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Design and Implementation of Chaos Based ROF in LTE Networks

Nimra Asif [1], Farhan Qamar [2], Adil-Masood Siddiqui [3]

[1] Dept. of Electrical Telecom Engineering, University of Engineering and Technology, Taxila, Pakistan, Email: nimraasif51@gmail.com
[2,3] Dept. of Electrical Telecom Engineering, University of engineering and Technology, Taxila, Pakistan, Email: farhanqamar@mcs.edu.pk, dradil@mcs.edu.pk

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Abstract

Now a day, to meet the exponentially increasing demands of high data rate & sufficient bandwidth to access broadband services, the ROF (Radio over Fiber Technology) provides a remarkable solution, which deliberately integrates the RF communication technology with the advanced Optical fiber network. Various advanced modulation schemes such as DPSK, CPFSK, O-QPSK, Q-CPFSK, and SCM are adopted in ROF technology to accomplish the demand of high data rate with integration to Optical network. Our study is described in three sections in this paper: I. First section describes introduction to ROF technology, its worldwide advantages such as high-power, high-quality signals, high mobility, low maintenance cost and its various applications II. Second section covers the implementation of Chaos in ROF technology to induce the enhanced security and secrecy within the system III. Third section is based upon simulation results to evaluate best modulation scheme giving better Q-factor & minimum BER for improved system performance

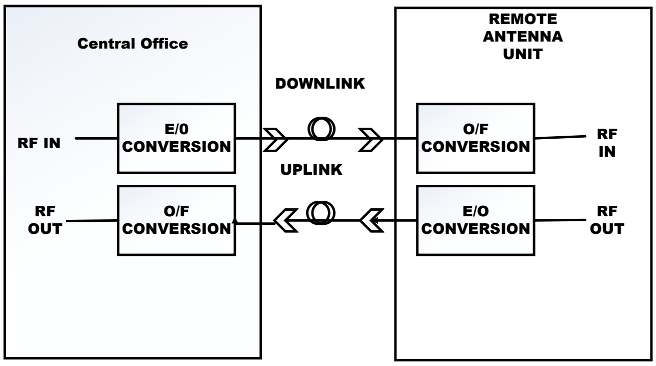
Keywords: High Coverage Area, Broadband Network, Optical Fiber, Centralized Resource Management, Chaotic Masking, Coherent Detection, Dynamic Resource Allocation

Introduction:

During some past decades, the communication network has experienced a significant rise in the number of users worldwide & ultimately also demand of high data rate has also increased. Moreover, high coverage area accommodation & connectivity has also become an essential requirement for a successful communication industry. Hence to meet this explosive demand of high capacity in broadband network, there is a need of an evolved system architecture deployment with reduced cost. Rof is one of those evolved networks, in which high data carrying a radio signal with high frequency is imposed on a light signal to distribute over optical fiber link [1]. Radio over fiber makes use of the optical fiber to distribute the Radio frequency signal [2], hence Radio over fiber is preferred over previous networks in many aspects; low cost, low complexity in structure, future proof reliability, low attenuation, high immunity to interferance, low power consumption, centralized resource management etc. [3].

ROF employing Advance Modulation techniques:

In order to fulfill high data rate transmission demand, ROF technology entails the use of advance modulation techniques; Duo-binary modulation schemes, SCM ASK, PAM, FSK, PSK, DPSK and CPFSK, OOK etc. Among of these, we have employed SCM ASK scheme in this paper in order to evaluate the performance of basic ROF communication system.



Chaotic Security Implementation:

Although SCM ASK has already been implemented but there were some security issues regarding user data signals that are essentially required to be addressed in detail. Hence, in this paper we will implement some security techniques like Chaotic masking to transmit Radio signal with high protection from unauthorized access so that no one can interpret the information coded signal without authority of sender & receiver. A chaotic signal is sensitive to initial conditions & has a random noise like time series, so it is very hard to be detected & intercepted by unauthorized access [4]. The chaotic signal is a function of variation in the intensity of a laser diode frequency. To implement the chaotic technique, two chaotic oscillators are required: one at transmitter while at receiver side. These oscillators add the original modulated message signal onto the chaotic signal by a mathematical function. The message bits are masked in the chaotic signal & can be intercepted by receiver only if both transmitter & receiver are properly synchronized & receiver knows the chaotic signal [5]. Potential sources being utilized to produce chaotic signals Includes Vertical cavity surface emitting Lasers [6],[7] Erbium doped fiber ring lasers [8],[9] Semiconductor lasers [10]-[16], Semiconductor ring lasers [17], Optoelectronic oscillators [18],[19], Random feedback fiber distributed lasers [20]. Among these chaotic sources semiconductor lasers are the most generally utilized as a part of the field of secure optical correspondence where high speed and larger bandwidth chaos is proposed

Chaos Applications:

Since chaotic signals are noise like & considerably aperiodic signals with infinite number of states, hence chaotic waveforms find its wide applications in military as well as physical layer security (PLS) paradigms in Cryptography [21] for secure communication from unauthorized access & to improve the secrecy performance of communication system because of low probability of interception. Chaos has also significant implications in medical field. ECG in Cardiography, HRV & medical Image Cryptography all involves chaos theory in order to diagnose diseases at initial stages & to observe current health condition of patients[22]. Since chaotic signals have large bandwidth,so it provides high range resolution which is desirable for Radar. Hence, some main applications of chaos are Chaotic Signals Radar & UBW Imaging radars[23] because of its aperiodic & deterministic properties. Moreover, chaotic signals are noise like having good auto correlation & cross-correlation, hence can also be used in anti-jamming purposes. Since as particularly, they are noise like hence it is very difficult for hackers to detect & jam the transmitted signals [24].

SCM ASK scheme implementation in Radio over Fiber:

In order to use bandwidth of optical fiber more efficiently and meet demand of high speed long haul optical transmission, we will implement subcarrier multiplexing scheme (SCM) employing ASK technique in this paper. Optical SCM is a multiplexing technique in which multiple baseband signals are optically modulated to high frequency carriers and then are multiplexed together in RF domain forming a composite Radio Frequency signal which is ultimately modulated to LASER optical signal for transmission on optical fiber [25]. SCM scheme is more modified and efficient variant of WDM technique because of simpler and low-cost implementation because the stability of RF oscillators and frequency selectivity of microwave filters are comparatively more efficient than that of their optical counterparts. Hence microwave devices are comparatively more advanced than the optical ones[26]. Moreover coherent detection for RF oscillator is easier than optical coherent detection because of low phase noise of RF oscillators.

Applications:

SCM scheme finds its vast applications significantly in monitoring of many optical parameters such achromatic dispersion and optical signal to noise ratio (OSNR) [27].

Another application of SCM is in bidirectional broadband distribution systems in which SCM provides facility of transmitting multiple subscribers from a single laser. Thus, SCM reduces the cost of overall system by sharing of lasers and optical fibers among the subscribers. Other applications of SCM are in CATV and interactive multiuser LAN's where it enables the bandwidth of each source to remain constant even in case of increasing number of nodes [18].

The transmission system of ROF is classified into two parts; this partition depends upon frequency range of radio signal which is to be transported:

1. RF over fiber (radio frequency over fiber)
2. IF over fiber (intermediate frequency over fiber)

In first architecture high frequency RF signal is used for modulating light before being sent over optical fiber link. In second architecture low frequency IF signal is used for modulating light before being sent over optical link [29]

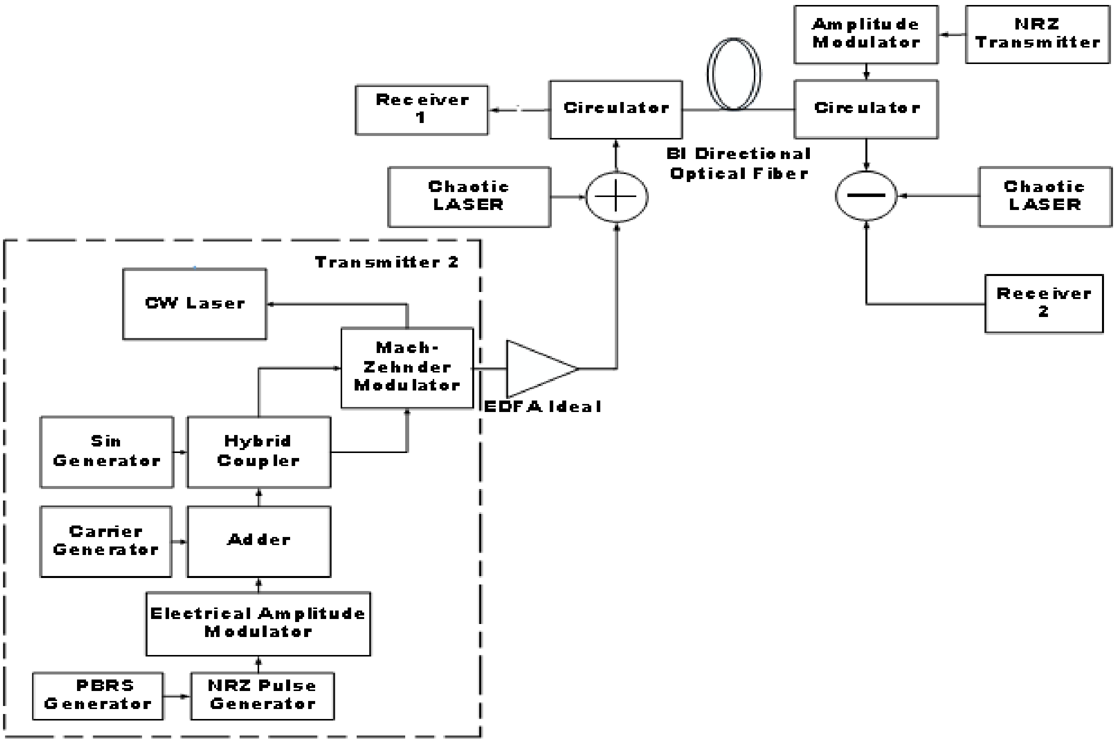
ROF Applications:

There are numerous utilizations of RoF innovation comprise of satellite correspondences, portable radio interchanges, broadband access, versatile broadband framework and remote LAN. The specialized utilizations of RoF are orthogonal frequency Division Multiplexing (OFDM), Wavelength Division Multiplexing (WDM). The WDM application is effectively converged with the diverse uses of remote framework [30]. Advantages of RoF are Low Attenuation, substantial bandwidth, diminished power consumption and dynamic resource allocation. ROF can be used in cellular network as it is used in millimeter wave and overall system price is reduced. ROF can be used to distribute wireless LANs operating at frequency Gigahertz frequency using OFDM scheme. ROF is used to increase modulation scheme, and it overcome the limitations of wireless like phase modulation, chromatic dispersion and attenuation. ROF is also implemented in satellite media. ROF also finds wide applications in LTE networks such as implementation of network architecture in different scenarios; ROF transport for provision of wireless services from a central station to multiple Base stations. ROF also provides 4G services to end subscribers by interconnection of multiple base stations enabling the last mile access and also in femto cell networks [31]

Chaos masking Model:

In order to secure the signal three techniques are used:

- Chaos masking
- Chaos shift keying
- Chaos modulation
- The comparison between performance of these three schemes can be observed in Table 1



Receiver side:

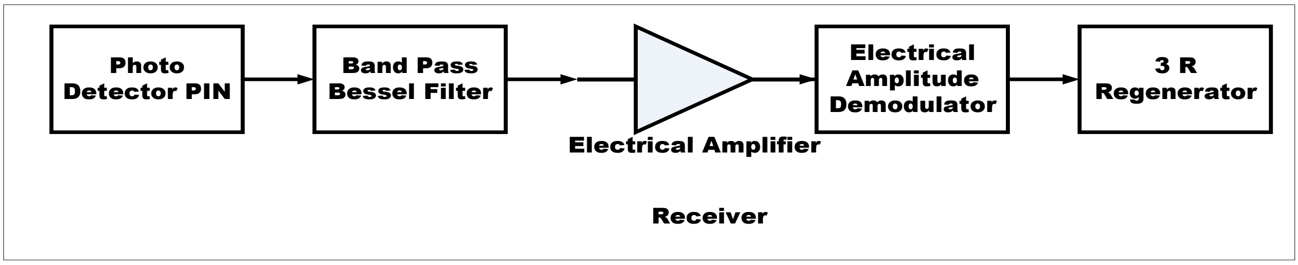


Table 1: Performance comparison of message signal encoding techniques

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		✓	

Since we have to design highly secure long haul ROF communication system with efficiency of reduced cost and low complexity in structure, hence we have chosen CMS among these schemes. The basic chaos masking communication model can be seen in Fig.2.In this technique, the chaotic signal is simply generated by the chaotic laser and the original message signal is added to it which is transmitted over the transmission channel. On the receiver side, the message signal is decoded by simply subtracting the chaos from the received signal.

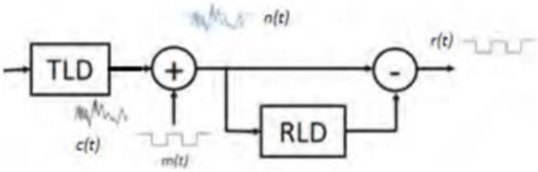


Figure.2. Basic Chaotic masking communication model

This model can be mathematically expressed in following equation:

$$n(t) = m(t) + c(t) \qquad (1)$$

$$r(t) = n(t) - c(t) \qquad (2)$$

$$r(t) = [m(t) + c(t)] - c(t) \qquad (3)$$

$$r(t) = m(t) \qquad (4)$$

where n(t) and r(t) denote the transmitted signal and received signal respectively. The core of a secure optical communication system using CMS scheme is enclosed in a fact that two chaotic lasers are separately deployed and essentially be synchronized with each other [32],[33]. The synchronization of chaotic lasers is basically the evolution of transmitted optical pulses produced by chaotic laser on transmitter side that are regenerated by chaotic laser on receiver side. Moreover, both lasers operation conditions and parameters are also kept same in order to enable perfect synchronization [34]. The chaos generated by this model has a pulsating nature which depicts comparatively more chaotic behavior than non-pulsating chaos. The degree of chaos can be measured from calculation of Lyapunov exponents, which shows larger values for positive side of pulsating chaos [35] depicting instability of system for positive side of chaos, therefore we propose that produced chaos is highly un-detectable. The optical produced chaos can be expressed in laser rate equations [36] given below:

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

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

In eq [5], where “n” denotes carrier concentration, “J” represents injection current density, “e” is elementary charge, “d” represents active layer thickness, G(n) denotes mode amplification rate on account of stimulated emission while “$\mathrm{г}_n$” is lifetime period of carrier. While in second eq [6], there is “S” which represents photon density, “$\mathrm{г}_{ph}$” lifetime period of photon, “β_{sp}” is coupling factor because of spontaneous emission & “$\mathrm{г}_r$” represents lifetime period of radiative recombination.

Eq [5] can also be expressed as:

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

In eq [7], $n=N/N_a$, N represents number of active layer carriers and “V_a” defines volume of active layer

Eq [7] can be modified to form following solution:

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

Where “I” denotes active layer injection current, “N_{ph}” represents number of photons while g(n) defines amplification rate because of stimulated emission in the active region.

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

In eq [9], $r_a = V_a/V_m$.
Eq [9] can be solved and modified into following equation:

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

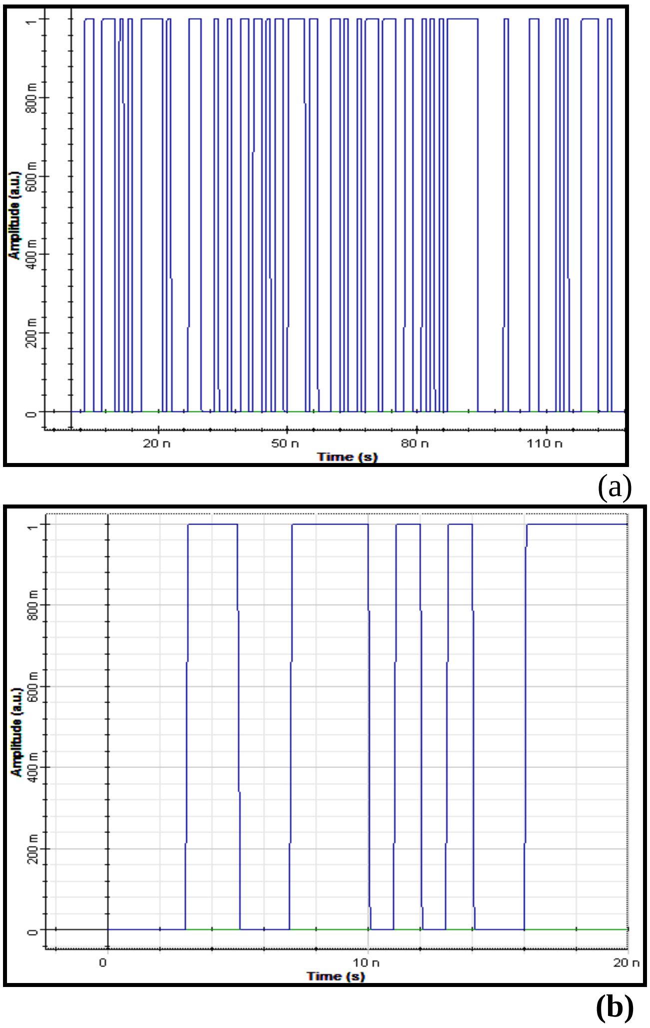


Figure.3.(a) Time domain plot of Original message signal.
(b) Time domain plot of message signal on larger scale

Eq[6] can be re-written and modified as follows:

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

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

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

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

Eq[10] and Eq[14] are required rate equations for generating chaos by using semiconductor lasers.

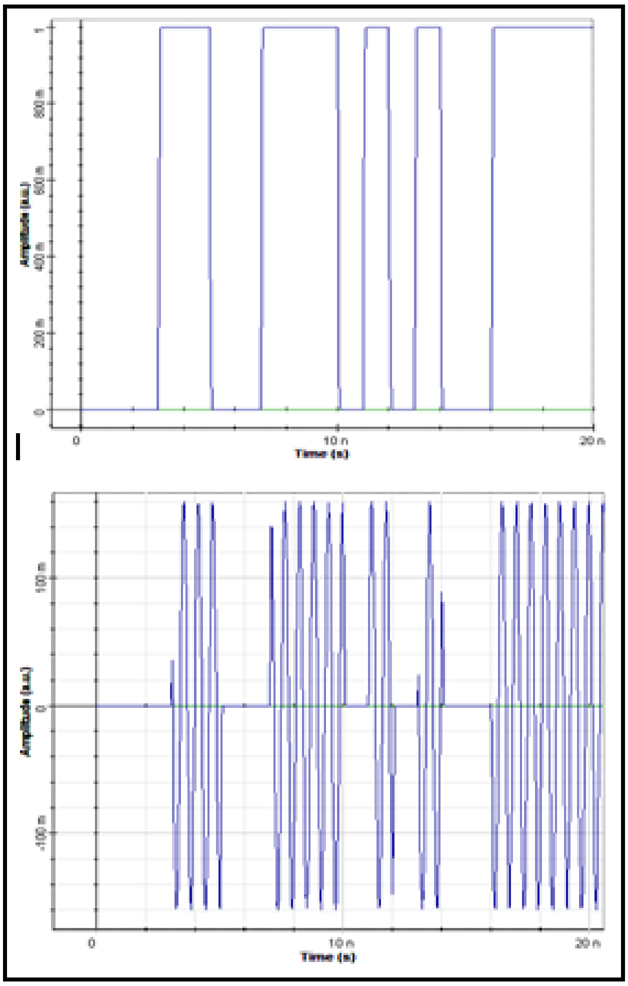


Figure.4. Original Message signal vs. ASK modulated signal

Different parameters and their corresponding values which are used to control chaos in this model are presented in Table 2 and 3.

Table.2. Physical parameters of Chaotic laser

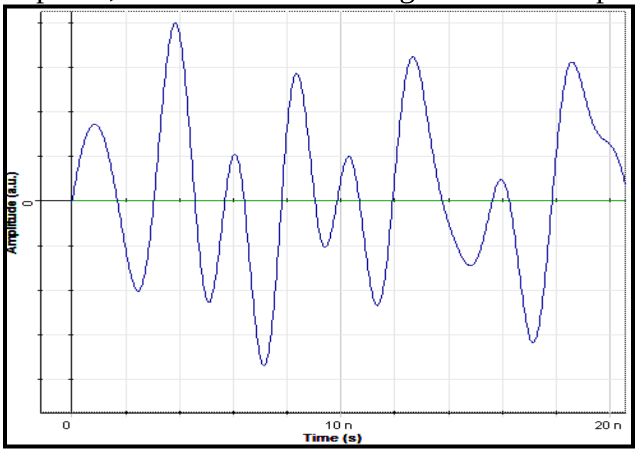
Symbol	Physical Parameters	Value
N	Carrier density at transparency	$1x10^{18}$
β_{sp}	Fraction of spontaneous emission coupled into the lasing mode	$8x10^{-7}$
Γ_a	Mode confinement factor	0.4
V_a	Active Layer Volume	$1.5x10^{-10}$
τ_{ph}	Photon lifetime	$3x10^{-12}$
τ_n	Electron lifetime	$1x10^{-9}$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

Table.3. Operating parameters chaotic laser

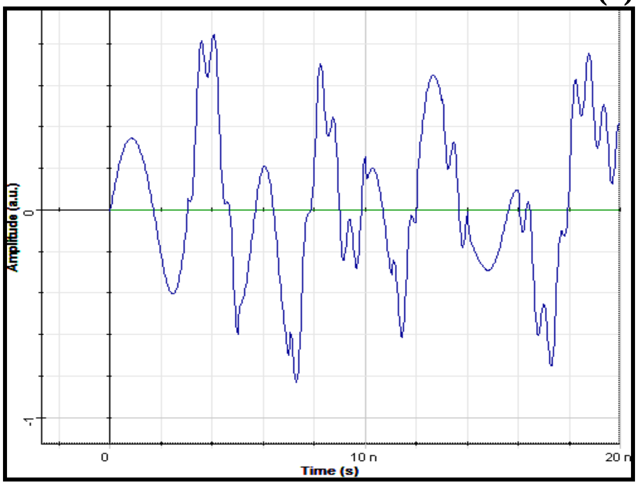
Parameter	Values
Wavelength	1550nm
Power	20dBm
Power at Bias Current	0dbm
Bias Current	30mA
Modulation Peak Current	35mA
Threshold Current	33.45mA
Threshold Power	0.145mW

Results and Discussions

The simulation setup for the proposed ROF SCM ASK network model has been shown in fig.1. This system has been designed and simulated by using simulation software; Opti system version7.0. This system has been modeled for duplex communication, so there is one transmitter and one receiver section on both sides of optical fiber. One the transmitter side, the data is generated by pseudo random bit sequence generator up to bitrate of 1Gbps to be transmitted to destination. This bit stream is fed to NRZ pulse generator to generate a proper signal waveform to be transmitted in analog form on communication medium, which is shown in Fig.3. There are two modulators being used in our model; first is electrical modulator to bring the signal into RF domain and the other is main optical modulator to transmit RF signals from one wavelength optical signal [37]. This baseband message signal is firstly modulated to a broadband signal up to 1.7Gigahertz using AM modulator to generate RF signal, as shown in Fig.4. and then is combined with multiple sub carriers of distinct frequencies generated by Carrier generator with frequency 49.35 MHz and frequency spacing between subcarriers up to 6MHz and thus an ultimate composite RF signal is generated.Fig.5(a). shows the subcarrier signal and Fig.5(b) shows the signal after mixing of message signal with subcarrier. The generated RF subcarriers are in turn multiplexed by 90^0 hybrid couplers [38] to be mismatched in phase, which aids in reducing chromatic dispersion of signal during optical transmission.



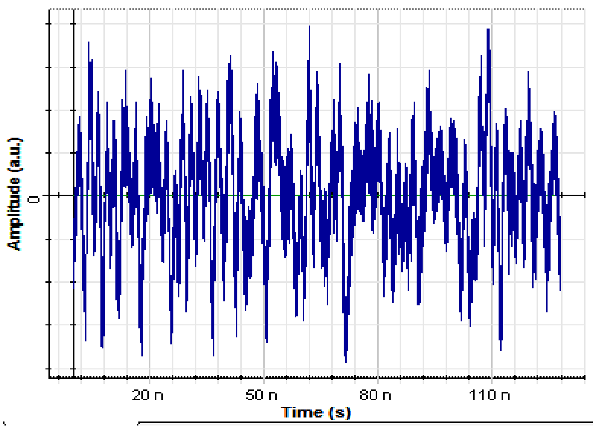
(a)



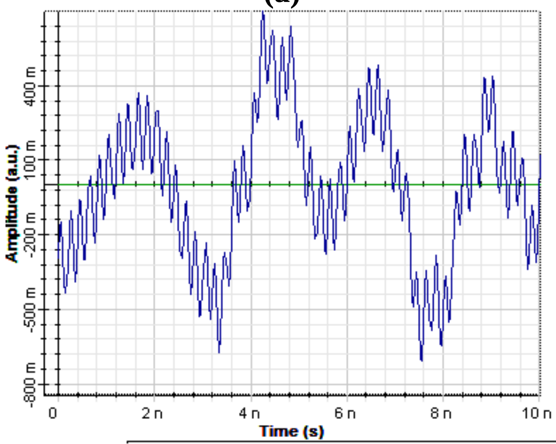
(b)

Figure.5. (a) SCM carrier signal (b) Message added to the SCM signal

The hybrid coupler suppresses one sidebands of optical double side bands of the electrical signal in order to utilize bandwidth more efficiently[39]. This composite signal is applied to the LiNB Mach zehnder modulator which converts from electrical to optical signal using CW laser of central frequency 193.1 THz and 6 dBm power to be transmitted on optical fiber. Hence, ROF signal and their zoomed time domain plot before chaotic masking can be seen in Fig.6(a) and Fig.6(b) respectively.



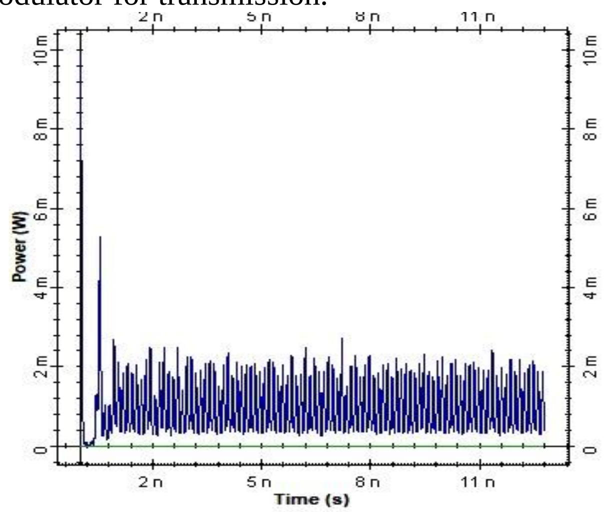
(a)



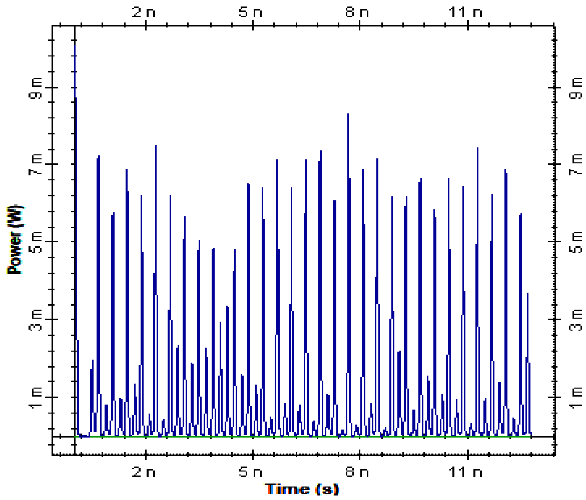
(b)

Figure.6. (a) ASK/SCM Radio over Fiber message signal with data rate 1 Gb/s. (b)ASK/SCM ROF signal produced by transmitter on larger scale

At the next level, chaotic masking is implemented on ROF signal by adding chaotic signal generated by Chaotic Laser to it by using an optical adder and ultimately a chaotic ROF signal is generated. This Chaotic ROF signal and its larger scale time domain plot is shown in Fig.7(a) and Fig.7(b) respectively. Since, we have already mentioned that this model have been designed for bidirectional duplex communication, so there is also a receiver along with a transmitter on each side of optical fiber and any signal transmitted from the transmitter side has two destination points to deliver the signals. Hence, in order to render two-way communication for any receiver, optical signal is applied to the optical Circulator which either directs the signal to receiver on same side of transmitter or transmits it to the Bidirectional optical fiber of length 10 km. Optical delay is also introduced in optical fiber to reduce interference between two optical signals in opposite directions. On the Receiver side, there is also a transmitter along with receiver. Optical circulator provides optical signal either to transmitter or receiver. But before this provision, at first chaos is removed from the received using an optical subtractor to which chaos generated by receiving side Chaotic Laser of same frequency and then this optical ROF signal is transmitted to either photodetector or Reflective filter. For transmitter, optical circulator provides optical signal to optical Reflective bidirectional filter so that it can receive the transmitted bandwidth signal in optical format and optical modulated signal is generated directly using AM modulator for transmission.



(a)



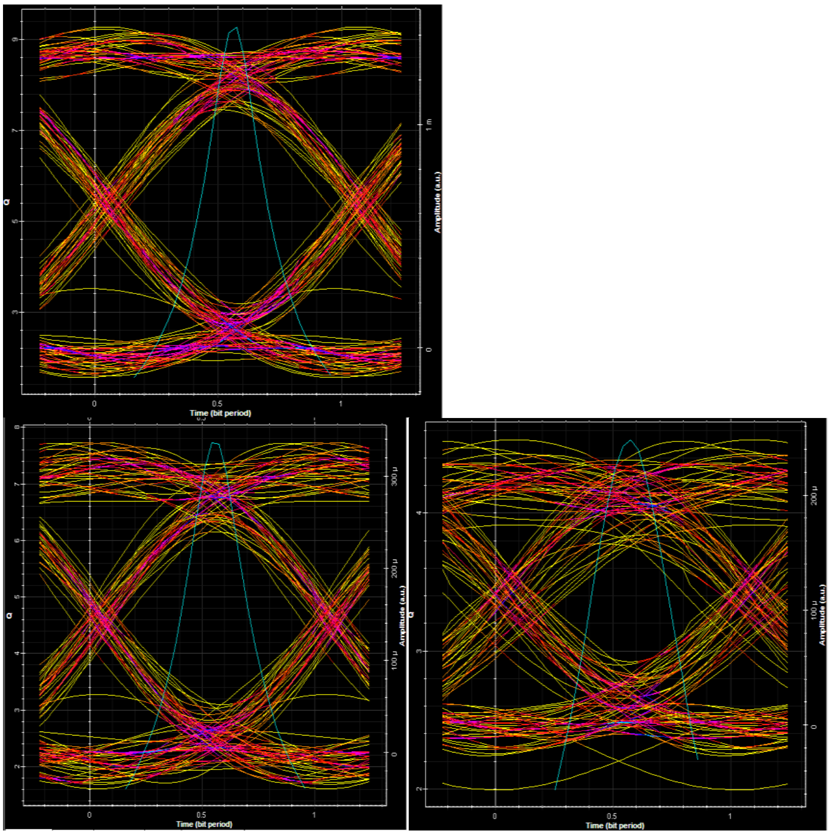
(b)

Fig.7. (a) Generated Chaos hiding the message signal (b) Chaos masked signal on large scale

For receiver section, optical signal from circulator is applied to Photodetector PIN diode with high responsibility to correctly detect and generate electrical signal from optical one. The recovered electrical RF signal is given to two different filters: Low pass and Band pass filter. Low pass filter with cut off frequency 0.7 GHz is used to receive the original transmitted signal removing high frequency noise components from it, while Band pass filter with central frequency 1.7 GHz recovers the original RF signal. It is provided to Electrical Amplifier with high gain of 15 dB to amplify and in turn is passed through AM demodulator of the same central frequency as AM modulator to correctly generate the transmitted message signal.3R Generator recovers the original waveform of transmitted message signal and is observed through BER analyzer. The eye diagram results for different lengths of SMF can be observed in Fig.8(a), Fig8(b) and Fig(c) respectively. The opening of eye diagram decreases due to effect of optical fiber impairments on signal while passing through it. Similarly, the basic receiver block is also on transmitter side to recover the transmitted signal. Different parameters with their values used in this model for optimized performance are given in Table.4.

Table.4. SCM ROF model operation parameters

Parameters	**Values**
Bitrate	1 x 10^9 bps
No subcarrier channels	78
Channel spacing	6 MHz
AM modulator frequency	1.7 GHz
LiNB Mach- Zehnder modulator extinction ratio	30 Db
CW Laser frequency	193.1 THz, 6dBm
Fiber Length	10 km
Photodiode Responsitivity	1.2 A/W



(a) **(b)** **(c)**

Fig.8. Eye diagram results for different lengths of optical fiber
(a) 10 km (b) 30 km (c) 50 km

Conclusion

In this paper, we have designed basic Radio over fiber communication model and also demonstrated the security implementation techniques using ASK modulation formats, in order to avoid interference. Beside these, in order to transform message signal to Radio Frequency signal we have implemented Subcarrier multiplexing by which multiple high frequency signals are added to the message signal and a composite RF signal is formed. Later, this RF signal is modulated to optical laser signal in order to render it compatible for transmission over optical fiber. Our main achievement from this project is to gain enhanced security benefit from the ROF model by implementation of chaos masking in which message signal is hided in a random undetermined chaotic signal and cannot be intercepted or decoded by un-authorized persons. The combined implementation of SCM and ASK schemes in our project has ensured the efficient provision of high data rate and large bandwidth. The performance of ASK/SCK RoF model have been analyzed and evaluated using the worldwide simulator Optisystem 7.0. The results have been already discussed which shows that increasing the fiber length and the number of carriers impose significant impacts on RF signal, which can be clearly observed through eye diagrams

References

[1] Joseph, Arun, and Shanthi Prince. "Performance analysis and optimization of radio over fiber link." *Communications and Signal Processing (ICCSP), 2014 International Conference on*. IEEE, 2014.

[2] Zin, A. M., et al. "An overview of radio-over fiber network technology." *Photonics (ICP), 2010 International Conference on*. IEEE, 2010.

[3] Singh, Gurprakash, and Arokiaswami Alphones."OFDM modulation study for a radio-over-fiber system for wireless LAN (IEEE 802.11 a)." *Information, Communications and Signal Processing, 2003 and Fourth Pacific Rim Conference on Multimedia.*

Proceedings of the 2003 Joint Conference of the Fourth International Conference on. Vol. 3. IEEE, 2003.

[4] Ditto, William, and Toshinori Munakata. "Principles and applications of chaotic systems." *Communications of the ACM*38.11 (1995): 96-102.

[5] Kharel, Rupak. *Design and implementation of secure chaotic communication systems*. Diss. Northumbria University, 2011.

[6] S. Xiang et al., ‘‘Conceal time-delay signature of chaotic verticalcavity surface-emitting lasers by variable-polarization optical feedback,’’ Opt. Commun., vol. 284, no. 24, pp. 5758–5765, Dec. 2011.

[7] S. Priyadarshi, Y. Hong, I. Pierce, and K. A. Shore, ‘‘Experimental investigations of time-delay signature concealment in chaotic external cavity VCSELs subject to variable optical polarization angle of feedback,’’ IEEE J. Sel. Topics Quantum Electron., vol. 19, no. 4, Jul./Aug. 2013, Art. no. 1700707.

[8] S.Zafar, M.K. Islam, and M.Zafrullah, ‘‘Effect Of parametric variation generation and enhancement of chaos in erbium-doped fiber-ring lasers,’’ Opt. Eng., vol. 49, no. 10p. 105002, 2010.

[9] S. Zafar, M. K. Islam, and M. Zafrullah, ‘‘Generation of higher degree chaos by controlling harmonics of the modulating signal in EDFRL,’’ Optik-Int. J. Light Electron Opt., vol. 122, no. 21, pp. 1903–1909, 2011

[10] M. Sciamanna and K. A. Shore, ‘‘Physics and applications of laser diode chaos,’’ Nature Photon., vol. 9, no. 3, pp. 151–162, Feb. 2015

[11] M. C. Soriano, J. García-Ojalvo, C. Laudio, R. Mirasso, and I. Fischer, ‘‘Complex photonics: Dynamics and applications of delaycoupled semiconductors lasers,’’ Rev. Mod. Phys., vol. 85, no. 1, pp. 421–470, Mar. 2013.

[12] V. Annovazzi-Lodi, G. Aromataris, and M. Benedetti, ‘‘Multi-user private transmission with chaotic lasers,’’ IEEE J. Quantum Electron., vol. 48, no. 8, pp. 1095–1101, Aug. 2012.

[13] N. Jiang et al., ‘‘Chaos synchronization and communication in mutually coupled semiconductor lasers driven by a third laser,’’ J. Lightw. Technol., vol. 28, no. 13, pp. 1978–1986, Jul. 1, 2010.

[14] Reidler, Y. Aviad, M. Rosenbluh, and I. Kanter, ‘‘Ultrahighspeed random number generation based on a chaotic semiconductor laser,’’ Phys. Rev. Lett., vol. 103, no. 2, pp. 024102-1–024102-4, Jul. 2009.

[15] Uchida et al., ‘‘Fast physical random bit generation with chaotic semiconductor lasers,’’ Nature Photon., vol. 2, no. 12, pp. 728–732, 2008.

[16] Argyris, D. Syvridis, L. Larger, and V. Annovazzi-Lodi, ‘‘Chaos-based communications at high bit rates using commercial fibre-optic links,’’ Nature, vol. 438, pp. 343–346, Sep. 2005.

[17] R.M. Nguimdo .Verschaffelt, J.Danckaert, and G.vander Sande,‘‘Loss of time-delay signature in chaotic semiconductor ring lasers,’’ Opt. Lett., vol. 37, no. 13, pp. 2541–2543, Jul. 2012.

[18] R. Lavrov, M. Peil, M. Jacquot, L. Larger, V. Udaltsov, and J. Dudley, ‘‘Electro-optic delay oscillator with nonlocal nonlinearity: Optical phase dynamics, chaos, and synchronization,’’ Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top., vol. 80, no. 2, p. 026207, Aug. 2009.

[19] K. E. Callan, L. Illing, Z. Gao, D. J. Gauthier, and E. Schöll, ‘‘Broadband chaos generated by an optoelectronicoscillator, ’’Phys.Rev.Lett.,vol.104, no. 11, p. 11390, Mar.2010

[20] W. Zhang et al., ‘‘Random distributed feedback fiber laserbased on combination of er-doped fiber and single-mode fiber,’’IEEE J. Sel. Topics Quantum Electron., vol. 21, no. 1, Jan/Feb. 2015, Art. no. 0900406.

[21] Liu, Bo, et al. "Physical layer security in CO-OFDM transmission system using chaotic scrambling." *Optics Communications* 291 (2013): 79-86.

[22] Wang, Meng-Hui, and Zong-Yi Lee. "Application of extension method and chaos theory in ECG identity recognition system." *Industrial Informatics (INDIN), 2016 IEEE 14th International Conference on*. IEEE,

[23] Corron, Ned J., and Jonathan N. Blakely. "Chaos for communication and radar." *Proc. NOLTA*. Vol. 322. 2011.

[24] Van Nguyen, Binh, et al. "A Brief Overview on Chaotic Communication Systems and Their Applications in Military Environments (2016): 545-546.

[25] Wolcott, T., and Heide Thelander. "Subcarrier Multiplexing: More than Just Capacity." *Light wave Magazine* (2001)

[26] Hui, Rongqing, et al. "Subcarrier multiplexing for high-speed optical transmission." *Journal of lightwave technology* 20.3 (2002): 417.

[27] Liu, Ning, et al. "New transmitter configuration for subcarrier multiplexed DPSK systems and its applications to chromatic dispersion monitoring." *Optics Express* 15.3 (2007): 839-844.

[28] Darcie, Thomas E. "Subcarrier multiplexing for lightwave networks and video distribution systems." *IEEE Journal on selected areas in Communications* 8.7 (1990): 1240-1248.

[29] Reddy, Vimala, and Lochan Jolly. "Radio over Fiber (RoF) Technology and Integration of Microwave and Optical Network for Wireless Access." *International Conference and Workshop on Emerging Trends in Technology (ICWET), Malaysia*. 2015.

[30] R. Karthikeyan and Dr. S. Prakasam, “A Survey on Radio over Fiber (RoF) for Wireless Broadband Access Technologies”, International Journal of Computer Applications (0975-8887), Volume 64, No. 12, February 2013.

[31] Llorente, Roberto, Maria Morant, and Javier Martí. "Radio-over-Fibre Networks for 4G." *Fourth-Generation Wireless Networks: Applications and Innovations*. IGI Global, 2010. 268-291.

[32] Revathi, S., and G. Aarthi. "Performance analysis of Wave Length Division and Sub Carrier Multiplexing using different modulation techniques." *International Journal of Engineering Research and Applications (IJERA)* 1.2 (2014): 317-320.

[33] Sharma, Vivek Ruder, and Meenakshi Sharma. "Design and analysis of SCM-RoF system deploying VCSEL." *Signal Processing and Integrated Networks (SPIN), 2015 2nd International Conference on*. IEEE, 2015.

[34] Coelho, Diogo Vieira Nogueira, et al. "Studies of different modulation techniques in the integration of SCM optical communication system." *Silicon Photonics and Photonic Integrated Circuits*. Vol. 6996. International Society for Optics and Photonics, 2008.

[35] K. Kusumoto and J. Ohtsubo, ‘‘1.5-GHz message transmission based on synchronization of chaos is semiconductor lasers,’’ *Opt. Lett.*, vol. 27, no. 12, pp.989991, 2002.

[36] Donati, Silvano, and Claudio R. Mirass "Introduction to the feature section on optical chaos and applications to cryptography." *IEEE Journal of Quantum Electronics* 38.9 (2002): 1138-1140

[37] Qamar, Farhan, et al. "Secure Duobinary Signal Transmission in Optical Communication Networks for High Performance & Reliability." *IEEE Access* 5 (2017): 17795-17802.

[38] Ali, S. Zafar, M. K. Islam, and M. Zafrullah. "Comparative analysis of chaotic properties of optical chaos generators." *Optik-International Journal for Light and Electron Optics*123.11 (2012): 950-955.

[39] Numai, Takahiro. "Fundamentals of semiconductor lasers." *Fundamentals of Semiconductor Lasers*. Springer, Tokyo, 2015. 89-186.