Investigating the Performance of low-cost millimeter wave for long-distance Front haul RoF system based on Pre-distortion & FBG techniques

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Research Article

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Investigating the Performance of low-cost millimeter wave for long-distance Front haul RoF system based on Pre-distortion & FBG techniques

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Abstract

In this work, the effects of both Pre-distortion devices and fiber brag grating (FBG) techniques on the optical (mm-wave) in Front haul RoF have been investigated. The scope of this work is to design a simple and low-cost but efficient RoF mmm-wave-based system by utilizing a single Dual Drive Mach- Zehnder modulator (DDMZM) to feed up-converted baseband signals of different transmission rates 1,2.5, 5, 10 Gbps at input frequencies of 15, 30, 60, 65 GHz respectively. The Predistortion (PD) technique has been proven to enhance the linearity of transmitter amplifiers, which results in boosting the power efficiency of the proposed model and hence combats the non-linearity, which is one of the main problems in the RoF link. Two pulse generators have been tested in this work: Return-to-Zero (RZ) and Non-Return-to- Zero (NRZ). A single-mode fiber (SMF) is equipped with FBG to compensate for link dispersion along with an erbium-doped fiber amplifier (EDFA) and at a far terminal, an optical Gaussian filter (GOF) is employed to mitigate attenuation and band limit the optical received signal, respectively. The simulation results revealed that a Q-factor of around 8.67, and BER of 2.05E-18 can be achieved when combining both Pre-distortion and RZ format along with Pre-FBG technologies with a fiber link of 140km at 5Gbps bitrate utilizing 15 GHz local oscillator 60 GHz mm-wave. The findings showed that a 130 GHz mm-wave is generated with Q-factor of 7.4, and BER of 5.08E-14 with fiber length of 140 km and a data rate of 1Gbps.

Keywords: Pre-distortion, Dual-Drive-Mach-Zehnder-Modulator, Fiber Brag Grating, Millimeter-Wave, Non-Return-to-Zero, Radio-over-Fiber, Return-to-Zero.

1 Introduction

Demands for various wireless multimedia services, radio-over-fiber (RoF) technology have been adopted more and more to address the current and future demands of access networks. A technology called mm-wave Radio over fiber (mm-wave RoF) is investigated in order to provide the ultra-high data rate, demanded by the 5G wireless communication system which claims to make better use of the RF spectrum and apply cutting-edge modulation and access methods. This means that while mm-wave frequencies offer enormous bandwidths in the wireless domain and overcome the issue of spectral congestion at lower frequency ranges that allow broadband wireless access services, optical fiber technology offers high bandwidth and supports lengthy transmission lines [1, 2]. Broad wireless communication, radars, phased-array antennas, contemporary instruments, imaging, medicinal, and terahertz applications are only a few areas where mm-wave signals have been proposed as a potential solution for a laser that is directly or indirectly modulated in a central station (CS) and then transmitted through an optical fiber to a photodiode [3]. This produces (mm-wave), which are then sent to a radio with antennas in the base station (BS) [4]. Due to the dispersion of the propagated signal in the optical link which is increased by increasing the bitrate the system, the nonlinearity become dominant factor that mitigates the performance of fronthaul RoF system, especially when operating at high frequencies (mm-wave) [5]. This work has suggested and then after integrates different techniques to combat this nonlinearity along with the proposal of Low-cost design (employing single Dual Derive Mach-Zehnder Modulator (DDMZM)) as a (double side band) DSB external modulator of electrical signal. The optical generation of mm-wave using the external modulation technique is likely to be more accurate, because of its stability and low phase noise characteristics [6]. Consequently, the first technique, is employing Predistortion (PD) device which improves the linearity of transmitter amplifier and hence, enhance the power efficiency of the signal propagated throughout the link [5, 7]. The second technique is based on using Fibers Bragg Grating (FBG) which is a frequent key component employed as a dispersion compensation mechanism. FBG has some features like negligible nonlinearity, low insertion loss and small size which can substantially improves the mm-wave RoF system performance at long link length [8]. Thus, the all-fiber design and versatility of Fiber Bragg Grating, together with its extremely selective filtering capabilities, make this technology an excellent choice for both existing and future networks [9]. In this work the dispersion compensation of FBG aid to extend the link length to more than 140 Km fiber link leading to error free transmission of at maximum 10 Gbps signal. Two pulse generators have been tested in this work: Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ), with up to 140 km fiber link length and a signal power of 15 and 8.6 dBm. The RZ modulation format was proven to combat the link nonlinearity at high transmission bit rates [10]. Some approaches to (mm-wave RoF) systems for photonic generation of mm-wave have been reported in the literature to improve system performance and capacity. [2] proposed an inverted optical filter to suppress the carrier for a millimeter wave optical signal. As a result, it is shown how well an inverted optical filter and carrier supersession can produce a signal of 60 GHz millimeter wave (mm-wave). In particular, it is produced by utilizing a simple and reasonably priced (low-cost) design that only requires an inverted optical filter and a single dual drive Mache-Zehnder modulator (DD-MZM). [11] demonstrated that an effective Pre-distortion approach can be used to lessen the impact of chromatic dispersion of the optical channel and frequency chirp of the laser source on RoF systems. The radio frequency signal is first converted to digital form using an analog to digital converter, followed by the Pre-distortion operation and conversion back to analog form of the signal. The theoretical underpinnings of the suggested technique are thoroughly examined, and approximations are also offered to make it more practical. [12] demonstrated that in order to facilitate mm-wave transmission via fiber-based networks, wavelength conversion and mm-wave switching utilizing a semiconductor optical amplifier (SOA) are considered. To create a switched signal of optical single sideband that transmits combined 5G signals of filter bank multicarrier (FBMC), they specifically make use of the nonlinear special effects in SOA. [5] proposed a hybrid optimization technique known as the hybrid Memetic algorithm used for parameter estimation of the digital predistorter. This approach combines the advantages of the Tabu search algorithm with the Memetic algorithm. The outcomes of the hybrid Memetic algorithm are quite promising, according to simulation studies. [13] inverted optical filters are being researched as a means of reducing the carrier for optical millimeter wave signals. As a result, it is shown how well an inverted optical filter can produce a 60 GHz (mm-wave) signal according to carrier supersession. To create it specifically, an inverted optical filter and a single dual drive Mache-Zehnder modulator (DD-MZM) are utilized, a system's design and analysis that aims to maximize data rate while minimizing BER for long-distance communication. Their proposed system uses a 100 GHz carrier and four 10-Gbps-per-channel WDM-RoF channels. The four channels in the proposed system are multiplexed using a WDM technique, and the data is sent across a single-mode optical fiber with a length of 30 to 70 kilometers. By using quadrature phase shift keying (QPSK) and binary phase shift keying (BPSK), the most compact full-duplex optical system of (mm-wave-RoF) with error-free transmission across 10, 25, and 50 km of single-mode fibers (SMF) has been tested.[1] pointed out that controlling the effect of phase noise, which originates from phase imbalance, on the optical mm-wave signal is necessary to maximize the performance of optical mm-wave system. Thus, by altering the phase at the phase shift, the phase imbalance may be reduced of dense wavelength division multiplexing radio-over-fiber (DWDM-RoF). [4] Proposed a design of a (mm-wave -RoF) access network through two modulation stages for the generation of multiple millimeter wave (mm-wave) signals with frequencies of 20, 40, 60 and 80 GHz for the transmission rate of 10 Gbps as a function of the variation of link distance and signal power. By using two stages first based on dual-parallel Mach–Zehnder modulator (DP-MZM) and second contains only one modulator (MZM), connected to three pulse generators: Non-Return-to-Zero (NRZ), Return-to-Zero (RZ) and Gaussian, which were selected individually to each simulation in OptiSystem software. A single-mode fiber (SMF) and optical filter Gaussian (GOF) and an erbium-doped fiber amplifier (EDFA) were also used to send signals to base stations (BSs). [14] illustrated the generation of (mm-wave) signal by using the Dual-sideband Optical Carrier Suppression (DSB-OCS) technology in radio over fiber (RoF) systems. For data transmission across the RoF systems, the suggested system uses a Dual-Electrode Mach-Zehnder Modulator (DE-MZM) with a carrier of 40 GHz. Group of features that affect the system's performance, such as the dispersion parameters, phase imbalance, and modulation index have been investigated. The system's performance tests demonstrate that when the modulation index is increased, the mm-wave signal output power follows the MZM's transfer function. Additionally, phase imbalance and optical splitting ratio have an impact on the produced optical mm-wave signal power. The optical fiber dispersion was discovered to have an impact on the DSB-OCS system by reducing the signal-to-noise ratio (SNR) and the amplitude of the mm-wave. [15] proposed a method for equalizing the dispersive optical link. A simulation of a converged (mm-wave RoF) system at 60 GHz and offline signal processing has been performed. These three commonly used algorithms are the adaptive median filtering (AMF), the simple least mean square (LMS) algorithm, and the constant modulus algorithm (CMA). The CMA algorithm has been proven to outperforms the LMS and MF algorithms for QPSK in OFDM subcarriers, with improvements in EVM of 2 percent and 1.4 percent, respectively. However, for 16QAM in OFDM subcarriers, the LMS algorithm improves EVM by only 0.2 percent when compared to the MF algorithm, and CMA is not suitable for 16QAM modulation. [16] demonstrated that In a (5G mm-wave RoF) system utilizing direct modulation of DFB laser and optical injection locking, a 28.2 and 35.3 GHz mm-wave signals has been generated. The resulting low phase noise mm-wave signal allows OFDM transmissions that are 5G compatible. The fifth generation (5G) mobile communications network is expected to offer reception capacity and data transmission 1000 times higher than the present system of cellular phones, regardless of having a high level of flexibility and a cost-effective deployment that could be utilized by design strategies for activating and moving baseband functions. However, [17] claim that the fourth generation (4G) mobile communications network is the most anticipated due to its potential to reduce the telecommunications bottleneck. Using a semiconductor optical Amplifier (SOA) after an SMF with a length of up to 40 km and a dual-parallel Mach-Zehnder modulator (DP-MZM) in the CS, [18] suggested a ROF system according to the technique of four-wave mixing (FWM), for transmission rates of 2.5 Gbps and with RFs of 60, 40, and 20 GHz, which can provide frequency multiplication. They demonstrated a RoF system that had outstanding performance results for conducting and supporting many mm-wave wireless access points. The paper was structured as follows: Section 2 gave the theoretical analysis of the modulation approach, presented the operating principle and the suggested ROF system configuration. Section 3 presented simulations and results analysis has been discussed in section 4. In Section 5, the concluding points are stated.

2 Mechanism of suggested system

The mathematical background for the proposed transmitter can be initiated by considering the conceptual diagram of a DD-MZM is shown in Figure 1.

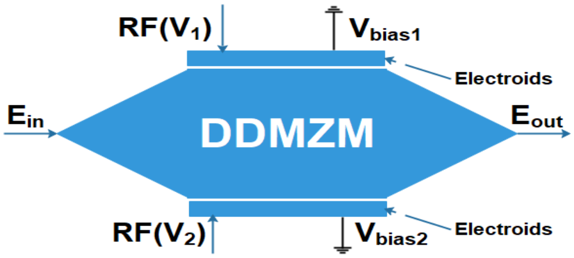


Fig. 1 Schematic diagram of DD-MZM. RF: radio frequency.

in each electrode the light propagation in a LiNbO3 crystal with a width L and a distance between plates of d. If E is the intensity of the electric field between its plates, the refractive index will relate to the value of E based on the equation below: [19, 20]

$$n = n_0 - \frac{1}{2} n_0^3 pE \qquad (1)$$

When n_o is the refractive index, E and P is the coefficient of electro-optics effect. Returning to the conversional equation of E:

$$E = v|d \qquad (2)$$

Then:

$$n = n_0 - \frac{1}{2} n_0^3 P \left(\frac{v}{d}\right) \qquad (3)$$

The optical field of an incident optical wave is:

$$\psi_{(t,0)} = \psi_{in}(t) = A_0\, exp(-j2\pi f_C t) \qquad (4)$$

Then for distance L:

$$\psi in(t, L) = A_0 \cdot exp(-j(2\pi f_{\acute{c}} t - \phi)) \qquad (5)$$

$$\text{When}\phi = \frac{2\pi nL}{\lambda_0} = \frac{2\pi L}{\lambda_0}\left(n_0 - \frac{n_0^2 \rho v}{2d}\right) \qquad (6)$$

$$= \phi_0 - \Delta\phi$$

Where, ϕ_o is a constant change in the distance of utilized electric voltage (v). Then,

$$\Delta\phi = \frac{\pi L n_0^3 \rho v}{\lambda_0 d} \qquad (7)$$

Thus, $\Delta\phi$ is the change of phase. The switching voltage v_π or half-wave voltage, is the voltage required for producing a phase transition π, and it's illustrated by:

$$\Delta\phi = \pi = \frac{\pi L n_0^3 \rho V_\pi}{\lambda_0 d} \qquad (8)$$

And $v_\pi = \frac{\lambda_0}{n_0^3 p} \frac{d}{L}$

Thus, sub eq (8) in eq (5) yields

$$\psi in(t, L) = A_0\, exp\left[-j\left(2\pi f_C t - \phi_o + \frac{\pi v}{v\pi}\right)\right] \qquad (9)$$

Hence, the used voltage has a direct relationship with the phase change. The phase of the optical carrier may be changed to correspond with the message signal if v(t) is the message signal.

For Dual Drive- MZM, two arms of phase modulator have hence been used. As a result, two applied voltages (v_1, and v_2) are used to the upper and lower arm, respectively. Based on equation (9) and by ignoring a source of losses, the electric field entering the lower or upper arm of the interferometer is (10):

$$E_{upper,lower} = \frac{A_0}{\sqrt{2}} exp(-j2\pi f_C t) \qquad (10)$$

In order to maintain the overall power, the factor $\frac{1}{\sqrt{2}}$ is implemented. The optical beams in both the lower and upper arms, in the presence of applied voltages v_1 and v_2, undergo a phase shift of ϕ_1 and ϕ_2. Thus, using eq. (6) along with eq. (10) we have:

$$\phi_j = \frac{2\pi L}{\lambda_0}\left(n_0 - \frac{1}{2} n_0^3 \rho v_j(t) \,/\, d\right) \qquad (11)$$

Where, j= (1, 2)

$$\equiv \phi_0 \frac{-v_j \pi}{v_\pi}$$

The upper and lower arms of the optical beams are:

$$\Psi_j = \frac{A_0}{\sqrt{2}} exp[-j(2\pi f_C t - \phi_j)] \qquad (12)$$

The second branch`s output is is represented by:

$$\psi_{out} = \frac{\psi_1 + \psi_2}{\sqrt{2}}$$

Therefore,

$$\psi_{out} = \frac{A_0}{\sqrt{2}} exp\left(-j_\pi f c\left[\frac{exp(j\phi 1)}{\sqrt{2}} + \frac{exp(j\phi_2)}{\sqrt{2}}\right]\right)$$

$$A_0 = A_0\, exp[j(\phi 1 + \phi_2)\,/\,2] * \frac{exp[j(\phi 1 - \phi_2)|2] + exp[-j(\phi_1 + \phi_2)/2]}{2} \qquad (13)$$

$$= A_0\, exp[j(\phi_1 + \phi_2)\,/\,2]\, cos[(\phi 1 - \phi_2)\,/\,2]$$

Then

$$A_{0ut} = A_0\, exp(j\bar{\phi})\, cos\left[\frac{|v_1(t)-v_{2(t)}|\pi}{2v_\pi}\right] \quad (14)$$

Where $\bar{\phi} = \frac{\phi_1+\phi_2}{2} = \phi_0 - \frac{[v_1(t)+v_2(t)]\pi}{2v_\pi}$

The following equations provide the instantaneous frequency chirp or frequency shift:

$$w_r = \frac{-d\bar{\phi}}{dt} = \frac{\pi}{2^v\pi}\left(\frac{dv_1}{dt} + \frac{dv_2}{dt}\right) \quad (15)$$

The output optical power is:

$$P_{out} = |A_{0ut}|^2 = P_0\, cos^2\left[\frac{[v_1(t)-v_{2(t)}]\pi}{2v_\pi}\right] \quad (16)$$

And to have a zero chirp

$$\frac{dv_1(t)}{dt} = \frac{-\,dv_2(t)}{dt}$$

$$v_1(t) = -v_2(t) + v_{bias}$$

Where, V_{bias} is a constant voltage. Let $V_1(t)$ be the message signal m(t). Ignoring constant phase shift, the output power is:

$$P_{0ut} = p_0\left[\left[m(t) - \frac{v_{bias}}{2}\right]\frac{\pi}{v_\pi}\right] \quad (17)$$

Or $A_{0ut} = A_0\, cos\left[\left[m(t) - \frac{v_{bias}}{2}\right]\frac{\pi}{v_\pi}\right] \quad (18)$

Therefore, considering V_{bias}=Vπ, the equation (18) becomes:

$$A_{0ut} = A_0\, sin\left[\frac{m(t)\pi}{v\pi}\right] \quad (19)$$

Where $m(t)\pi\ /\ v_\pi \ll 1$

$$\psi_{0ut} = \left(\frac{A_0\pi}{v_\pi}\right) m(t)\, exp[-j2\pi f_C(t)] \quad (20)$$

Now MZM acts as a product modulation and, hence, simulates (DSB-SC).

Case 2 when $[v_{bias} = v_{\dot{\pi}}\ /\ 2]$ (Q- Point)

$$A_{0ut} = A_0\, cos\left[\frac{m(t)\pi}{v_\pi} - \frac{\pi}{4}\right]$$

$$= \frac{A_0}{\sqrt{2}}\left[cos\left(\frac{m(t)\pi}{v_\pi}\right) + sin\left(\frac{m(t)\pi}{v\pi}\right)\right] \quad (21)$$

When $m(t) << V_\pi\ /\ \pi$

$cos\left[\frac{m(t)\pi}{v\pi}\right] = 1$ and

$\sin\left[\frac{m(t)\pi}{v\pi}\right] \approx \frac{m(t)\pi}{v_\pi}$

Therefore,

$$\Psi_{0ut} = \frac{A_0}{\sqrt{2}}\left[1 + \frac{m(t)\pi}{v_\pi}\right] exp(-j_2\pi fct) \quad (22)$$

The above equation is like **DSB-LC** electrical modulation.

Let $m(t) = \begin{cases} +v & for_{\ bit\ "1"} \\ -v & for\ bit\ "0" \end{cases}$

Let the output of the pre-distortion is:

$$V_{0ut}(t) = \frac{1}{\pi} sin^{-1}\big(v_{in}(t)\big) * a + b \quad (23)$$

Let b=0, a=1

$$v_{0ut}(t) = \frac{1}{\pi} sin^{-1}(v_{in}(t) \quad (24)$$

Hence, the output of Pre-distortion would be:

$$\widehat{m}(t) = \begin{cases} \frac{1}{\pi} sin^{-1}(-v_{in}(t))_{,for\ bit=0} \\ \frac{1}{\pi} sin^{-1}(v_{in}(t)),for\ bit{=}1 \end{cases}$$

Let P_{out} of **MZM** be:

$$p_{0ut\ 1} = p_0\, cos^2\left[\frac{\widehat{m}(t)\pi}{v_\pi} - \frac{v_{bias}\pi}{2v_\pi}\right] \quad (25)$$

At logic 1:

$$P_{out\ 1} = p_0\, cos^2\left[\frac{\frac{1}{\pi} sin^{-1}(v_{in}(t))\pi}{v_\pi} - \frac{v_{bias}\ \pi}{2v_\pi}\right] \quad (26)$$

At logic 0:

$$P_{0ut\ 0} = p_0\, cos^2\left[\frac{\frac{1}{\pi} sin^{-1}(-v_{in}(t))\pi}{v_\pi} - \frac{v_{bias\ \pi}}{2v_\pi}\right]$$
(27)

3. Simulation setup

Six different scenarios have been proposed in this work based on low- cost (single DDMZM) mm-wave RoF system. The scenarios were constructed depending on two types of modulation format (NRZ, RZ) presence (or not) of Pre-distortion block, and finally depending on both of the presence or not of the FBG along with the location of FBG (Pre or Post). Simulation results are reported in term of the

Q-factor. Figure 2 demonstrates a classic (mm-wave RoF) system simulated in OptiSystem 19.00 software without both of dispersion compensation and Pre-distortion device. Thus, a generator of pseudo-random bit sequences is utilized in this system to produce a random stream of bits. This stream is encoded using the RZ/NRZ coding format individually. The RF signal generated by the sine generator (RF local oscillator) with different frequencies 15, 30, 60, 65 GHz is combined by the formatted user data before triggers one LiNb-Mach-Zehnder modulator, also known as a dual-drive Mach-Zehnder modulator (DDMZM). At the DDMZM input, a CW laser provides optical carrier with a wavelength of 1552.5 nm, and an input power of 8.6 dBm for RZ scheme, and 15 dBm NRZ scheme. After being amplified by an optical amplifier with a gain of 35 dB and a noise figure of 4 dB, the signal is sent from the DDMZM into the single-mode fiber (SMF), whose length has increased from 10 km up to 140 km (maximum length). To remove ripples, the single-mode cable-routed signal is sent through a Bessel optical filter with a frequency of 193.1 THz and a bandwidth of 20 GHz, then passed to an Optical Receiver, whose gain is 4. An optical receiver's job is to retrieve the data provided via the light wave system by converting the optical signal back into electrical form. Its major part is a photodetector, which uses the photoelectric effect to turn light into energy. The bit error rate analyzer tests the min BER and max Q factor.

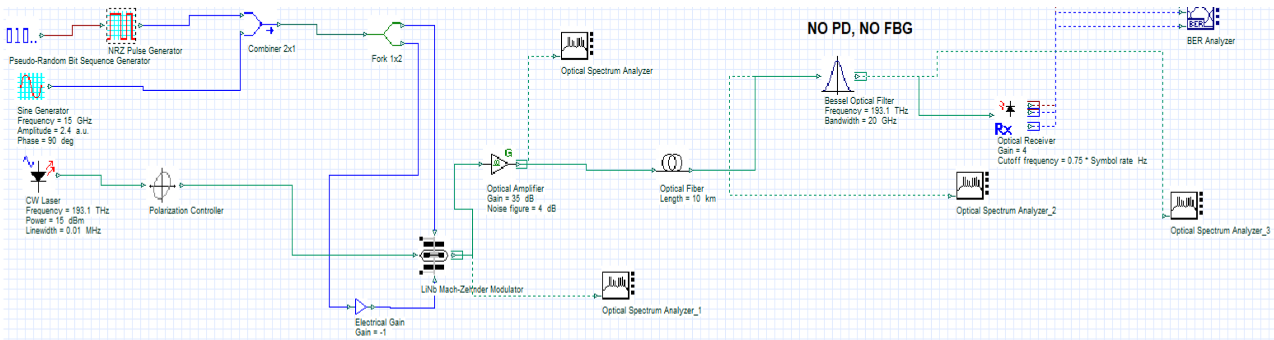


Fig. 2 Schematic view of a Classic mm- wave RoF simulation model.

Figure 3 presents the circuit diagram of the second scenario in which a Pre-distortion device is used alone (without FBG). Thus, to boost transmitted signal power and to combat the modulation nonlinearity, the encoded signal is sent to an Arcsine Pre-distortion.

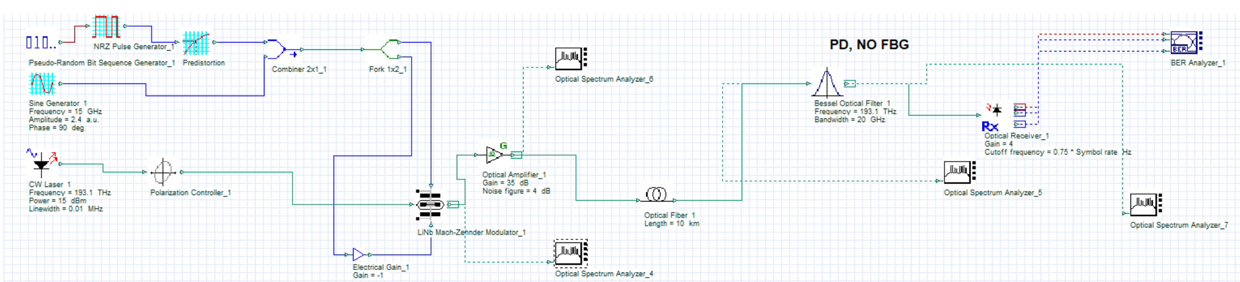


Fig. 3 Schematic view of Pre-distortion mm- wave RoF simulation modeling.

Fig. 4 and 5 show the conceptual diagram of third and fourth scenarios in which the impact of compensation of dispassion based on Pre- FBG and Post- FBG, respectively are investigated also at a typical encoring format(NRZ/RZ). Both have been simulated by preserving the values and variables mentioned previously for each of the pseudo-random generators, sine carrier generator, CW laser, optical amplifier, optical fiber, low pass Bessel optical filter, and optical receiver, this time a uniform FBG as a compensation technique with a frequency of 193.1THz and bandwidth of 5GHz is connected to the system. In fig. 4, the FBG in front of the optical fiber is a system of (Pre- FBG), while in fig. 5, the FBG is located after the optical fiber (Post-FBG).

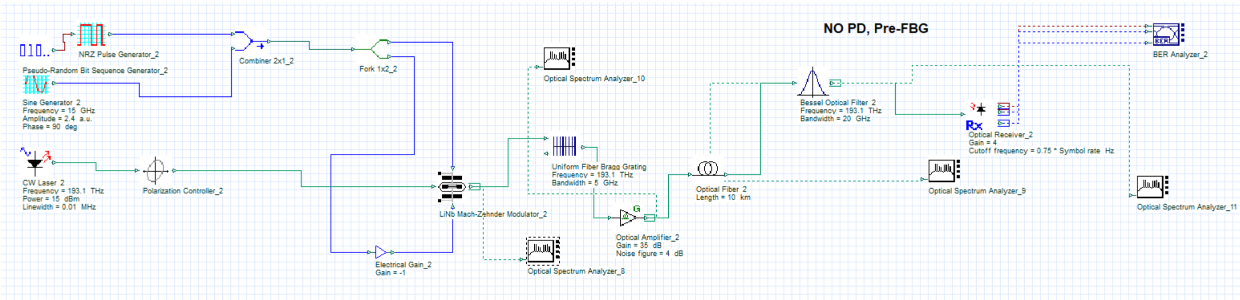


Fig. 4 Schematic view of Pre- FBG mm-wave RoF simulation modeling.

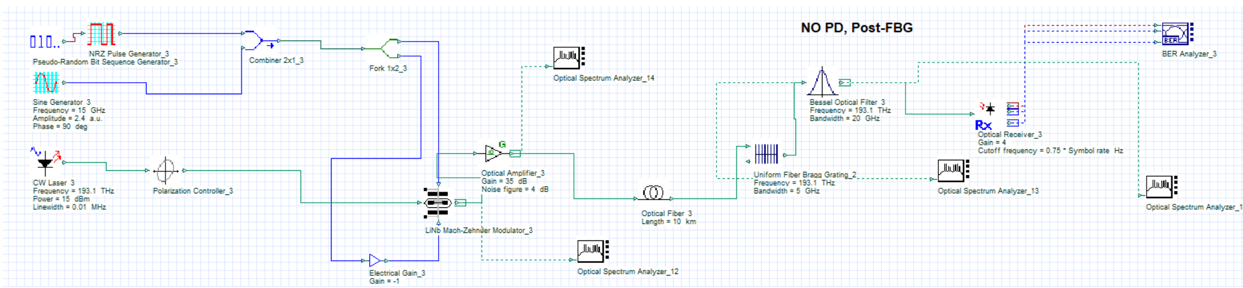


Fig. 5 Schematic view of Post- FBG mm- wave RoF simulation modeling.

Figures 6 and 7 present the system layout when integrating both of Pre-distortion device and the two scenarios of the depression compensation Pre-FBG and Post- FBG respectively. Again, the data stream is encoded using the RZ/NRZ coding formats individually. The RF signal generated by the sine generator (local oscillator) with frequencies of 15, 30, 60, 65. A uniform post-FBG and pre- FBG with a bandwidth of 5 GHz and a frequency of 191.3 THz has been employed.

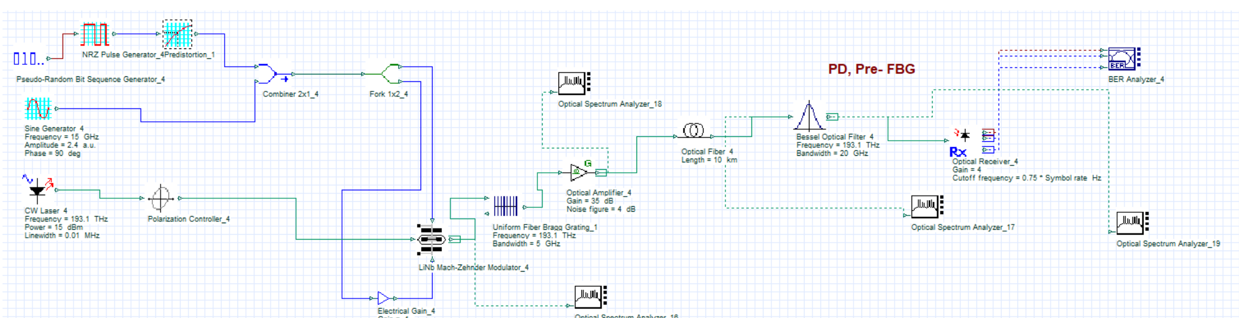


Fig. 6 Schematic view of Pre-distortion Pre- FBG-mm- Wave RoF simulation modeling.

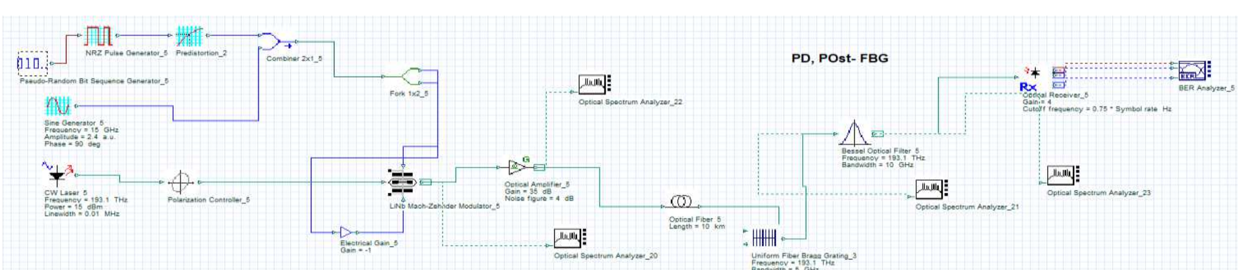


Fig. 7 Schematic view of Pre-distortion Post- FBG-mm- Wave RoF simulation modeling.

4. Results and discussion

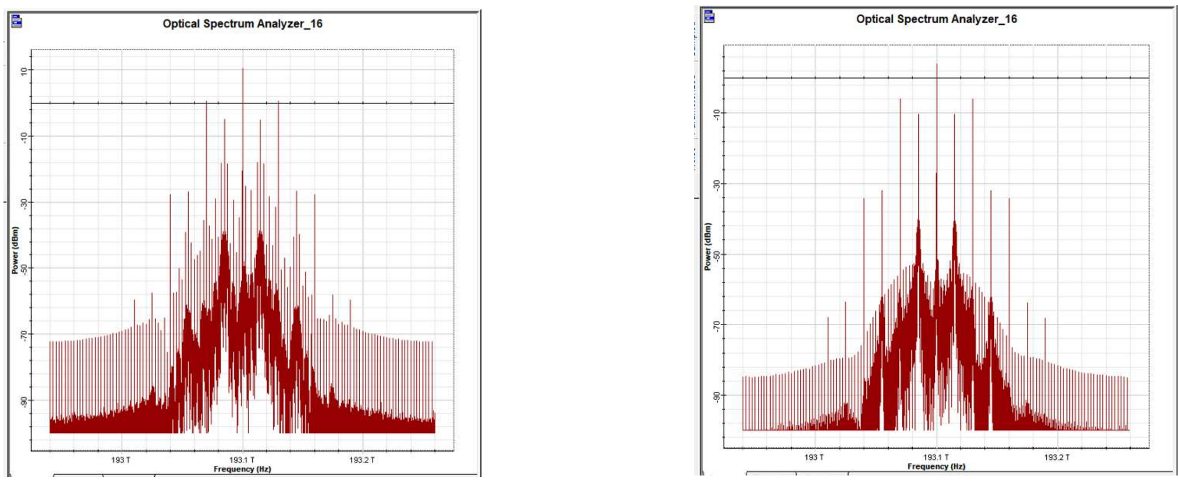
In this study, the (mm-wave RoF) using DD-MZM (low-cost) based on Predistortion and FBG is investigated. The performance with two coding formats — (RZ) and (NRZ) was simulated and examined using OptiSystem 19.00 software. Based on the simulation settings listed in Table 1, the six scenarios (demonstrated by fig 2-7) were utilized alternatively in the simulations. The results obtained from the eye diagram and optical spectrum as a function of the variation of the following parameters: fiber length from 10 to 140 km, input power of 8.6 dBm for NRZ and +15dBm for RZ, and mm-wave frequencies of 15, 30, 60, 65 GHz were used to analyze the performance of the system for the transmission rate of 1, 2.5, 5, 10 Gbps. The spectrum at the output of the DDMZM modulator is depicted in figure 8a below for the proposed pre-distortion-Pre-FBG-mm-wave-RoF scheme and using RZ coding. The carrier frequency has the highest power of 10.2 dBm as compared to the other 5-side bands generated, and hence the type of modulation is DSB. Figure 8b shows the optical spectrum out of the DDMZM modulator for the conventional Pre-FBG-mm-wave scheme, NRZ coding. In this case, the carrier frequency still has the highest power of 9.44 dBm as compared to the other 5-side bands generated with a type of modulation of DSB.

Table 1 Simulation Parameter setup**.**

Parameters	**Value**
C/W Laser Line width	0.01 GHz
C/W laser reference wavelength	1550 nm
C/W laser frequency	193.1 THz
Length of the Fiber link	10- 140 Km
Input transmitted Power	8.6 dBm/ NRZ, 15 dBm/ RZ
RF Local Oscillator (GHz)	15 , 30, 60, 65
Bit Rate (Gbps)	1, 2.5 , 5 , 10
FBG Bandwidth	5 GHz
MZM Extinction Ratio	15 dBm
MZM switching voltage	4 V
MZM RF Voltage	4 V
DD-MZM Bias Voltage	0 V

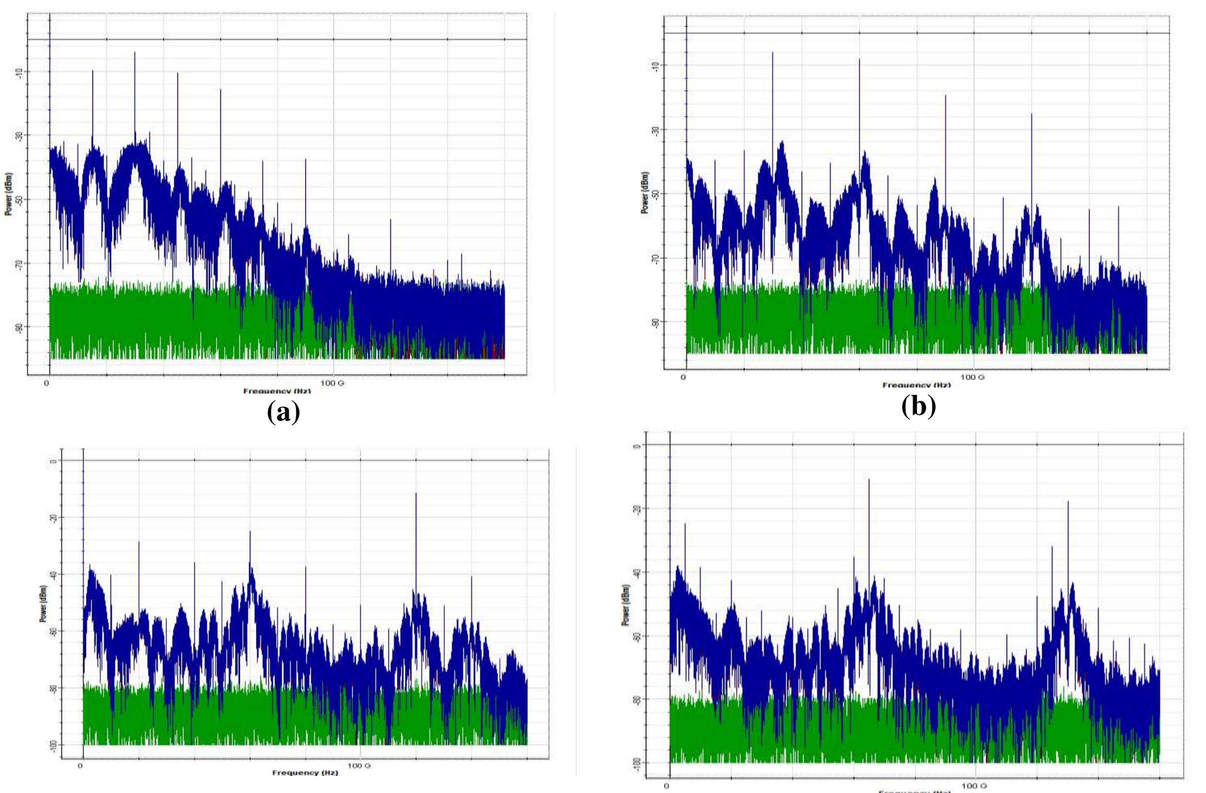
It is worth to mention that the spectrum has been calculated at 60 GHz local oscillator and at bit rate of 1 Gbps for a link length of 140 km. Fig. 9 shows the spectrum at the photo detector with the generated mm-wave by each different local oscillator at a fiber length of 20 km. The findings revels that in fig 9a the mm-waves generated namely at 15, 30, 45 and 60 GHz with received power of -10 dBm, -4 dBm, -10dBm,-15dBm respectively which include input frequency and its double ,triple

quadruple frequencies respectively. Fig 9b shows the case at input frequency of 30 GHz in this case the generated mm-wave at 30, 60, and 90 GHz with received power of -5, -8, -19 dBm respectively which includes input frequency and its double, triple frequencies respectively .Fig 9c depicts the generated mm-wave at 60 GHz local oscillator with double the input frequency at 120 GHz with power of -12 dBm. Finally, fig. 9d demonstrates the spectrum of the generated mm-wave at the photo detector by 65 GHz input frequency from which it’s clear that mainly two mm-waves are generated at 65 GHz with power of -11 dBm and 130 GHz (double input frequency) with -18dBm respectively.



(a) **(b)**

Fig. 8 Transmitted signal at CS: Output Spectrum of the CW Laser (carrier) and Spectra periodic optical sidebands at the DD-MZM output for the Predistortion-Pre-FBG-mm-wave-RoF frequency equal to 60 GHz, 1 Gbps, 140 Km **(a)** RZ coding **(b)** NRZ coding.



(c) **(d)**

Fig. 9 The generated mm-wave signal spectrum at the photo detector, by the proposed PD with Pre-FBG-mm-wave scheme for different local oscillators, **(a)**15GHz **(b)** 30GHz **(c)** 60GHz **(d)** 65GHz at 20km, NRZ coding format, and input power of 8.6dB.

Figure 10a shows a max Q- factor of 223.5, with BER=0 for the local oscillator of 15 GHz, 2.5 Gbps bit rate at input power of 15 dBm, and RZ coding. It has been attained by predistortion-mm-wave RoF at 10 Km of fiber length, but finally the Predistortion-Pre-FBG-mm-wave-RoF scheme outperforms predistortion-mm-wave RoF scheme by its smooth degradation on rate of Q-factor vs. fiber length and hence still gives a good high Q-factor of 23.2 with BER 7.7E-120 at a distance of 140 Km that overpass all other schemes which either give unacceptable or poor Q-factor of 6.5 with BER 3.78E-11. Fig. 10b shows a 15 GHz RF local oscillator along with 5 Gbps bit rate with an input power of 15 dBm, RZ modulation format. In this case, the predistortion - mm-wave scheme gives a maximum Q-factor of (263) with BER=0 at a distance of 10 Km (fiber length) compared to 121 with BER=0 reported by the conventional scheme (classical mm-wave-RoF). However, the Pre-distortion-Pre-FBG-mm-wave-RoF scheme still gives a good -factor of 8.67 with a BER of 2.05E-18 up to a maximum test distance of 140 Km, whereas all other schemes failed to generate an acceptable Q-factor and BER. Again pre-distortion-Pre-FBG-mm-wave-RoF showed a smooth and low curve of Q-factor degradation vs. link length increment. Figure 10c shows a result of 15 GHz, 10 Gbps, with input power of 15 dBm, RZ coding. In this case, the overall performance of all proposed schemes is worse than other rates 1,2.5,5 Gbps. Thus, the maximum attainable Q-factor of 18.1 with BER=2.42E-74 has been reported by the pre-distortion-mm-wave-RoF scheme at a distance of 25 Km, which also outperforms the classical mm-wave-RoF (Q-factor of 16.1 and BER of 7.9E-60) by 2. In spite of the pre-distortion- Pre-FBG-mm-wave-RoF scheme showed a smooth rate Q-factor along with BER degradation, the values of Q-factor recorded were all poor and unacceptable. Figure 10d shows the results of 30 GHz local oscillator frequency, 2.5 Gbps bit rate with input power of 15 dBm, RZ coding, in this case, the maximum attainable Q-factor of 115 at a distance of 10 km, has been recorded by using the classical mm-wave-RoF scheme whereas a Q-factor of 110 with BER=0 has been reported by the pre-distortion-mm-wave-RoF scheme. A Q-factor of 10.6 at BER=9.5E-27 is reported when utilizing predistortion-Pre-FBG-mm-wave-RoF at a distance of 140km. On other hand a Q-factor of 7.6, with BER=7.56E-15 and a Q-factor of 7.5, with BER=1.8E-14 are provided by both classical & conventional schemes respectively, at the same distance. Fig. 10e shows the simulation results of 30 GHz, 5 Gbps, with input power of 15 dBm, RZ coding. In this case, the maximum Q-factor of 51.6, with BER=0, is attained when utilizing the Pre-distortion-mm-wave-RoF scheme at a distance of 10 Km, while the same scheme still provides at a maximum distance of 82 km with Q-factor of 29, and BER=4.5E-193, then this scheme outperforms all other schemes. Fig. 10f shows the simulation results for the case of 60 GHz RF local oscillator, 1 Gbps, with input power of 15 dBm, RZ coding. In this case, a maximum Q-factor of 74.5 with zero BER, at a distance of 10 km, has been reported by the Pre-distortion-Pre-FBG-mm-wave-RoF scheme, which also outperforms other conventional schemes till 140 km, with a Q-factor of 20.9, BER=8.25E-98, which slightly outperforms the pre-FBG-mm-wave-RoF scheme that gives 19 Q-factor with BER=3.03E-84 for the same distance. Figure 11a shows a simulation results of 15 GHz local oscillator frequency, 2.5 Gbps bit rate, with input power of 8.6 dBm, NRZ coding. In this case, the maximum Q-factor of 165, BER=0 has been achieved by the pre-distortion-mm-wave-RoF scheme at a distance of 10 Km. For the same distance, the Pre-distortion-Pre-FBG-mm-wave-RoF scheme gives a Q-factor of 139 with BER=0. When the distance is increased to 140 km, the pre-distortion- Pre-FBG-mm-wave-RoF scheme still generating an acceptable value of Q-factor of 11.8 with BER=9.9E-33, whereas other conventional schemes all give an unacceptable Q-factor or BER of below 3.5. Fig. 11b shows a results of link length vs. Q-Factor for 15 GHz local oscillator, 5 Gbps, with input power of 8.6 dBm, NRZ coding. In this case, the maximum Q-factor of 97.4 at BER=0 has been provided by the pre-distortion-mm-wave scheme at a distance of 10 km fiber link length. While when the distance increased to 125 km, the pre-distortion- Pre-FBG-mm-wave-RoF scheme scored a Q-factor of 6.6, BER= 1.13E-11, which still shows low degradation rate of the Q-factor vs. optical link distance increment compared to other techniques, which all show very poor results and high fluctuation in Q-factor values. Fig. 11c shows a simulation result at 30 GHz local oscillator along with, 2.5 Gbps bitrate, at input power of 8.6 dBm, NRZ coding. Based on the pre-distortion-mm-wave-RoF scheme, a maximum Q-factor of 163 with BER=0 is reported at a distance of 10 km. For the same distance, both of conventional and Pre-distortion-Pre-FBG-mm-wave-RoF schemes give a Q-factor of 69 and 44 with BER=0, respectively. When the fiber link length is increased to 82 Km (maximum distance), the pre-distortion-Pre-FBG-mm-wave-RoF system shows better results than both conventional schemes by more than 1.8 (Q-factor gain). It hence outperforms other scenarios which either show unacceptable or deficient performance results. Figure 11d shows the simulation results of 30 GHz, 5 Gbps, with input power of 8.6 dBm, NRZ coding. A Classical scheme (no PD nor FBG) provides a maximum Q-factor of 62.8 with BER=0 at a distance of 10 km, whereas at the same distance, the pre-distortion-mm-wave-RoF scheme gives a Q-factor of 37.5 with BER=3.4E-307. After increasing the link distance to 125 km, the (pre-distortion-mm-wave-RoF) scheme still provides an acceptable Q-factor of 8.4 and BER = 2.15E-17, outperforming all other schemes that provide unacceptable performance parameters. Fig. 11e shows a Q-factor results of 60 GHz, 1 Gbps rate, with input power of 8.6, NRZ coding. In this case, the maximum Q-factor of 424, BER=0 is provided at a link length of 10 km when simulating a conventional (classical)system, but at a distance of 140 km, the pre-distortion-post-FBG-mm-wave-RoF shows a supper result of Q-factor of 15.2 with BER=1.52E-52, which is also comparable to the results provided by the Pre-distortion-mm-wave-RoF system with Q-factor of 12.8, BER=2.65E-38 at the same 140 Km distance. As a result, pre-distortion-Post-FBG-mm-wave-RoF and pre-distortion-mm-wave produce comparable results. Fig. 11f shows the simulation results in term of Q-Factor at 65 GHz, 1 Gbps, with input power of 8.6 dBm, NRZ coding. In this case, when the frequency is increased to 65 GHz of the local oscillator, the Pre-distortion-Pre-FBG-mm-wave-RoF outperforms other conventional systems and gives a Q-factor of 7.4 with BER=5.08E-14 at a distance of 140 km, while other schemes give moderate or unacceptable results. It is worth mentioning that a high fluctuation in performance results is clearly noticeable for all other proposed systems. Fig. 12a shows simulation results at 15 GHz, 2.5 Gbps, with a power changing from -15 to +15 dBm for a distance of 20 Km, NRZ coding. In this case, at a power of 1.66 dBm, the maximum Q-factor of 88.05, BER=0 is provided by the classical -mm-wave-RoF compared to the Q-factor of 51, with BER=0 for the pre-distortion-Pre-FB-mm-wave-RoF scheme. While when the power has been increased to +15dBm, the maximum Q-factor of 54.06 with BER=0 has been recorded by Pre-distortion-Pre-FBG-mm-wave-RoF at a fiber link length of 20 Km. Hence, the pre-distortion-Pre-FBG-mm-wave-RoF scheme outperforms all of the other conventional systems. Fig. 12b shows the same calculation at 30 GHz, 5 Gbps, with input power changing from 8 to 14 for a distance of 20 km, NRZ coding. The maximum Q-factor of 60.6 with BER= 0 is provided by the Pre-FBG-mm-wave-RoF scheme at a power of 8.33 dBm. With the power increasing to +15 dBm, the maximum Q-factor has been reported by the pre-distortion-mm-wave-RoF of 54 with zero BER. Hence, the pre-distortion-Pre-FBG-mm-wave-RoF outperforms all the other conventional and peer systems. We emphasize that the data were collected for the variation of mm-wave input frequencies of 15, 30, and 65 for both NRZ and RZ coding for the same power change; however, for organizational purposes in this study, we only displayed the two examples mentioned above. Figure 13a, 13b, and 13c display the eye diagrams at 60 GHz, 1 Gbps at input power of 15dBm at a distance of 140 km that are obtained for designs, classical-mm-wave-RoF, pre-FBG-mm-wave-RoF, and Pre-distortion -Pre-FBG-mm-wave-RoF, for RZ coding, respectively. Figure 13a, for the classic-mm-wave-RoF scheme, illustrates that the eye diagram is inhomogeneous. Fig. 13b shows a better eye diagram than the eye diagram obtained from the classic-mm-wave-RoF scheme. According to Fig. 13c for the Pre-distortion-Pre-FBG-mm-wave-RoF scheme, the eye diagram of the received signal at a distance of 140 km is completely clear and open. Due to optical fiber flaws including attenuation and chromatic dispersion, eye diagrams began to get distorted as transmission distance grew. The eye diagrams from fig. 13c, on the other hand, are far more capable of overcoming the effects of attenuation and chromatic dispersion since they are completely open and clear, with less distortion than those in traced by other schemes. Fig. 14 a, b and c illustrate the eye diagrams at 60 GHz, 1 Gbps at a power of 8.6 dBm at a distance of 140 Km that are obtained for designs, classic-mm-wave-RoF, pre-FBG-mm-wave-RoF, and pre-distortion-Pre-FBG-mm-wave-RoF, for NRZ coding, respectively. The explanation of these pictures is completely identical to the previous explanation of the previous case of RZ coding, but a little bit worse that RZ case and with less input power.

Table 2 comparison of existing mm- wave systems with our proposed system.

Contribution ref. no.	Carrier Frequency (GHz)	Data Rate (Gbps)	Techniques	Max. Q-factor	Min. BER	Distance (Km)	Applications
[21]	45 & 60	2.5& 7.5	Millimeter-Wave Frequency Radio over Fiber Systems		10E-9 10E-8	50	5G
[22]	28	4.8	a novel 5G architecture for the backhaul optical network that is based on UDWDM		10E-9	60	5G
[23]	60	1	Generation of 60 GHz mm-wave using narrow band brag filter	10	0	70	5G
[2]	60	2.5	Generation of mm-wave signal with carrier suppression using inverted optical filter (notch filter)	21	----	20	5G
[2]	60	10	Generation of mm-wave signal with carrier suppression using inverted optical filter (notch filter)	8		2	5G

[24] /RZ coding	-----	-----	using power transmitter optimization and dispersion compensation on optical transmission systems	46.3	0	5	5G
[24]/NRZ coding	---	----	using power transmitter optimization and dispersion compensation on optical transmission systems	25.7	1.6E-146	5	5G
[25]		5	A full duplex front-haul radio over fiber system is designed for a system consisting of four base stations.	7.5	---	90	5G
Our Proposed system	60	2.5	PD-Pre-FBG-mmwave scheme/ RZ coding	23.2	7.7E-120	140	5G
	60	5		8.67	2.05E-18	140	
	60	10		18.1	2.42E-74	25	
	90	2.5		10.6	9.5E-27	140	
	90	5		29	4.5E-193	82	
	90	1		20.9	8.25E-98	140	
Our Proposed system	60	2.5	PD-Pre/Post-FBG-mmwave scheme/ NRZ coding	11.8	9.9E-33	140	5G
	60	5		6.6	1.13E-11	125	
	90	2.5		7.8	2.10E-15	82	
	120	1		15.2	1.52E-52	140	
	130	1		7.4	5.08E-14	140	

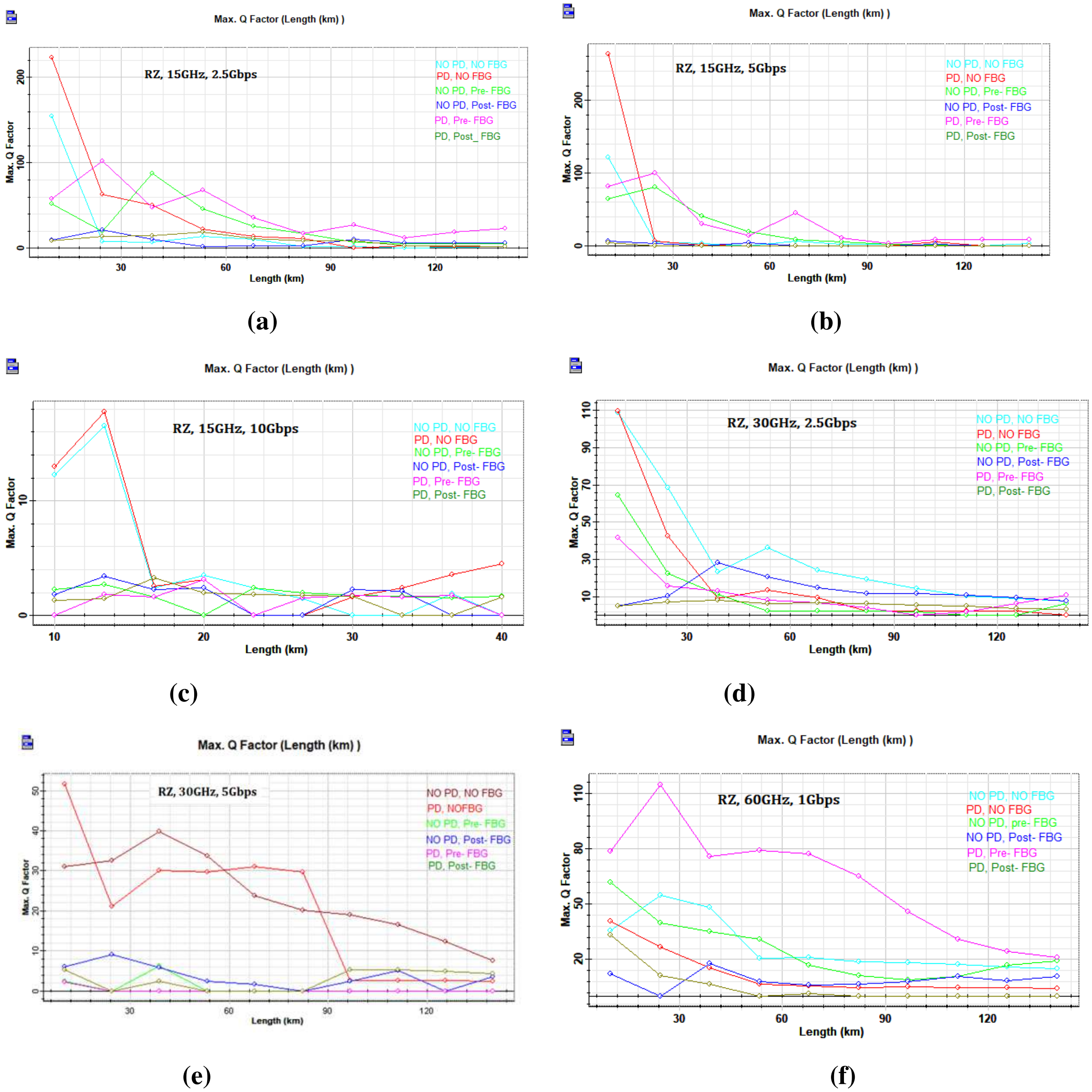
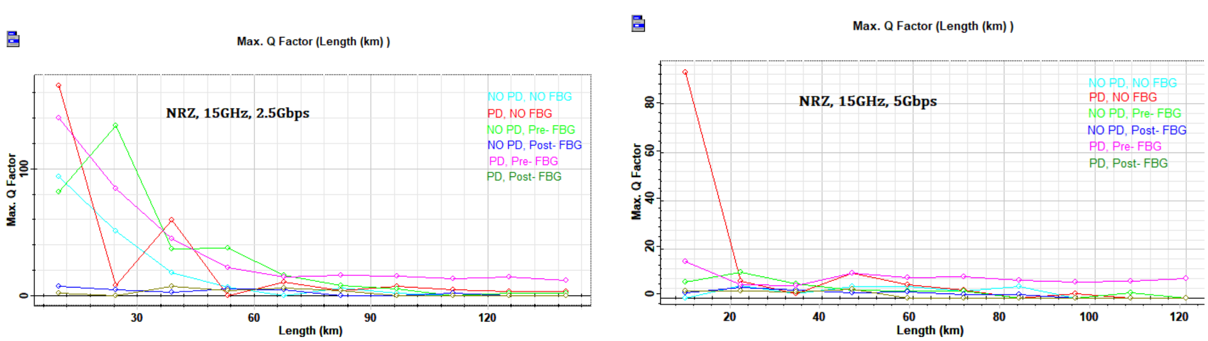


Fig. 10 Optical fiber length (Km) vs. max Q- factor for RZ modulator, all at power of 15 dBm, (a) 15 GHz, 2.5 Gbps (b) 15 GHz, 5 Gbps (c) 15 GHz, 10 Gbps (d) 30 GHz, 2.5 Gbps (e) 30 GHz, 5 Gbps (f) 60 GHz, 1 Gbps.



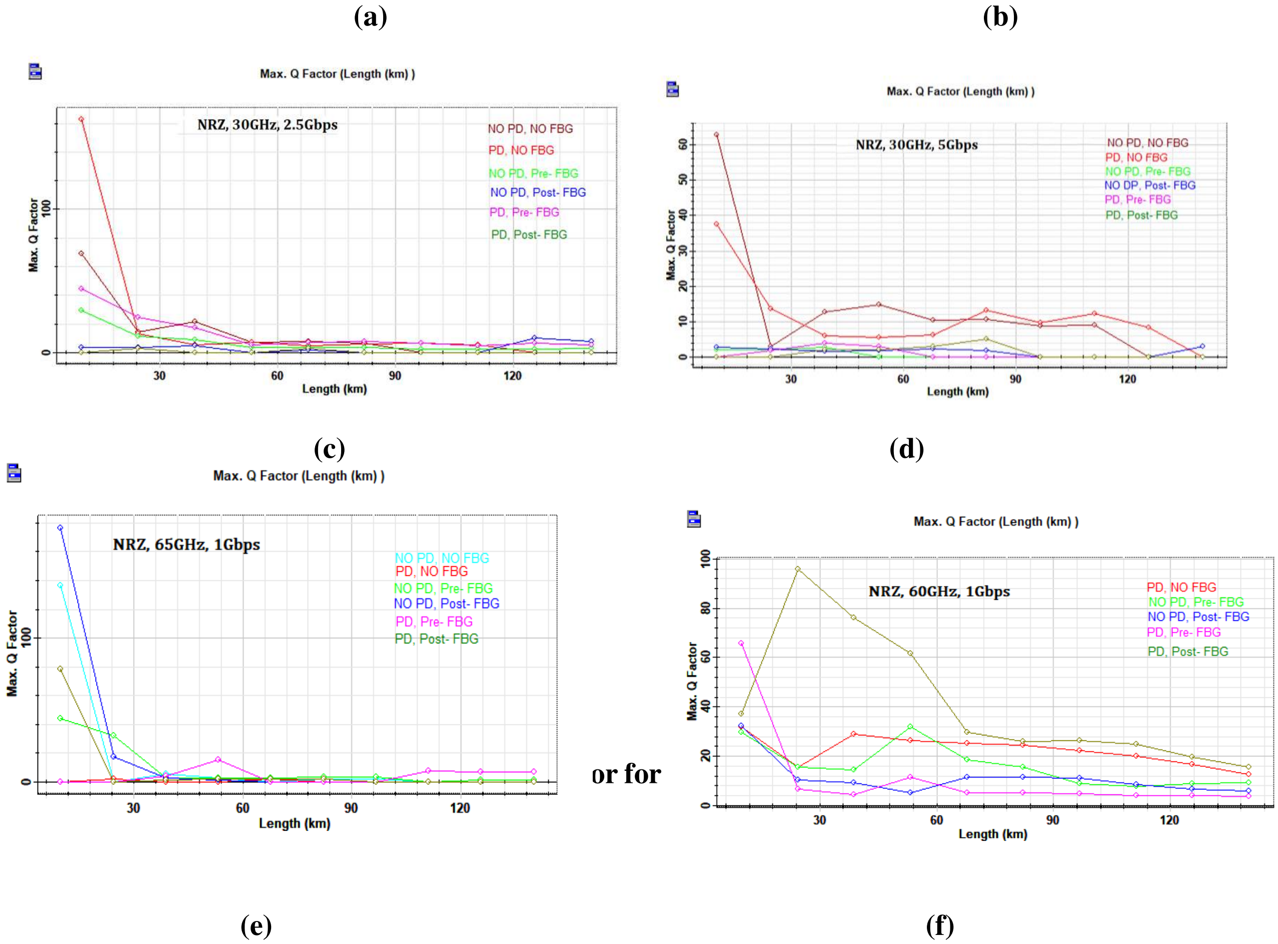


Fig. 11 Optical fiber length (Km) vs. max Q- factor for NRZ modulator, all at power of 8.6 dBm, **(a)** 15 GHz, 2.5 Gbps **(b)** 15 GHz, 5 Gbps **(c)** 30 GHz, 2.5 Gbps (d) 30 GHz, 5 Gbps **(e)** 60GHz, 1 Gbps **(f)** 65 GHz, 1 Gbps.

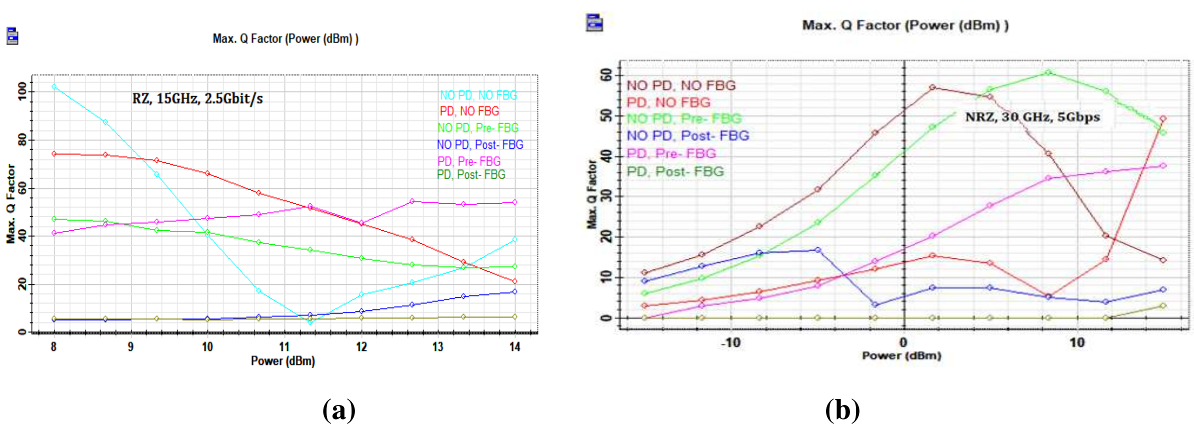
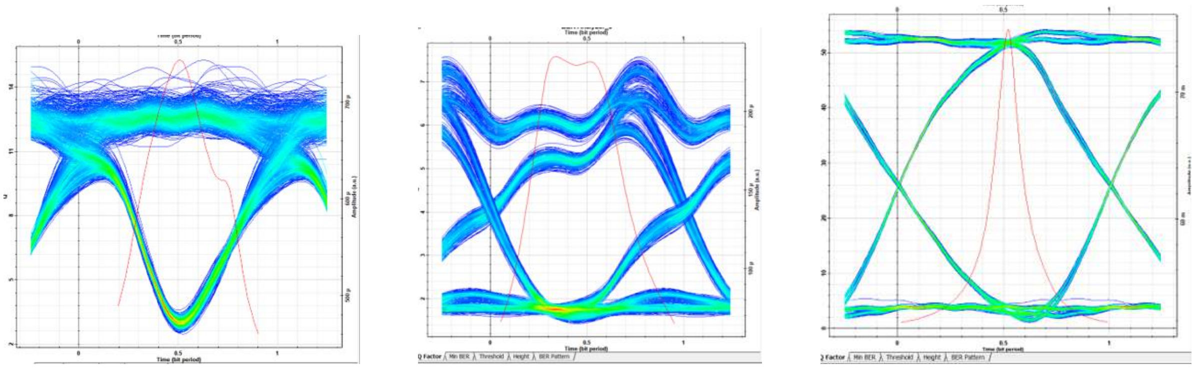
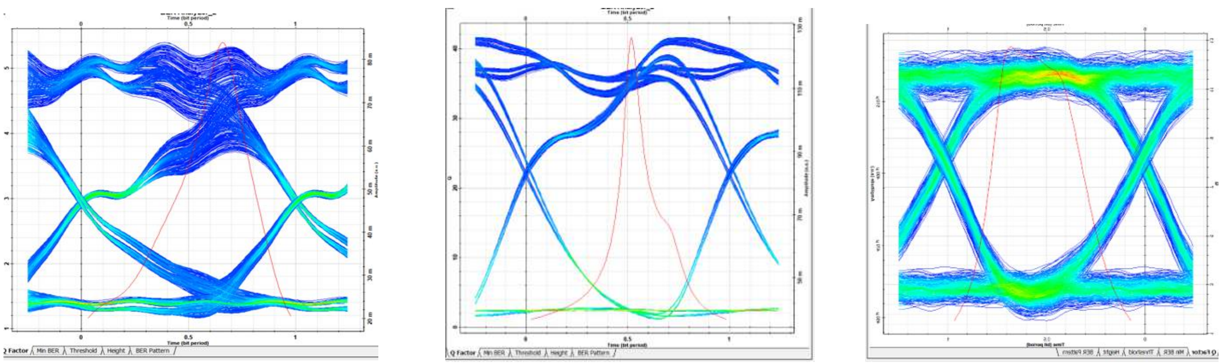


Fig. 12 Power changing in dBm vs. Max Q-factor, NRZ modulator, 20 Km fiber link length **(a)** 15 GHz, 2.5 Gbps **(b)** 30 GHz, 5 Gbps.



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

Fig. 13 Eye diagram of the received signal for 60 GHz, 1 Gbps, power of 15 dBm, and 140km, mm-wave RoF and for modulation formats of RZ **(a)** classic-mm-wave-RoF scheme **(b)** pre-FBG mm-wave-RoF scheme **(c)** Predistortion-Pre-FBG-mm-wave-RoF scheme



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

Fig. 14 Eye diagram of the received signal for 60 GHz, 1 Gbps, power of 15 dBm, and 140km, mm-wave RoF and for modulation formats of NRZ **(a)** classic-mm-wave-RoF scheme **(b)** pre-FBG mm-wave-RoF scheme **(c)** Pre-distortion-Pre-FBG-mm-wave-RoF scheme.

Particularly for 5G applications, 10 Gbps of analog data with 60 GHz millimeter-signal is sent via 60 Km of optical fiber. The suggested RoF transmission system's performance is assessed using the Q-factor, BER, and eye diagrams. It may be inferred from the findings and discussion section that RZ- encoding schemes work better up to a fiber transmission distance of 45 km, but that NRZ- encoding schemes perform better than RZ-encoding schemes for longer fiber transmission distances. Successive transmission of the 60 GHz millimeter signal and 10 Gbps data is achieved with acceptable eye diagrams, Q-factor, and BER.

5. Conclusion

It has been determined in this study that mm-wave signals can be produced successfully using the Predistortion-Pre-FBG-mm-wave-RoF method for both RZ and NRZ coding in a simple, affordable architecture, balancing the received signal strength of the desired produced signal by using a digital Predistortion with a Pre-FBG. When implementing the data over a long distance of 140 km, the OPTSYSTEM simulation has shown that the proposed design has good transmission performance in both predistortion-mm-wave and Predistortion-Pre-FBG-mm-wave-RoF scenarios, when utilizing RZ format which showed superior results over NRZ format at high frequencies and long distances. The maximum Q factor for 140 km is 20.9 for 1 Gbps data transmission using 60 GHz, power of 15 dBm, and RZ coding. Additionally, the resulting signal for the 140 km SMF length has a Max Q factor of 12.8 for 60 GHz (120 GHz mm-wave), 1 Gbps, with a power of 8.6 dBm, NRZ coding. Additionally, with a Q-factor of 16.1 and BER=7.9E-60 for RZ coding, the performance of the suggested predistortion-Pre-FBG-mm-wave-RoF scheme is still too effective up to 10 Gbps for 140 km. Also, 10 Gbps has been tested for which the predistortion-mm-wave-RoF gives Q-Factor of 18.1 with BER of 2.72E-74 for a distance of and utilizing RZ format and a local oscillator of 15 GHz. It is determined that Predistortion-Pre-FBG-mm-wave-RoF may be taken into consideration to create efficient mm-wave with low cost and over long distances in our suggested scenarios of modulating the data. As shown by the findings, which revealed that the Q-factor value and the eye diagram were outstanding for the two coding schemes utilized. The suggested RoF Predistortion-Pre-FBG-mm-wave-RoF technique may be regarded as having a straightforward structure, being priced, and being appropriate for the deployment of contemporary wireless communication systems at long distances.

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Conflict of Interest

Both authors declare that they have no conflicts of interest

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