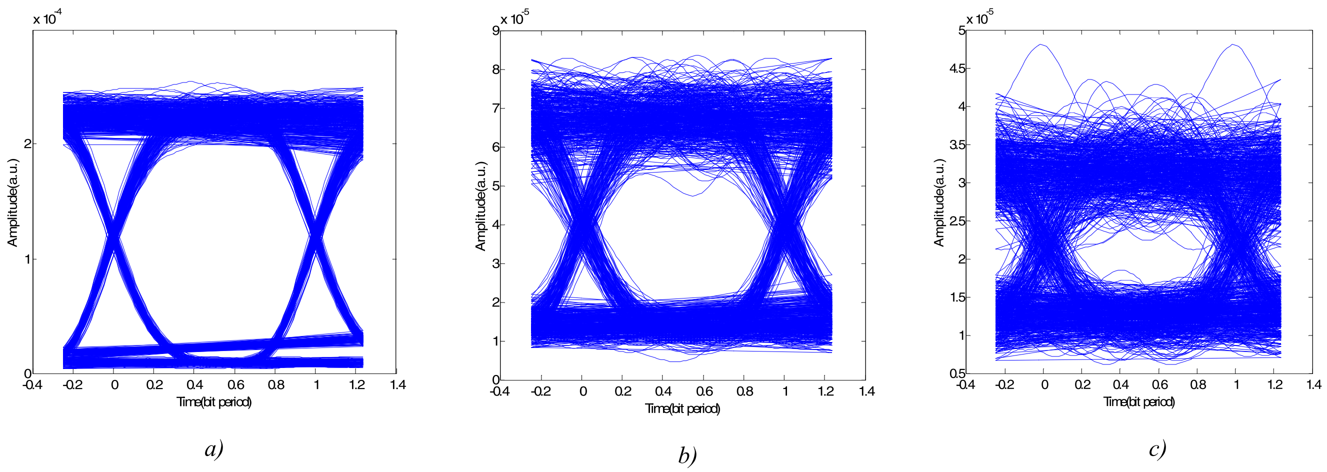


FIGURE 10. Eye-diagram of duobinary signal at different SMF length. a) 110 Km. b) 150 km. c) 170Km.

message can be seen in Fig. 4(a) and Fig. 4(b) respectively. The duobinary message shown in Fig. 5(a) is embedded in chaos through CMS. The power of chaotic laser is also set to 20dBm & it also operates at 1550nm in order to hide the signal completely. The resultant noise-like waveform produced after masking duobinary message with chaotic waveform can be seen in Fig. 5(b).

The effect of introducing security feature in duobinary message using chaos can also be seen by analyzing the optical spectrums of original duobinary message and chaos embedding duobinary message. Fig. 6(a) shows the optical spectrum of duobinary message at the transmitter side before mixing it with chaotic waveform. Fig. 6(b) shows the total change in spectrum due to applied chaos which is not discernible for the intruders.

The transmitted chaos after propagation through the channel gets deteriorated as it is evident from the scatter plot between transmitted and received chaos shown in Fig. 7(a). After adjusting the amplifier gain, insertion of appropriate length of DCF and handling the delay corresponding to link parameters, the improved scatter plot between transmitted and received chaos is shown in Fig. 7(b).

The final message retrieved by the receiver after subtracting chaos can be seen in Fig. 8. Waveform shown in Fig. 8 can be compared with the waveform of original message also shown in Fig. (5a).

Response of amplifier can be seen by taking the scatter-plots between the transmitted chaos through amplifier and its output. The response is plotted for the three different lengths of SMF-28 which are used in our setup i.e 110km, 150km and 170km. The power of laser is set to 20dBm for all the three lengths whereas the gain of amplifier is adjusted according to the length of fiber by taking the standard value of loss as 0.2dB/km. Fig. 9 shows that the increase in gain of amplifier also increases the effect of nonlinearties in amplifier which makes the signal distorted. The reason behind the distortion is that as the amplifier amplifies the optical signal, the amplitude of signal increases which undergoes the Kerr effect resulting in the increase of nonlinearties of the amplifier. The effect of amplifier nonlinearities has been studied in our previous work [41].

The eye-diagrams for different lengths of fiber are depicted in Fig. 10. The eye-opening decreases due to link and amplifier impairments incurred with the increase in fiber length.

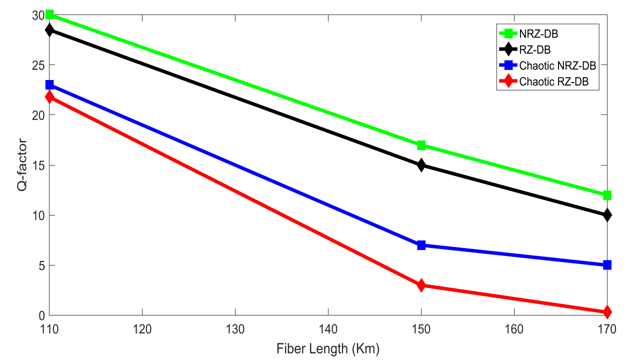


FIGURE 11. Q-factor vs Length of fiber.

The eye-diagram up to fiber length of 110 km shows suitable results at the receiver side as compared to the 150km and 170km lengths of fiber.

The Q-factor as a function of fiber length is shown in Fig. 11. Fig. 11 clearly shows that as the length increases from 110Km, there is drastic decrease in Q-factor. This is because the linear impairments are easily controlled but the non-linear impairments such as amplifier and fiber non-linearities cannot be fully avoided which results in drastic drop of Q-factor with the increase in fiber length. A comparison is also shown in this figure between the NRZ/RZ duobinary systems with & without the deployment of CMS. Results show that CMS resulted in penalty of Q-factor. Also, NRZ-duobinary showed better performance than RZ-duobinary when used in combination with CMS.

V. CONCLUSION

In this paper, we demonstrated the security implementation of multilevel data format by explicitly targeting the duobinary modulation format due to its increased efficiency as compared to simple RZ & NRZ. By implementing our proposed scheme, we have not only taken the benefit of increased throughput of communication system but also made it secured at the same time. Thus, our work gives detailed view of implementation of secure duobinary optical communication system, starting from duobinay message generation till restoration of original message at the receiver side after its transmission over the optical fiber in chaotic waveform which ensures its security & integrity. Duobinary message is added to the chaotic waveform generated by the chaotic laser through message masking scheme due to the simplicity of this scheme. The chaotically masked duobinary signal is transmitted over different SMF lengths i.e.110 km, 150 km and 170 km. An analysis is made for RZ/NRZ-duobinary signal deviation with the link parameters before and after applying CMS. Synchronization is successfully achieved between transmitter & receiver by matching the physical & operating parameters of chaotic lasers at transmitting & receiving side. Dispersion compensation fiber is used to nullify the dispersion effects before synchronizing and subtracting the receiver chaos to recover the duobinary signal. Optical amplifier is used to increase the optical fiber length & effect of amplifier's nonlinearities on chaotic waveform propagation to limit the fiber length, is observed by increasing the gain of amplifier w.r.t fiber length. The future work will include higher order modulation schemes i.e QAM & OFDM with other chaos message encoding schemes to ensure transmission of high data rates in secure environment.

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FARHAN QAMAR received the B.Sc. degree in computer engineering and the M.Sc. degree in telecommunication engineering from the University of Engineering and Technology, Taxila, Pakistan. He was with different sections of Huawei and Mobilink for over seven years. He is currently an Assistant Professor with the Telecom Engineering Department, UET, Taxila, where he is also acting as the Principal Investigator with the Advance Optical Communication Group. His area of interest includes chaos communication, optical networks, 5g networks, advance modulation formats, and radio over fiber.

MUHAMMAD KHAWAR ISLAM received the B.Sc. degree (Hons.) in engineering from AJK University, the Ph.D. and B.Eng.Sci. degrees from the University of New South Wales, Sydney, Australia. He was a Research Fellow with the Optoelectronic Research Centre, City University of Hong Kong. He is currently a Professor with the Faculty of Department of Electrical Engineering, Taibah University, Al Madinah Al Munawarah, Saudi Arabia. He was on trapping solitons in fiber Bragg gratings and secure optical communication-based on chaotic fiber lasers. He has co-authored over 60 publications in reputed Journals and peer-reviewed conferences. His research interests include solitons, chaos, high-speed optical communication systems and networks, secure optical communication systems, optical amplifiers, fiber lasers and antenna.

SYED ZAFAR ALI SHAH received the Ph.D. degree from the University of Engineering and Technology, Taxila, Paksitan. He has also involved on neural networks-based pattern recognition besides. He is currently an Assistant Professor with the Faculty of Department of Electrical Engineering, Airs University, Pakistan. His area of research is Optical Chaos Generation and Control. He has done publications on fiber laser chaos generation, enhancement, propagation, and DWDM chaos issues.

ROMANA FARHAN received the B.Sc Eng. and M.Sc. Eng. degrees in computer engineering from the University of Engineering and Technology (UET), Taxila, Pakistan, in 2008 and 2011, respectively. She is currently pursuing the Ph.D. degree with the Department of Computer Engineering, UET, Taxila, Pakistan. Her research interests include network and system security with focus on wireless security.

MUDASSAR ALI received the B.S. degree in computer engineering and the M.S. degree in telecom engineering, in 2006 and 2010, respectively, and the Ph.D. degree from the School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Pakistan, in 2017. University of Engineering and Technology, Taxila, Pakistan, with a major in wireless communication. From 2006 to 2007, he was a Network Performance Engineer with Mobilink (An Orascom Telecom Company). From 2008 to 2012, he was a Senior Engineer Radio Access Network Optimization with Zong (A China Mobile Company). Since 2012, he is currently an Assistant Professor with the Telecom Engineering Department, University of Engineering and Technology, Taxila, Pakistan. His research interests include 5G wireless systems, heterogeneous networks, interference coordination, and energy efficiency in 5G green heterogeneous networks.