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Design Issues of Digital and Analog Chaotic RoF Link Using Chaos Message Masking

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ABSTRACT This work presents the joint use of Radio Over Fiber and optical chaos to investigate the secure ROF link. Merging the two technologies, optical chaos for physical layer communication security and Radio over Fiber creates new design issues which have been identified and studied in detail in this paper for both analog Radio Frequency/Intermediate Frequency and digitized data. A semiconductor laser diode is driven into chaotic region using direct modulation scheme and RoF signal is added by chaos message masking scheme. The chaotically masked signal is transmitted over an optical communication link to investigate the propagation issues and synchronization of chaos at the receiver. The transmitted chaos is synchronized at the receiver to unmask the signal by using subtraction rule. To investigate the performance of chaotic communication system for Radio over Fiber transmission, the figure of merits like Bit error rate, Quality factor, Eye Opening Penalty and Root-mean-squared phase jitter are studied for digital data and Signal to Noise ratio and Total Harmonic Distortion are studied for analog waveform to address the effects of link length and data rate/message bandwidth.

INDEX TERMS Chaos, chaos message masking, radio over fiber, secure optical communication, quality of service.

I. INTRODUCTION

The three biggest discoveries of 21st century are theory of Relativity, Quantum Mechanics and Chaos Theory. While sensitive dependence on initial conditions was first encountered by Henri Poincare during study of three body problem, the formal discovery of chaos was done by Lorenz in 1960s during computer simulation of weather dynamical model constituting three nonlinear coupled differential equations. Since then chaos has been discovered in many natural phenomena and man-made systems. The chaos is governed by two trajectories nearby in phase space diverge exponentially away with time as measured by Lyapunov exponent calculation. This divergence in chaotic dynamics leads to unpredictability of waveform which can be used for applications like random number generation and to hide message signal in secure communication. Two chaotic systems starting at same time would produce completely different outputs due to inability to ensure exactly same initial conditions was the major issue. So, chaos could not be utilized for end to end communication system design until discovery of synchronization scheme by Pecorra and Carol in 1990, whereby a seed from transmitter signal to receiver was used to synchronize receiver chaos with transmitter. The parameters and driving conditions were supposed to be identical or very closely matched for successful synchronization. Today, three decades of extensive numerical and experimental work is available in literature using semiconductor lasers [1]–[4] and Erbium doped fiber ring laser (EDFRL) [5]–[9]. Optical Chaos has been utilized for secure optical communication of messages using different encoding schemes; Chaos Message Masking (CMS), Additive Chaos Modulation (ACM) and Chaos Shift Keying (CSK). In CMS scheme, message is added to chaos generated by the chaotic source; thus, message does not modify chaos. In ACM scheme, message is added to chaos generation system and thus modifies chaos. In CSK scheme, a parameter of chaos generator is modified with switching of ones and zeros. On receiver side we have only one chaos generator and examine bit to bit as which transmitted chaos is closest to receiver chaos.

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With the rapid progress in photonics integrated circuits and the benefits of optical fiber over coaxial cable, many Radio Frequency (RF) systems are incorporating optical domain over short distances in radio [10]–[15] and radar technologies [16]. This demands addition of physical security using optical chaos [15] which has become quite mature after 30 years of research. However, RoF is the technology of choice for short distance RF signal transfer [10]–[16] generally between Base Station Subsystem (BSS) and Central Station (CS) in cellular networks and also in photonic/RF radars distributed antennas [16]. RoF has the advantage of lower attenuation, lesser noise and reduced interference problems. Therefore, it is very well expected that photonics portion in RF radios and radars will keep increasing in near future especially with advent of Multiple Input Multiple Output (MIMO) radios / radars and bandwidth hungry applications like video on demand and Internet of Things (IoT). The RoF signal can be a modulated RF signal like Amplitude Modulation (AM), Frequency Modulation (FM), Frequency Shift Keying (FSK), Amplitude Shift Keying (ASK) or a higher order m-QAM in analog or digitized form; the former is called Analog RoF and the latter is called digital RoF as explained by Nathan et al [10]. In both cases the signal is converted to optical signal by externally modulating a laser diode using a Mach-Zehnder Modulator (MZM). Direct modulation is not preferably used in this part of system as it can lead to chaos [3]–[4] or unwanted waveforms.

The application of optical chaos for physical security is a very active area and in recent works, Zhang *et al.* [17] and Zhang *et al.* [18], [19] have numerically and experimentally demonstrated use of chaos in Passive Optical Networks (PONs) for security purposes. It may be noted that as block chain technology will be bringing more banking transactions on optical fiber, and Internet of Things (IoT) growth globally will require part of IoT related RF signals in urban areas to be communicated optically. The applications of optical chaos for an added layer of physical security besides algorithmic layer of encryption algorithms will ensure secure remote operation of increasing number of IoT devices.

II. BLOCK LEVEL DESIGN

Radio over Fiber has three main categories [10] i.e. RF over fiber, IF over fiber and digitized IF over fiber as shown in Fig.1. The first two categories belong to analog RoF and the third category belongs to digital RoF. It may be noted in Fig.1 (c) that instead of RF, preferably IF is digitized because of much lower A/D sampling rate requirement of IF as compared to RF. However, whatever is the case we have either analog signal or digital signal to be masked by chaotic pulses generated at a higher pulse rate and amplitude and both cases have been studied in detail in this work. The RF signal can be any analog modulated RF signal (AM, FM or PM) or a modulated data in ASK, PSK, FSK, BPSK or m-QAM format. The figure of merit for digital case is min BER, max Q factor, Eye opening penalty (EOP) and phase jitter while in case of analog RoF the figure of merit is Total Harmonic Distortion (THD) and Signal to Noise ratio (S/N) found after recovery of analog signal. As we combine RoF with chaos, two main contradictory design requirements come to surface i.e. security of message hiding and reliable signal recovery at receiver. Security requires the message signal amplitude to be at least ten times smaller than the chaotic pulses max amplitude while this costs on other hand increase in the BER in digital domain while a decrease in S/N and increase THD in analog domain with smaller signals as shown in a quantified manner in this paper.

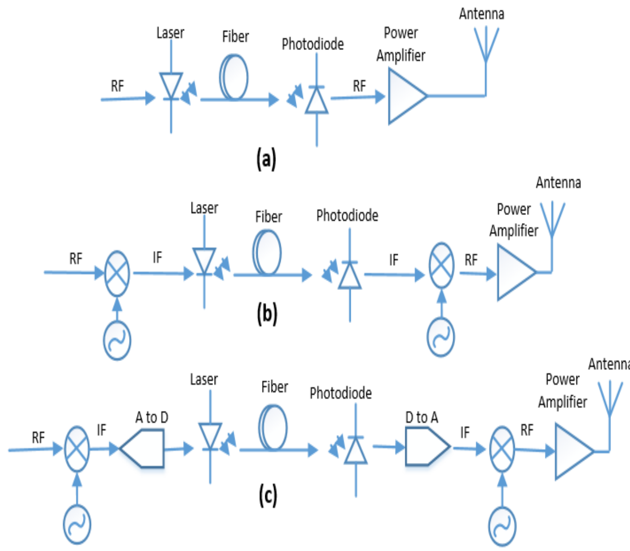

FIGURE 1. **(a) RF over fiber (b) IF over fiber (c) Digitized IF over fiber.**

The detailed block diagram of analog RoF scheme is given in Fig.2(a). RF is first down converted to IF signal and then converted to optical signal by modulating a semiconductor laser with MZM. Another semiconductor laser is used to generate chaos by direct modulation scheme. Both optical signals are added and transmitted over SMF-28 fiber which is followed by an amplifier and Dispersion Compensation Fiber (DCF). The received optical signal is used to synchronize an identical semiconductor directly modulated laser so that same chaos is produced which is then subtracted from received signal after required amplitude equalization. The subtracted signal is filtered and converted to electrical domain to recover analog IF signal. The IF signal is again up-converted to RF signal, amplified by a power amplifier and transmitted by an antenna.

Similarly, the detailed block diagram of digital RoF with chaos message masking is shown in Fig.2(b). The IF signal is digitized first using an A/D converter as per the Nyquist criteria sampling rate. The digitized data is converted from parallel to serial and then converted from electrical domain to optical domain using a MZM and a CW laser source at 1550nm. The binary threshold detector converts distorted pulses to clean data.

It may be noted that both analog and digitized data and added chaos as shown in Fig.2(a) and Fig.2(b) undergo

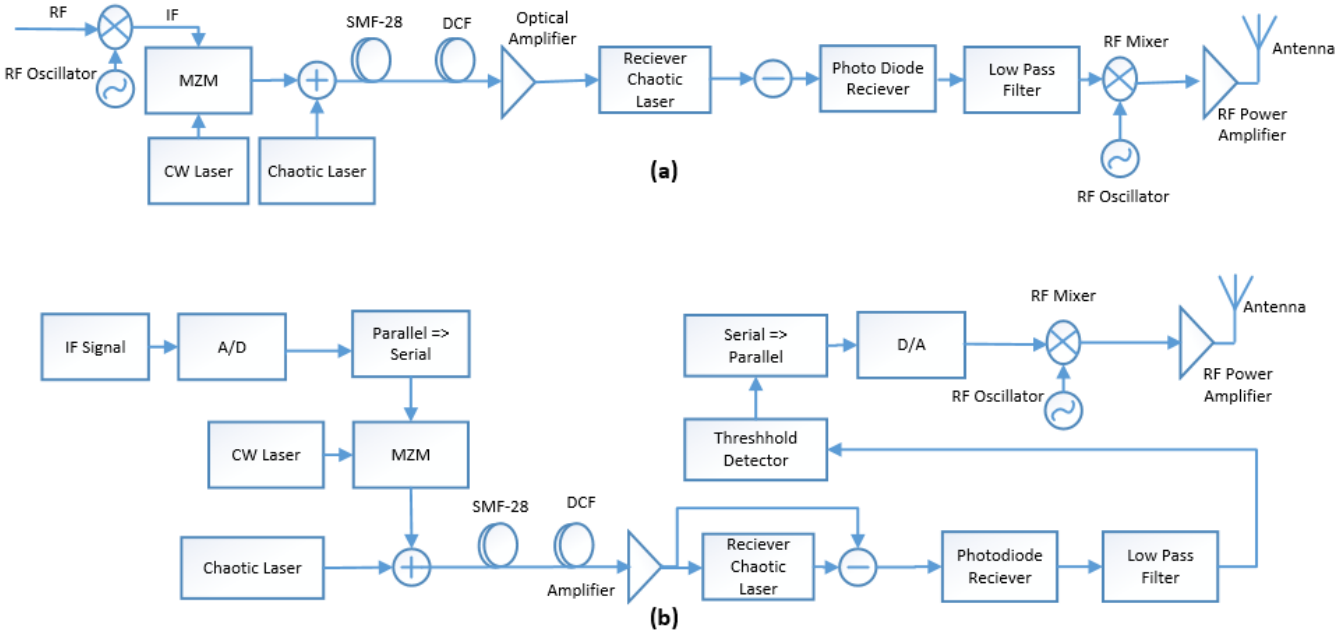

FIGURE 2. RoF with Chaos Message Masking (a) Analog scheme (b) Digital scheme.

all propagation effects which need to be managed like attenuation, dispersion and nonlinearities. Attenuation is compensated by adding amplifier of gain equal to loss faced, dispersion is compensated using DCF of opposite group velocity dispersion (GVD). Nonlinearities cannot be compensated easily, and effort shall be made that power is kept low so that nonlinearities don't get triggered. However, reducing chaos pulses power further requires reducing message signal power since the latter is to be kept less than one tenth of former and too weak a message signal increases BER.

III. MAIN DESIGN ISSUES

By merging two mature technologies i.e. Chaos and RoF, we get the best of two worlds. The main focus in this work is to study the issues and effects as we combine RoF with optical chaos in designing a secure RoF system. The RF signal is converted to an equivalent optical signal by RF-Optical modulation using MZM or electro-absorption modulator (EAM). The pulsed optical chaos is added to optical version of analog RF signal to produce a composite optical signal. The following important issues need careful consideration:

a) The RoF links are special in manner that they are smaller length links i.e. from 5km to 50km, owing to the small distances between CSS and BS. This reduces the penalty of attenuation, dispersion and nonlinearities and these anomalies are not as prominent as in long haul links.

b) There are two modes of analog RoF, one is based on converting RF signal directly to optical signal for transmission and the other is based on down-converted IF to be transmitted. In both cases we are dealing with analog sine waves in pure or modulated forms. The switching between RF and optical domains may introduce total harmonic distortion (THD) and reduced S/N.

c) In case of digital RoF, the analog RF signal needs to be down-converted to IF, digitized and converted from parallel to serial bit stream before masking by chaos. This introduces A/D quantization noise and increased requirement on bit rate due to parallel to serial conversion by a factor of n-bits where n is A/D conversion bits per sample. RF phase noise also starts becoming prominent at higher data rates.

d) The amplitude ratio of chaos and RF signal shall be high enough to hide the later in time domain. The down side is the fact that higher amplitudes trigger nonlinearities. While to better mask the message, chaos amplitude is kept high, new nonlinearity issues arise because of the higher amplitude of optical chaos pulses. These effects include refractive index related issues like self-phase modulation (SPM) in single channel and cross-phase modulation (XPM), Four-wave mixing (FWM) in Wavelength Division Multiplexed (WDM) channels and scattering related problems like stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) in single and WDM channels. The nonlinearities introduced by the channel appear as noise in the recovered signal and disturb the synch diagram especially at higher chaotic pulse amplitudes. The nonlinearities need to be quantified in amplitude and phase domain. For example, the phase noise and amplitude noise.

e) The number of chaotic pulses per cycle of maximum RF frequency sine wave shall be high enough so that the RF analog signal shall not be visible in time domain. This is limited by possible bandwidth using ordinary semiconductor lasers barring VCSELs.

TABLE 1. System parameters for chaos generation.

Parameters	Values
Laser frequency	193.1 THz
Laser Power	30 mW (for digital link) 20 mW (for analog link)
Power at bias current	1 mW
Modulating Sine Wave frequency	20 GHz (for digital link) 10 GHz (for analog link)
Active Layer Volume	$0.15\text{x}10^{-9}$ cm^3
Mode Confinement Factor	0.4
Carrier Lifetime	$1\text{x}10^{-9}$ sec
Photon lifetime	$3\text{x}10^{-12}$ sec
Carrier Density at transparency	$1\text{x}10^{18}$ /cm^3
Threshold Current	33.45 mA
Threshold Power	0.015 mW

f) The RF spectrum of RF signal shall be hidden in RF spectrum of chaos properly so that spectral filtering techniques cannot be applied directly to segregate message from chaos. In this case chaos needs to be higher bandwidth which in turn depends on the fact that the dynamic range of peak amplitude pulses shall be high.
   i. The chaos decoding noise will stay in the RF signal and it will get reflected in eye diagram and BER of decoded digital signal. The decoding noise occurs because the pulses produced at the receiver will not have exactly same width and exactly the same amplitude as the pulses which experienced dispersion and dispersion compensation.
   ii. The shape of pulses gets distorted by channel nonlinearities.
   iii. The amplitude needs equalization at receiver.
   iv. The path nonlinearities due to chaos pulse amplitude will have a residual effect on recovered signal.

IV. MATHEMATICAL MODEL

The semiconductor laser is used to generate chaos by sinusoidal direct modulation of input current waveform in the presence of DC bias current in Optisystem. The semiconductor laser rate equations for direct current modulation to generate chaos [3]–[4] are given below:

$$\frac{dS}{dt} = -\gamma_c S + \Gamma G(N, S) S \quad (1)$$

$$\frac{dN}{dt} = \gamma_S N - G(N, S) S + \frac{J_0 + J}{ed} \quad (2)$$

where N(t) is carrier density and S(t) is photon density, J_0 is the bias current, J(t) is the modulation current, G(*N(t), S(t)*) is the optical gain coefficient (including nonlinear effects),

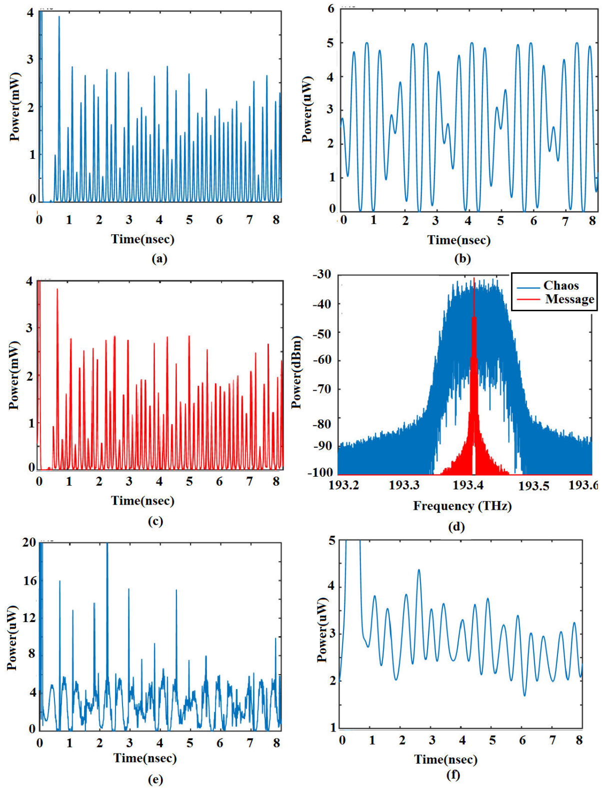

FIGURE 3. Analog RoF link results at 50 km. (a) Transmitter Chaos (b) AM modulated Optical Signal (c) Transmitter Chaos with message Signal (d) Optical Spectrum of Chaos and message signal (e) Unfiltered Decoded Signal (f) Filtered Decoded Signal with harmonic distortion.

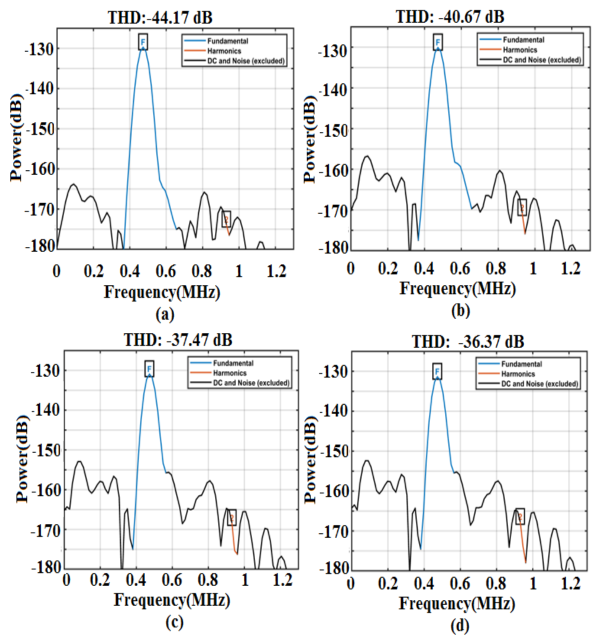

FIGURE 4. Recovered sine wave THD vs frequency.

Γ is the confinement factor, *d* is the thickness of active layer of the laser, $\gamma_c$is photon decay rate, and $\gamma_S$is spontaneous carrier decay rate. This model is already built-in in

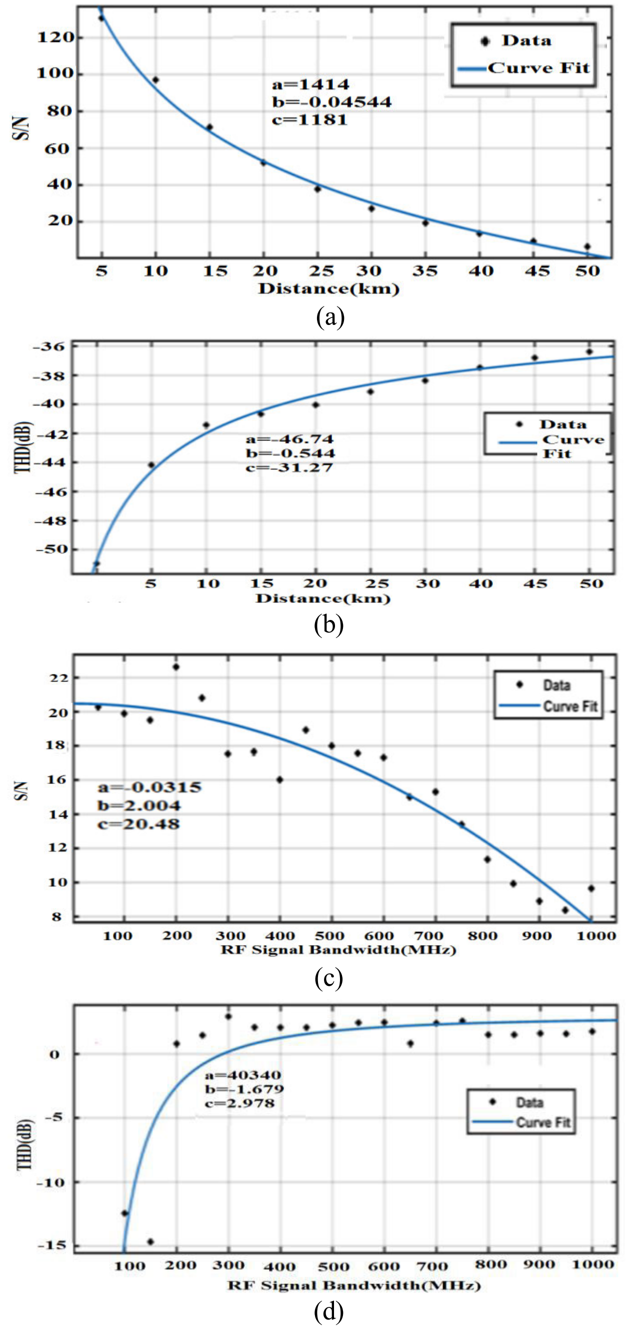

FIGURE 5. Analog Signal Degradation with link length and frequency (a)S/N w.r.t distance (b) THD w.r.t distance (c) S/N w.r.t bandwidth (d) THD w.r.t bandwidth.

OptiSystem library and only laser parameters and external modulation parameters are controlled to generate chaos as given in Table 1. It may be noted that higher modulating frequency has been used for digital link as our aim is to mask a higher data rate. This also increased the laser power requirement at higher modulation frequency.

The mathematical model of chaos propagation through standard optical fiber is based on Nonlinear Schrodinger Wave Equation (NLSE). The mathematical model of optical fiber propagation [15] is given in Eq. (3) and same is programmed in Optisystem software.

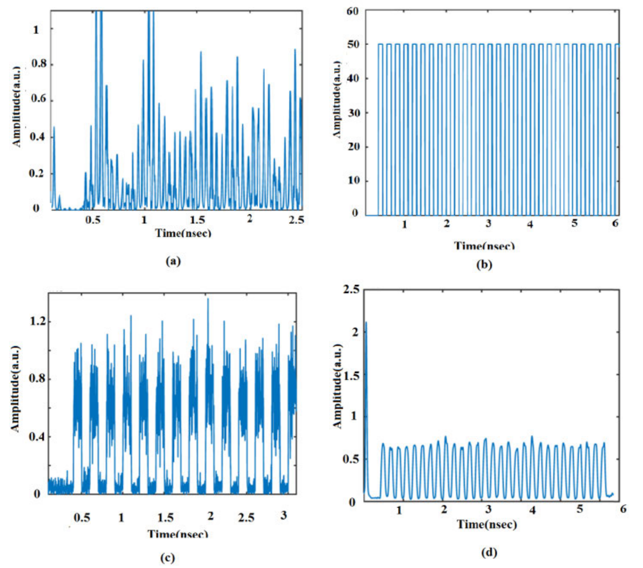

FIGURE 6. Digital Chaotic RoF link (a) Transmitted Chaos plus message (b) Transmitted Data (c) Subtractor output at Receiver (d) Filtered &Recovered data.

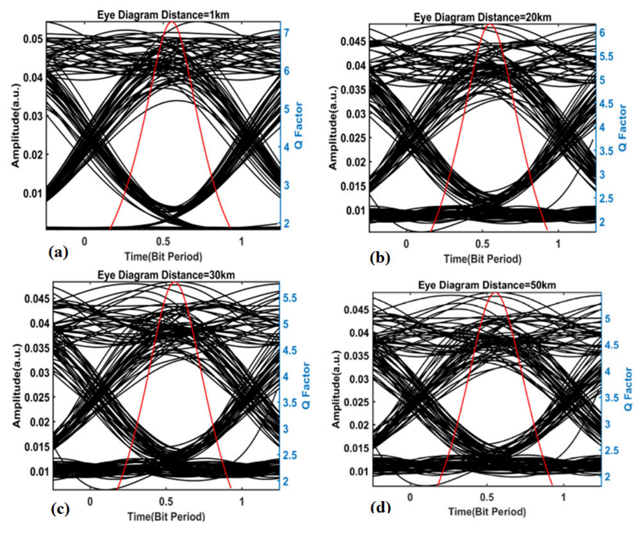

FIGURE 7. Eye Diagram and Q plot w.r.t Distance (a) 1km, (b) 20km (c) 50km.

$$j\frac{\partial A}{\partial z} = -\frac{j}{2}\alpha A - \gamma \left|A\right|^2 A + \frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial T^3} \quad (3)$$

In Eq. (3) above, A is the laser field amplitude, z is the propagation distance, T is time measured in a reference frame moving at group velocity, α is the coefficient of fiber attenuation, γ is the nonlinear coefficient, β_2 is second order and β_3 is third-order chromatic dispersion.

The mathematical model of Mach-Zehnder Modulator (MZM) [20] is given below in Eq. (4).

$$\begin{aligned} P_{out} &= P_{in}\cos^2\frac{\pi}{2V_\pi}\left(V\left(t\right)+V_b\right) \\ &= \frac{P_{in}}{2}\left[1+\cos\frac{\pi}{V_\pi}\right]\left(V\left(t\right)+V_b\right) \end{aligned} \quad (4)$$

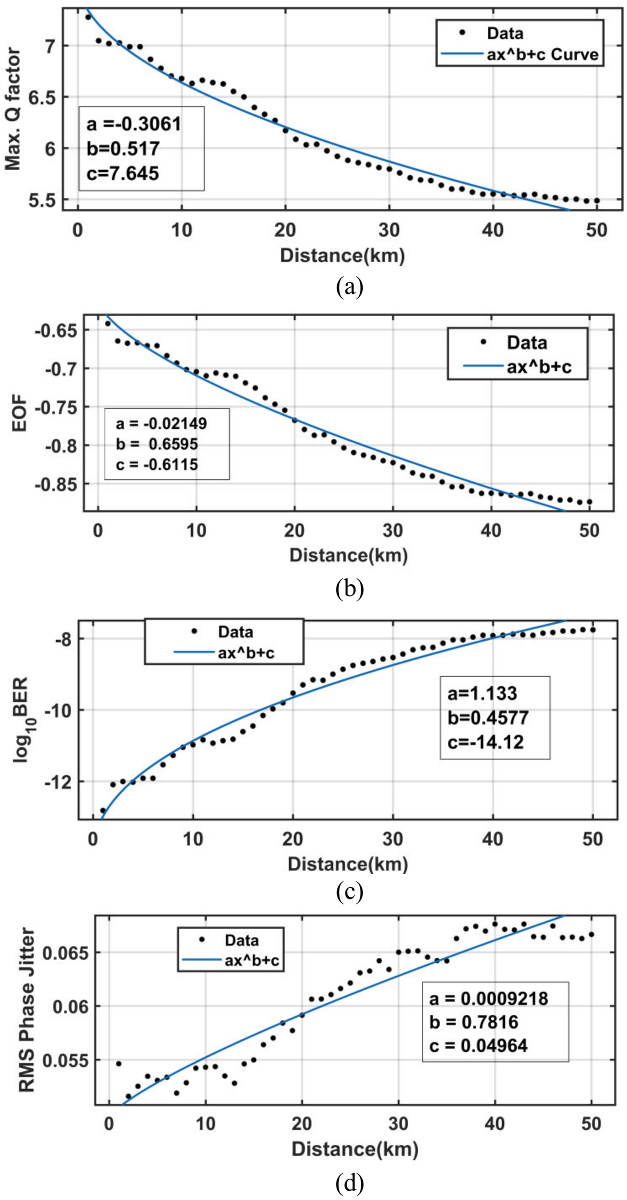

FIGURE 8. Effect of link length (km) on propagation (a) Max Q Factor (b) Max EOF (c) Min log(BER), (d) RMS Jitter.

In Eq. (4) P_{in} is the CW laser input optical power; $V(t)$ is the applied voltage of the input RF signals to be converted to RoF; V_π is the half-wave voltage of MZM and V_b is the bias voltage of the MZM, respectively.

The mathematical model of PIN photodiode [20] alone neglecting path attenuation, dispersion and any propagation/photodiode nonlinearities effects is given below at Eq. (5).

$$I_{out} = R_D P_{out} = R_D \frac{P_{in}}{2}\left[1 + \cos\frac{\pi}{V_\pi}\left(V(t) + V_b\right)\right] \quad (5)$$

In Eq. (5) R_D is the responsivity of photodiode, I_{out} is the output current of photodiode and P_{out} is the received optical power after the synchronized chaos is subtracted out at receiver.

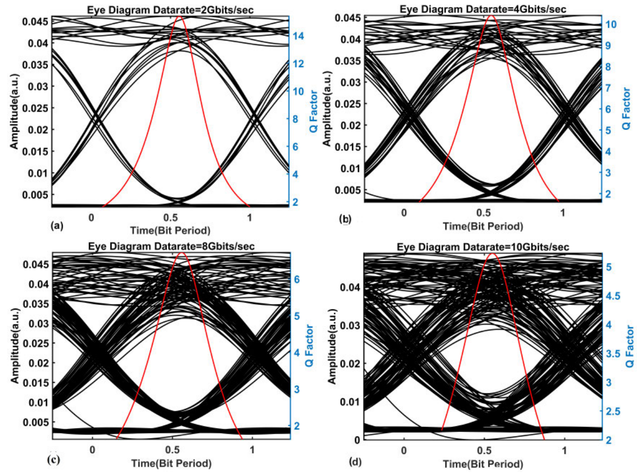

FIGURE 9. Eye Diagram and Q-plot with increase in data rate (a) 2 GB/sec (b) 4 GB/sec (c) 8 Gb/sec (d) 10 Gb/sec.

V. RESULTS AND DISCUSSIONS

A. ANALOG SCHEME

The simulation results of analog chaotic RoF link are shown in Fig.3 using Optisystem. The chaos generated by direct modulation of semiconductor laser is shown in Fig. 3(a) without any message added while Fig.3(b) shows the amplitude modulated RF signal. It may be observed that pulsed chaos has ground level between pulses which is slightly raised above zero and the shape of pulses is almost Gaussian. The message signal is added by chaos message masking and it can be observed that message power is kept so less as compared to chaos that it is not visible in time domain and frequency domain as shown in Fig. 3(c) and (d) respectively. Fig.3(d) shows the spectral profile of message (red color) and chaos (blue color) and it can be seen that chaos spectrum is ensured to have much wider bandwidth and higher power than message spectrum to achieve better masking. It may be noted that chaos spectral properties are controlled by varying laser modulation depth and power can be increased by increasing bias current. The subtractor output at receiver is shown in Fig. 3(e) which is filtered by a low pass filter to produce clean RF as shown in Fig. 3(f). It may be noted that filtered sine wave is not very smooth and the leftover effects of all nonlinearities of link and chaos decoding noise are not removed fully. This creates extra spectral content in the pure sine wave like harmonics which can be measured by THD. Beside harmonics some sub-fundamental frequency spectral content is also visible as sine wave frequency is increased.

The recovered sine wave and corresponding THD graphs for four different fiber lengths (5km, 10km, 30km and 50km) are shown in Fig.4. It may be noted that THD is generally increasing with the increase in distance.

By plotting the collected data and applying curve fitting, Fig.5(a) and (b) show decrease in S/N and increase in THD with increasing fiber link length. Similarly, Fig.5(c) and (d) show decrease in S/N and increase in THD with increase in analog message bandwidth.

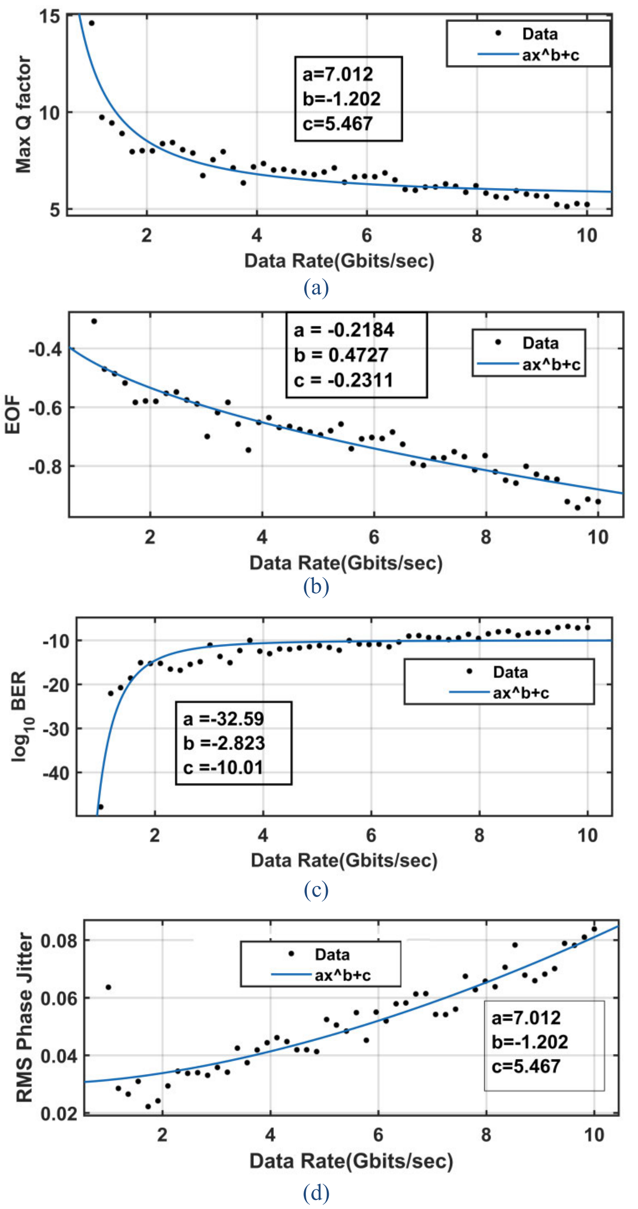

FIGURE 10. Effect of Data Rate (Gb/sec) on propagation (a) Max Q Factor (b) Max EOF (c) Min log(BER), (d) RMS Jitter.

The fitted curves are not linear and are different in nature from each other. The downward trend of S/N with increase in distance as shown in Fig.5(a) is an exponential decrease while the downward decrease of S/N in Fig.5(c) is an inverse parabola decrease. The upward trend of THD with increase in distance/bandwidth as shown in Fig.5(b) and Fig.5(d) are both logarithmic in shape at different rates owing to the dBs scale on y-axis i.e. on a linear y-axis the graphs would have been linear. The equation used for curve fitting is ax^b+c and the coefficients values of curve fitting are given within figures.

B. DIGITAL SCHEME

The digital message signal is masked with chaotic pulses as per the block diagram in Fig. 2 and the results are plotted in Fig.6. The pure chaos without the message signal is shown in Fig. 6(a), while Fig. 6(b) shows the message signal with a lower power level. The received chaos containing data signal is subtracted from the chaos synchronized at the receiver to unmask the data as shown in Fig.6(c). The recovered data after filtration is shown in Fig. 6(d).

Since the recovered data is not a perfect square wave and has phase jitter also, the Q plots and eye diagrams are plotted for different link lengths in Fig.7. It can be observed that increasing the link length deteriorates the Q plot and eye diagram.

Fig.8 shows the summarized results of maximum Q factor, maximum EOF (Eye-Opening Factor), log of min BER and phase jitter with different link lengths. It can be seen that maximum Q factor and maximum EOF decrease with increase in fiber length. On other hand min log of BER and phase jitter increase with fiber length. The equation used for curve fitting is ax^b+c and the unknown coefficients (a,b,c) of curve fitting are within each figure. The Max Q factor is decreasing like graph of 1/x while Max EOF is decreasing linearly. Min log(BER) is increasing like log(x) and RMS phase jitter is increasing like x^2 parabola.

The Q plot and eye diagram for increase in data rate from 1 Gb/sec to 10 Gb/sec are shown in Fig.9. It can be seen that eye-opening decreases vertically and horizontally due to increasing amplitude and phase jitter with increase in data rates. These results are obtained at fixed 50 km link length only by increasing the data rate and keeping the transmitted chaos parameters as same.

Fig.10 shows the same Q plots and eye diagrams results summarized in terms of different figures of merit. It can be observed that maximum Q factor decreases and levels off for increasing data rate, EOF decreases with data rate, $\log_{10}$ of BER increases and levels off while RMS phase jitter keeps increasing with data rate. The curve fitting is done with power equation ax^b+c and values of a, b and c are given inside plots.

C. SECURITY ISSUES

The propagation issues of chaotic RoF link are investigated in detail. The generated chaos is controlled by parameters given in Table 1. The security of the link depends mainly on how strong chaos is generated by laser i.e. how much it is unpredictable as measured by Lyapunov exponent and what are its random number properties characterized by its statistical measures shown in Fig.11. The time plot of chaotic laser output and detection of peaks for plotting peaks histogram are shown in Fig.11(a) and Fig.11(b) respectively. The histogram follows a Gaussian pattern and shows that chaotically generated laser pulse peaks follow a Gaussian like random number values with a certain mean and standard deviation. The time delayed embedded phase space plot of chaotic output for a time delay of $\tau = 5$ samples is shown in Fig.11(c). The phase space exhibit orbits which are closely spaced and don't cross each other indicating a chaotic set of trajectories which are longtime unpredictable. The long-term unpredictability is

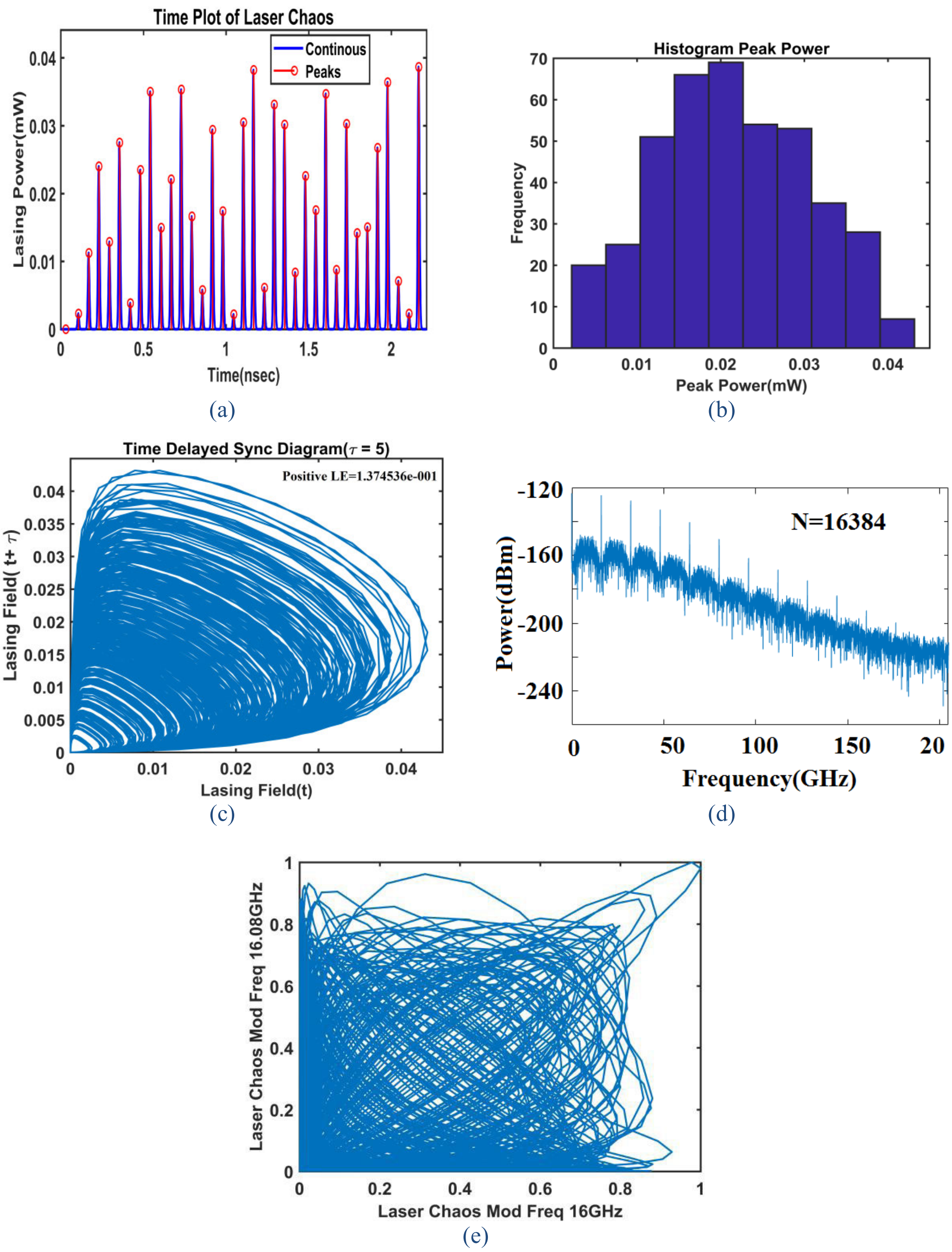

FIGURE 11. **Security Aspects of Chaotic RoF (a) Time Plot (b) Peaks Histogram (c) Time delayed Phase Space (d) Frequency Spectrum (e) Sync Diagram 0.5% Modulation Frequency Mismatch.**

measured by calculating positive Lyapunov exponent found to be 1.374536x10^{-1} using TISEAN software. The spectral properties of chaos which show a broadband noise like behavior useful in hiding message spectrally are reflected in Fig.11(d). The peaks in spectrum corresponds to fixed repetition time of pulses in chaos. The sync diagram of transmitted chaos for two identical lasers with only mismatch in modulation frequency i.e. 16.08GHz vs 16GHz is shown in Fig.11(e). The sync diagram which is 45-degree lines for same waveforms, is totally disturbed showing it is mandatory for the intruder to closely match this parameter in order to generate same chaos. These all indirect measures strongly indicate the security strength of chaotic RoF scheme studied in this paper.

VI. CONCLUSION

The design issues related to Chaotic RoF link both in analog RF and digitized IF are studied with the help of extensive simulations in Optisystem® in this work. The performance of system is investigated against THD and S/N ratio in analog RoF link and BER, Q-factor, EOP and RMS phase jitter in digitized RoF link. The attenuation and dispersion are compensated using amplifier and DCF respectively. The nonlinearities are un-compensated, and their ultimate effect is on BER and THD in digital and analog domains. The curve fitting is applied to find mathematical models of all effects studied, the models being valid only for the given range of parameters and shall not be extrapolated indefinitely beyond 10% of x-axis as RoF is already short distance scenario. It is observed that the chaos pulse frequency and magnitude should be higher than those of data for better masking abilities in time and frequency domains. The BER and phase jitter are found increasing and max Q factor decreasing with increasing link length and data rates as shown in this work. In analog RoF, S/N decreases, whereas, THD increases with increase in link length and message bandwidth. The effect of increasing chaos power which will increase nonlinearities and chaos decoding noise during synchronization of receiver are being studied in detail in a current future work.

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