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Performance Analysis of Full- Duplex NG-PON2-RoF System with Non-linear Impairments

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Abstract The motivation of this study springs from the need of exploiting the advantages of high data rate and increased mobility of the transmitted signal in the Next Generation Passive Optical Network stage 2 (NG-PON2) incorporated into Radio over Fiber (RoF) system. Nonetheless, such system is prone to degradation due to the nonlinear effects, namely, the non-linear impairments. Accordingly, this study suggests a design for a full-duplex NG-PON2-RoF system and it investigates the impact of the nonlinear effects on the performance of system, such as; Self-Phased Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM). However, these effects would result in a significant data loss in Time and Wavelength Division Multiplexing-Passive Optical Network (TWDM-PON). To achieve the intended purpose of this investigation, both the performance of the suggested system and the nonlinear effects of SPM, XPM, and FWM are measured with reference to the qualitative parameters, such as; Bit Error Rate (BER), Q-Factor, Power link Budget, and the Eye-diagram. The results show that the system performs efficiently; however, in the presence of the nonlinear effects, the performance of the systems degrades significantly affecting the signal quality. It is worth noting that the FWM effect yields the most negative impact followed by the XPM, and the SPM effect yields the least significant impact on the system. Also, the system yields the capacity of transmitting range of 20-100 Km, and it results in data rate of 40-80 Gbps. The proposed system is simulated using the software Optisystem 15.

Keywords: Radio over Fiber (RoF), Next Generation Passive Optical Network stage 2 (NG-PON2), Self-Phased Modulation (SPM), Cross-Phase Modulation (XPM), Four-Wave Mixing (FWM), and Time and Wavelength Division Multiplexing-Passive Optical Network (TWDM-PON).

1- Introduction

In the recent years, the number of users of the wireless networks has been considerably increasing due to the increase of smartphones as well as the applications that require considerable bandwidth such as video conferencing, online video gaming, and High Definition online broadcasting. The result is an unprecedented expansion in data traffic which is constantly growing. It is predicted that the sum of data traffic will be around 49 Exabytes (EB) by the year 2021. This expansion subsequently requires very high data rates transmitting radio signals for long distances over-the-air. The radio signals will be deteriorated when

transferred for long distances. Hence, there will be attenuation and increase in the signal density. Due to the signal deterioration, the infra structures of the wireless networks have to be constantly developed, where maintaining such networks is costly. However, to overcome these challenges, a new promising technology is to emerge; it is the matching between wireless networks and cable networks. This technology is known as RoF[1, 2] . It helps in simplifying base stations and lowering the cost of maintenance. It is noteworthy that the vector modulation methods are utilized widely in the RoF systems because of their exemplary bandwidth efficiency[3, 4]. The channel efficiency of such system reaches the optimal performance for transmitting digital data when utilizing QAM. Therefore, RoF is desirable because of its bandwidth efficiency as well as high data rate. Also, disadvantage is possible in such medium; when transferring signals for a long distance, chromatic dispersion could occur causing extra distortion.

Passive Optical Network (PON) is a telecommunication network which utilizes optic fiber cables for transmitting data. It is known as passive network due to the fact that, in this network, there is a passive optic splitter exploited to connect consumers' devices. There are neither active devices nor electrically powered parts in such type of networks. It utilizes energy efficiently. The application of this network is determined by the length of the fiber cable[5] .However, transmission of high capacity, service of multiplex capability, and flexible network operation go through continuous developments and they are among the top priorities of the Full Service Access Network Group (FSAN) and the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T). This resulted in the development of the NG-PON2, which consists of optical network unit (ONU) and optical line terminal (OLT). In addition, this network uses from four to eight channels with a structure of TWDM network with minimum value of a transmission distance of 40 Km. However, it uses bidirectional optical fiber of 10 Gps for the downlink and 2.5 Gps for the uplink, with splitter value of users of at least 256 [6].

Time and Wavelength Division Multiplexing-PON (TWDM-PON) is a different hybrid passive optical network, which transfers via the WDM of the source fiber. The wavelengths are transmitted to the end devices by utilizing a power splitter as RN[7] . This technology depends on combining the features of WDM-PON with those of TDM-PON. It provides high data rate of up to 40 Gbps for a distance of 40 Km without any adjustment on both ends of the optical fiber; the OLT and ONU. Even though there are several technologies such as WDM-PON, OCDM-PON, and OFDM-PON, TWDM-PON has been selected as the best technology that meets the requirements of the Next Generation Passive Optical Networks. This is because TWDM-PON is fully developed, and it matches the previous technologies. More importantly, it is cost-effective[8] .

The optical fiber technology is promising for developing the next generation networks. It has a high capacity to accommodate very large data rates transmitted for very long distances with low values of attenuation. Such networks have different qualities from the conventional networks. The optical fiber networks have low rates of noise and they are not affected by radio frequency interference. Also, they have a completely isolated medium. Ultimately, they are not affected by climate conditions or high-voltage exchange [9]. Yet, when transmitting the signals through a RoF network, there will be simple interaction between the light waves and the carrying material. This interaction will result in nonlinear effects[10].

The idea of RoF is integrated with NG-PON2 in order to exploit the benefits of high data rate and increased mobility. However, there are two types of effects that degrade the system quality, which represents non-linear effects in optical fiber; firstly, called the non-linear impairment, and secondly, names the inelastic scattering. It is worth noting that, the non-linear impairments of medium will be result in Kerr effect. Thus, according to this effect, with regard to the form of the input signal, the effects of different inelastic scattering, such as; stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) and the non-linear impairments, which categorizes into: dispersion, FWM, self-phase modulation (SPM) and cross-phase modulation (XPM) will be degrade the system quality. In this paper, the focus is only on the non-linear impairment effects[10, 11].

In the optical fiber, a phase shift could occur and it could be intensity dependent. Such shift results from a refractive index of the intensity dependent type.When modulating an optical beam, the optical intensity will be time-dependent and thus will be the medium refractive index. Therefore, self-activated false phase modulation will emerge from a propagation of an arbitrary wave occurring in Kerr condition. Therefore, SPM occurs if there is propagation of a single beam in the medium.

The XPM occurs if a variety of signals with various wavelengths propagates into a nonlinear fiber. It might occur in the WDM systems leading to perturbing the phase of each signal due to the phase fluctuations of the other signals. The XPM is as two times determintal as the SPM. It is very challenging to roughly calculate the effect of the XPM on the WDM systems. Nonetheless, the effect of the XPM can be reduced by two procedures. First, the bit rates of the adjacent WDM channels have to be precise. Second, the effecitive area has to be brodeaed in the optical fiber core.

FWM occurs during the process of transmission when the phase modulation of channels is caused by the pulsation of light and various wavelengths. Both of the pulsation of light and various wavelengths have to be carried over a fiber of multichannel. As a result for that, FWM new frequencies will be modulated ,

The 3rd order nonlinear susceptibility (x3) is responsible for generating the process of FWM. The nonlinear polarization which is responsible for power-dependent refractive index is also responsible for nonlinear polarization term at frequency of w_4. To clarify, frequency w_4 will be generated by X^3 when there are three optical fields with carrier frequencies of w1, w2, and w3, propagating with each other at the same time inside the optical fiber. In essence, the SPM and XPM are substantially significant in systems of high rate bit. Nonetheless, the FWM effect operates independently from the rate bit systems, and it is crucially determined by the space of the channel and fiber dispersion. Thus, the FWM effect increases when the channels spacing and fiber dispersion are decreased [12].

The authors discuss in [13] the RoF over GPON system using full-duplex technology for transmission distance of 2-20 Km. This network was simulated by using the optisystem software. The performance of the system was measured according to BER, OSNR, and the received power. The authors noted that the minimum value of the BER is at 20 Km transmission distance. It is obvious that the researchers in this study overlooked the Dispersion Compensating Fiber (DCF) in their design.

The authors in[14] investigated the effect of one nonlinear, the FWM, on the WDM-RoF-EPON. They utilized an SOA through compensating the dispersion. The space ratio of the transmission channels is 10.95 using unequal distances for the same optical fiber. The authors concluded that the performance of the system is enhanced by utilizing the FBG and DCF by evaluating the Q factor and Eye-diagram. It is necessary to point out that in this study the researchers investigated the effect of the FWM without considering the other nonlinear effects, namely, the SPM and XPM.

Reference[15] proposed a new system in which the TWDM-PON is used with the GPON. The researchers provide this system as a solution for achieving high data rate value. They used various types of modulation. The authors also measured the performance of the system by calculating the Q-factor and the eyediagram. They concluded that the optimal type of modulation for such system is the RZ-DQPSK. In addition, they noted that system provides a flexibility in data transmission. However, in their investigation, the authors neglected the effects of dispersion and attenuation on the system as well as the nonlinear effects.

Reference [16] focused on optimizing the launch power to decrease the nonlinear effects of the optical fiber in a NG-PON2 system within WR-ODN network. The authors concluded that there was marginal power accompanies the launch power, and when the marginal power is reduced the nonlinear effects decrease. Therefore, dispersion and nonlinearity greatly depend on the optical launch power for any wavelength.

The authors in [17] analyzed the RoF system in lightening the FWM. They simulated eight channels with input power of 0 dBm. These channels have spacing of 75 GHz. The results show, for their proposed system, that the FWM decreases when the input power is 4

dBm. There are drawbacks in this study. First, the authors designed the system with eight channels only which is part of the system. To analyze the performance of the whole system, 256-512 channels should be included. Second, they used a uni-adirection system instead of a bidirectional system.

It is evident now that the previous studies did not match the NG-PON2 with RoF. Also, none of the previous studies have considered all the nonlinear effects at once. In addition to that, all the studies have simulated the performance of their systems with transmission distance that ranges from 20 to 60 Km. Finally, some studies were conducted on unidirectional system. Therefore, this study addresses the issues overlooked by the previous studies, specifically, the current investigation will simulate a full- duplex NG-PON2-RoF System through the analyze the performance of the system in the presence of the nonlinear effects, namely the Kerr effects, in addition to the dispersion as a limiting factor in such system, where the transmission distance ranges from 20 Km to 100 Km. It is essential to clarify that the four transmitted frequencies are assigned for the uplink and the downlink. The analysis is carried out by transmitting four radio frequencies over Bidirectional Optical Fiber. The transmitted frequencies are in accordance with the standards of the NG-PON2 system enacted by the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T). The architecture of the prosed system is designed according to the TWDM network.

The rest of the paper is organised as follows: the tackles the architecture of the proposed system is discussed in section 2. Section 3 presents and discusses the performance evaluation of the proposed system. Finally, section 4 is drawn the concluding remarks of this paper.

2- Proposed Transmission System Model

The TWDM-PON- RoF architecture of the proposed design is illustrated in Figure (1). This architecture is built upon NG-PON2 which is a bidirectional optical system. The architecture has three sections. They are: OLT, ONU and Optical Distributed Network (ODN).
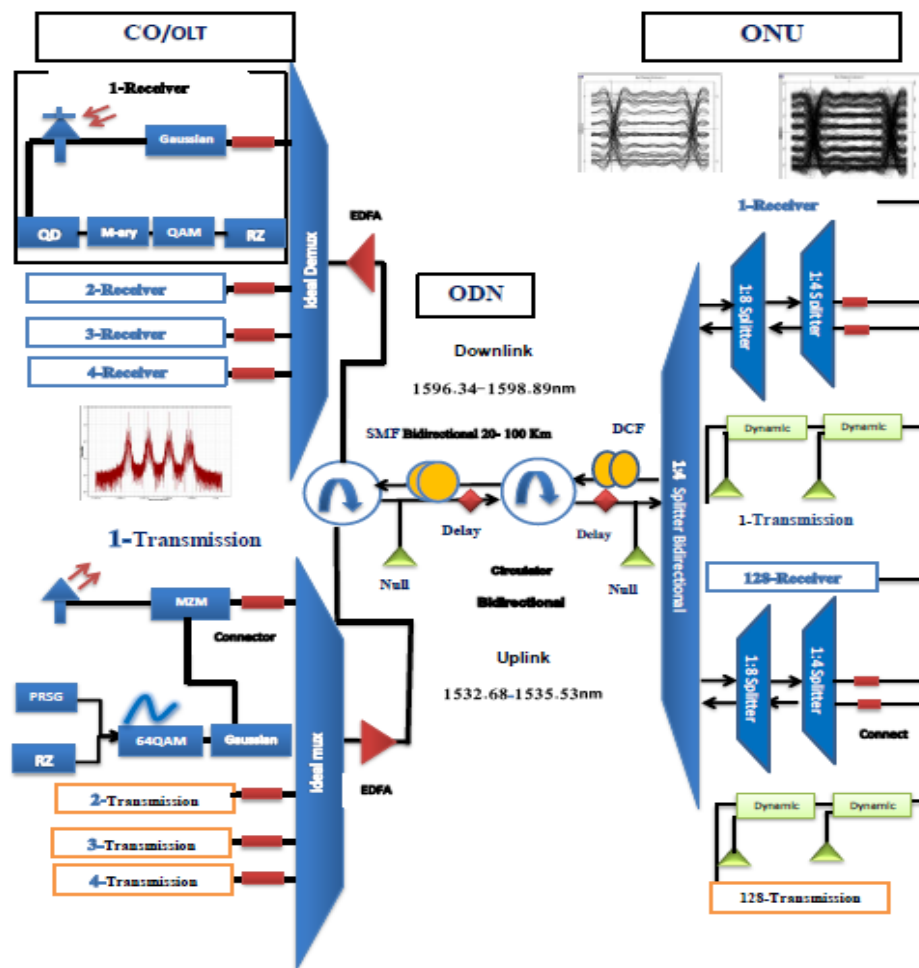
Fig.1 The proposed NG-PON2- RoF architecture system.

The OLT contains EDFA, TX, and RX. The TX (figure 1), also known as block transmission, has four channels of four downlink wavelengths. The TX also contains four Pseudo-Random Bit Sequence Generators (PRBSG). They are responsible for generating random data coded as Return to Zero (RZ). In this proposed design, each channel of these four was modulated from the electric form to the optical form of 7.5 GHz. To this end, four electric QAM modulators were used while the bits per symbol is 4 bits (16 QAM). Additionally, there are four Band Pass Gaussian filters. At this point, the Radio over Fiber matching is achieved through the Mach-Zehnder Modulator when meeting the CW laser. The CW laser represents the channel. Since the TX block has four channels, then there has to be four connectors between the channels and WDM MUX. The connectors are of an attenuation rate of 0.35 dB.
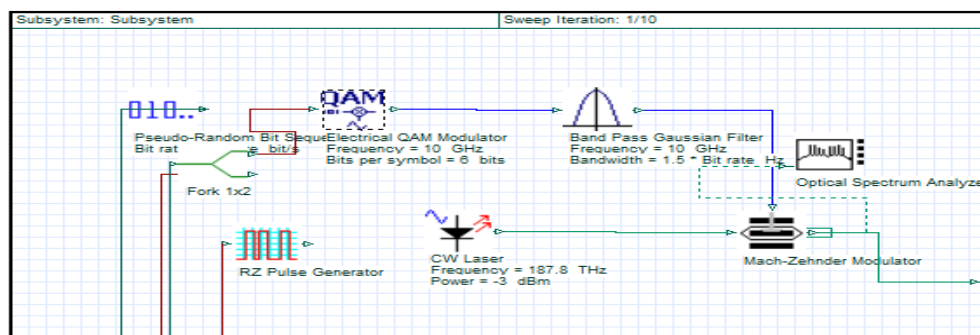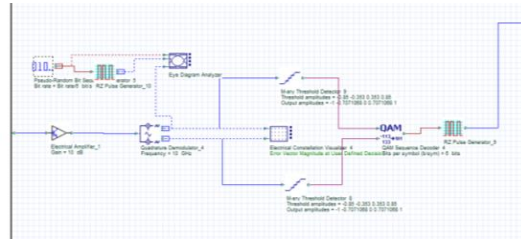

Fig.2 – Transmission (OLT)

The RX, also known as block receiver, has four uplink wavelengths, see figure (3)a and figure (3)b. It contains a power splitter, four photodetectors APD, four Gaussian optical filters, and four demodulators. The four demodulators are quadrature followed by 4 M-ary threshold detectors, 16-QAM sequence decoder (four), and 4 RZ pulse generators.
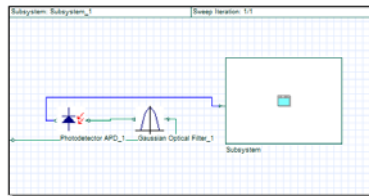

Fig.3-a – Receiver (OLT)   **Fig.3-b**– Receiver (OLT)

The second section in the proposed architecture is the Optical Distributed Network (ODN), see figure (4). It has two optical circulators, bidirectional optical fiber (20-105) km, three optical delay, two layouts, and power splitter 1:4, power splitter 1:8, power splitter 1:4 for each downlink and uplink wavelengths. Also, these power splitters are joined by connectors of 0.35 dB attenuation rate.
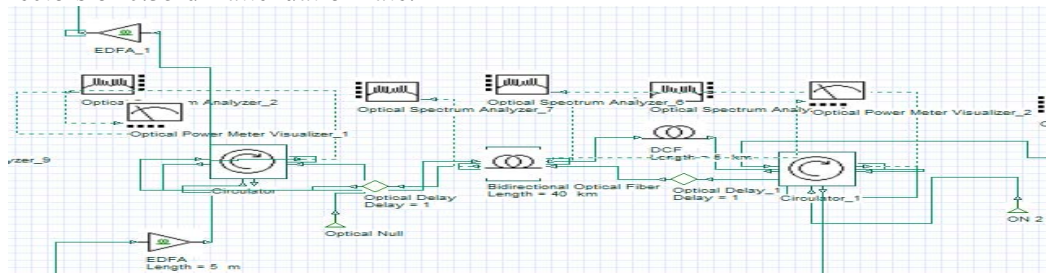

Fig.4 – Optical Distributed Network (ODN)

The third section of this architecture is the ONU. It contains EDFA, RX, and TX, as illustrated in figure (5). The RX, also known as block receiver, has four uplink wavelengths, see figure (1). It contains a power splitter, 128 photodetectors APD, 128 Gaussian optical filters, and 128 demodulators. The 128 demodulators are quadrature followed by 128 M-ary threshold detectors, 16-QAM sequence decoder (128), 128 RZ pulse generators.
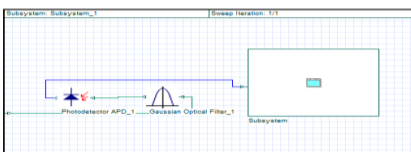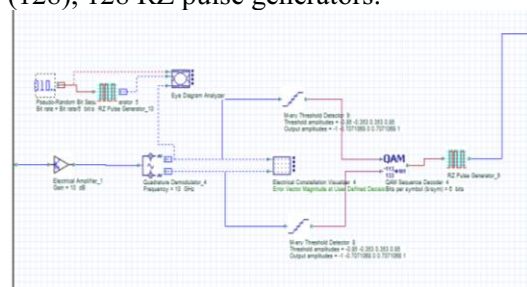

Fig.5-a – Receiver (ONU)   **Fig.5 -b**– Receiver (ONU)

The TX (figure 6), also known as block transmission, has 128 channels of four downlink wavelengths. The TX also contains 128 Dynamic switches and128 Pseudo-Random Bit Sequence Generators (PRBSG). They are responsible for generating random data coded as Return to Zero (RZ). In this proposed design, each channel of these 128 was modulated from

the electric form to the optical form of 7.5 GHz. To this end, 128 electric QAM modulators were used while the bits per symbol is 4 bits (16 QAM). Additionally, there are 128 Band Pass Gaussian filters. At this point, the Radio over Fiber matching is achieved through the Mach-Zehnder Modulator when meeting the CW laser. The CW laser represents the channel. Since the TX block has 128 users, then there has to be 128 connectors between the channels and powers splitters. The connectors are of attenuation rate of 0.35 dB.
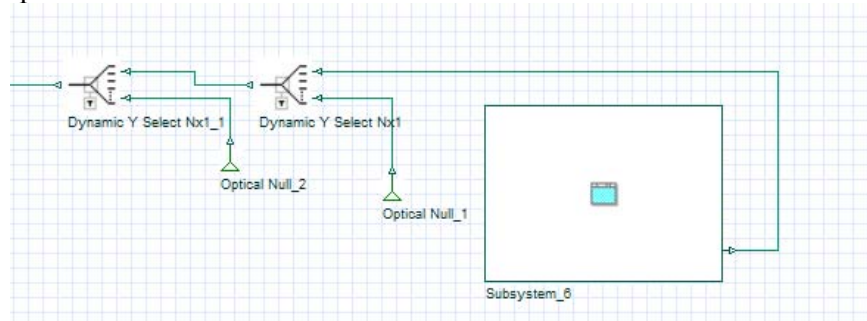
Fig.6 – Transmission (ONU)

However, it is crucial to note that the FWM was generated depending on the Refractive Index (n2) according to the equation [18]:

$$N2 = 3/8N\ Me(X\_iii^{((3))}) \tag{1}$$

where:

N2 = nonlinear Refractive index
N = refractive index
Me (xiii) = the real part which responsible for generating the nonlinear effect, FWM.

3-Results and Discussion

The system (NG-PON2) has been simulated first without the nonlinear effects, then it was simulated in presence of the nonlinear effects, namely; SPM, XPM, and the FWM. The aim of the simulation is to discover what would happen to the spectrum when it traveled for long distances. The power launch intensity has been measures by using the Optical Power Meter Visualizer. It is carried out while changing the nonlinear parameters in Bidirectional Optical Fiber as in figure (7).
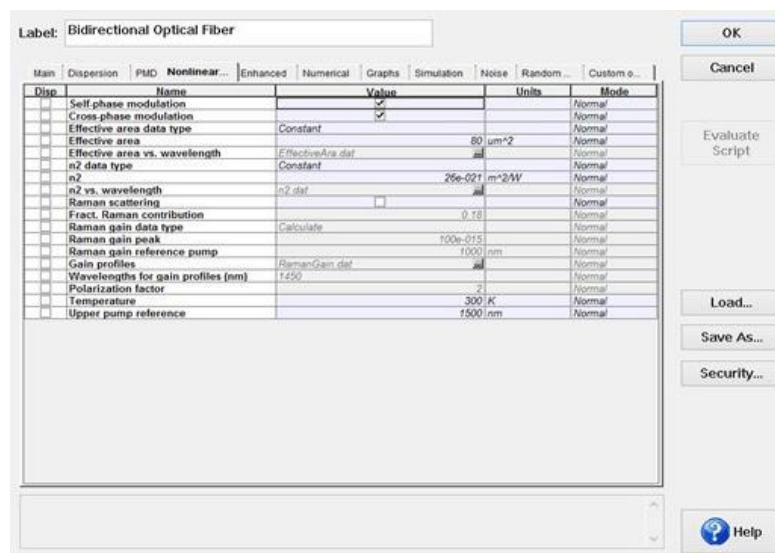
**Fig. 7** – SPM, XPM and FWM parameters

The spectrum in figure (8) shows the result of transmitting four wavelengths. The download frequencies of these wavelengths are 1596.34 nm, 1596.19 nm, 1598.04 nm, and 1598.89 nm respectively.
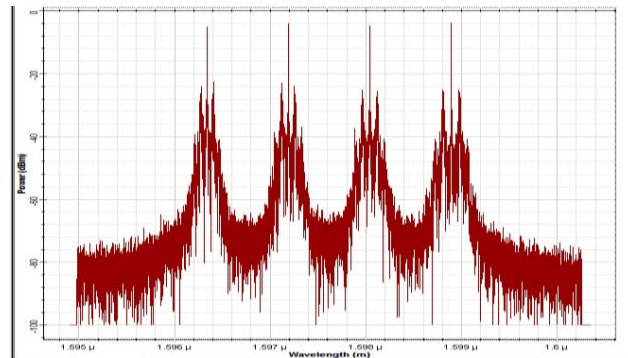
Fig.8 – spectrum download frequencies

For the first simulation, that is the performance of the system in accordance to linearity, the Q factor has been measured in relation to the distance of transmission for both the download and upload processes according to three values of the power launch. The values are -3 dBm, 7 dBm, and 11 dBm respectively. Figure (9) illustrates the download process. It could be noticed that from Fig. 10 the value of the Q factor decreases when the distance increases for the download process and if the power launch increases, the value of the Q factor will reach higher quality. It is noticed that at the distance of 55 Km, the value of the Q factor is within the acceptable standards of the NG-PON2 systems.
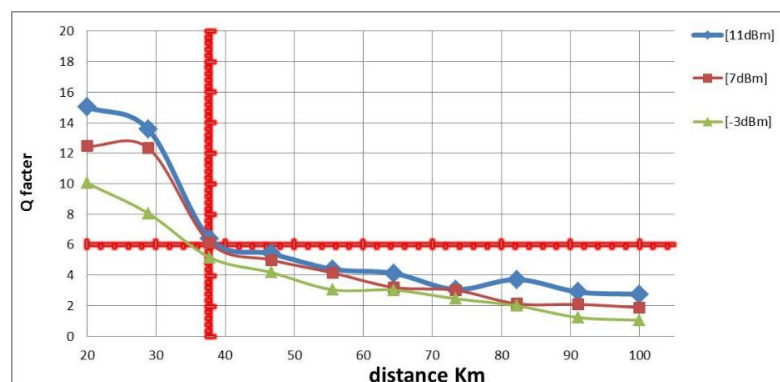
For the upload process, the results showed the same relation for the Q factor values to the transmission distance and the power launch values. There is direct proportional increase.
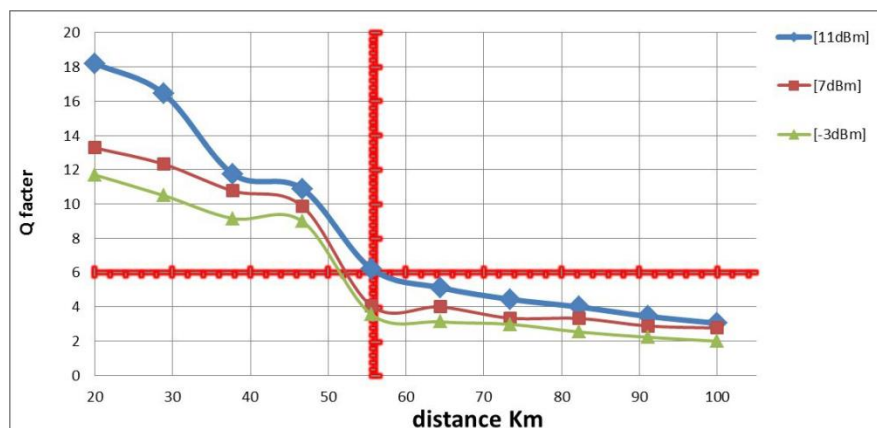
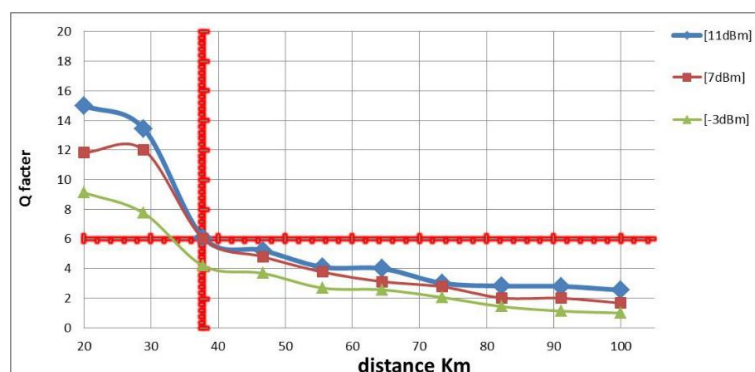**Fig.9** Q -factor to distance (downlink)
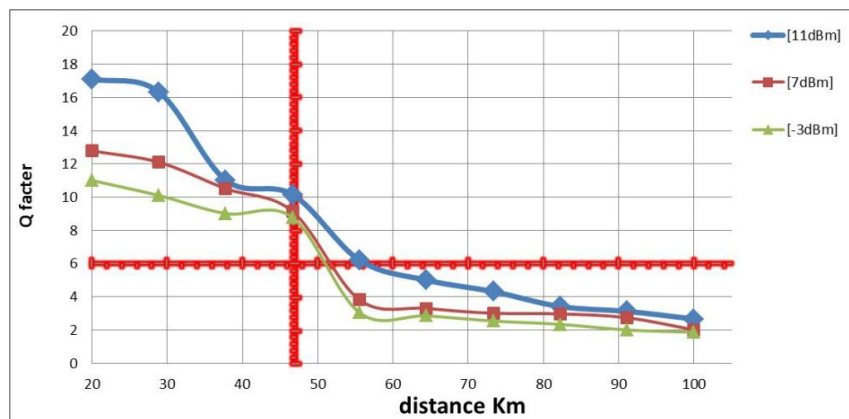
Fig.10 – Q Factor to Distance (uplink)

For the second simulation process showing the performance of the system in the presence of the nonlinear effects, the Q factor was also measured in relation to the distance of transmission for both the download and upload processes according to three power launch values. The values are -3 dBm, 7 dBm, and 11 dBm respectively. Figure (11) illustrates the download process.

Fig. 11 – Q Factor to Distance in the presence of the nonlinear effects (Downlink)

For the upload process, the results showed the same relation for the values of the Q factor to the transmission distance and the power launch values. There is direct proportional increase. For more details, see figures (12) .

Fig. 12 – Q Factor to Distance in the presence of the nonlinear effects (uplink)

For the system performance with the absence of the nonlinear effects, the results indicate that if the mean of the distance is 55.55 km, the system operates differently according to the values of power launch. When the values of the power launch are -3 dBm, 7 dBm, and 11 dBm, the mean values of the Q factor for the download process are 3.55, 4.5, and 6.22 respectively, corresponding to the power launch values, when the Q factor = 6.22 is the only standard value. That is, the performance of the system is acceptable.

For performance of the system in the presence of the nonlinear effects, the results indicate that if the mean of the distance is 55.55 km, the system operates differently according to the values of power launch. When the values of the power launch are -3 dBm, 7 dBm, and 11 dBm, the mean values of the Q factor for the download process are 2.68, 3.76, and 4.9 respectively corresponding to the power launch values. That is, the quality of the systems degrades significantly. The second parameter according to which the system is measured is the BER in relation to the wavelength. For the performance of the system with the absence of the nonlinear effects in the download process, see figures (13) .
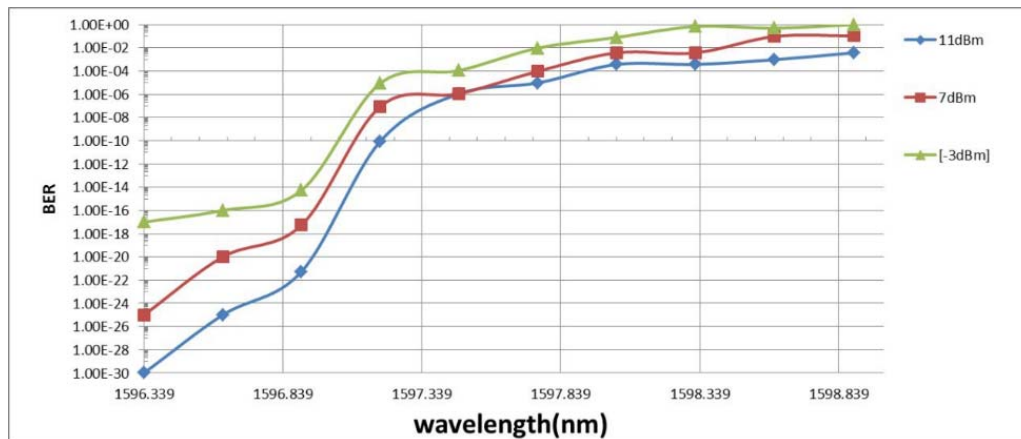

Fig. 13 – BER to Wavelength

It seems that the transmission channels have insignificant distortion. For the power launch of 11dBm, the mean value of the BER for the wavelength 1597.18 nm is 9.07E-11. This is an acceptable value for the system to operate normally. For the performance of the system in the presence of the nonlinear effects in the download process see figures (14) .
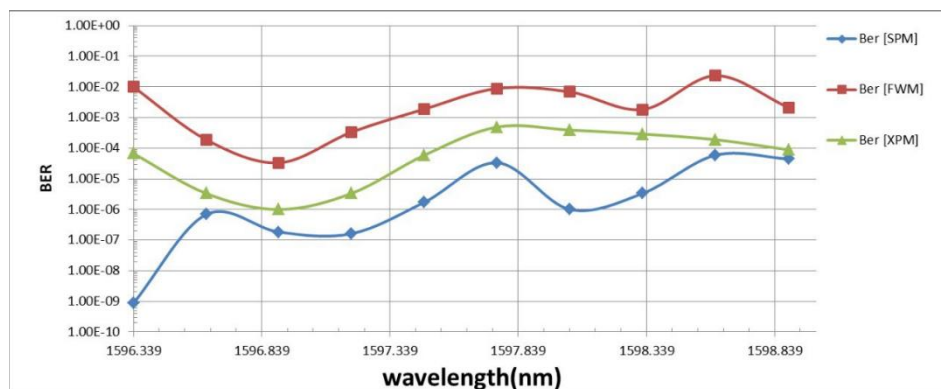
Fig. 14 – BER to Wavelength in the presence of the nonlinear effects

For each of the nonlinear effects, the BER parameter is measured. It seems that the most degrading effect is the FWM, then the XPM, followed by the SPM. At the wavelength of 1597.18 nm, the values of the BER for the FWM, XPM, and SPM are 3.35E-04, 3.35E-06, and 1.62E-07 respectively. These values indicate that the system does not operate properly. The receive power losses are measured for the whole system, see figures (15) .
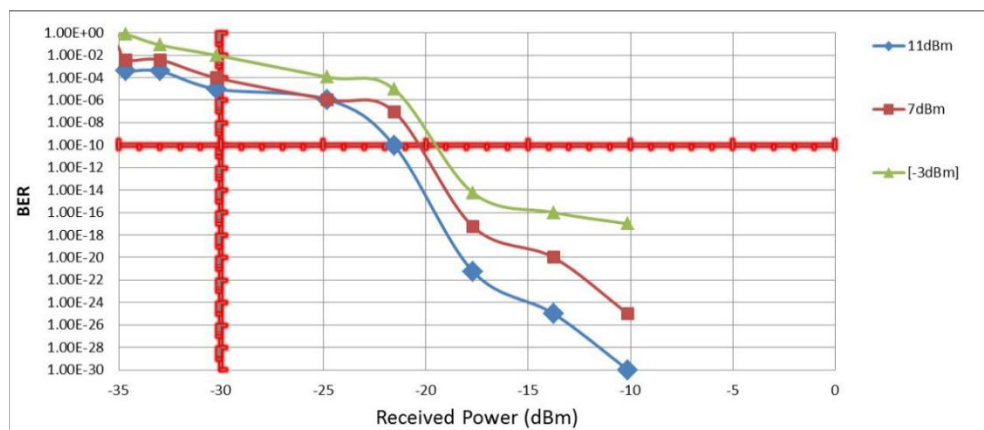
Fig. 15 Received Power to BER

Due to the presence of the nonlinear effects, there is a significant loss in the receive power in relation to the BER. The values of this loss ranges from -23.98 dBm to -36.98 dBm. However, the BER increases whenever the loss values of the receive power increase too.

Finally, to judge the quality optical signal of the proposed system without the presence of the nonlinear effects, a graphical representation has been carried out at transmission distances of 20 Km, 50 Km, and 100 Km. The Eye-Diagrams (figure 16), and (figure 17) below illustrate the quality of the signal for the download and upload processes.
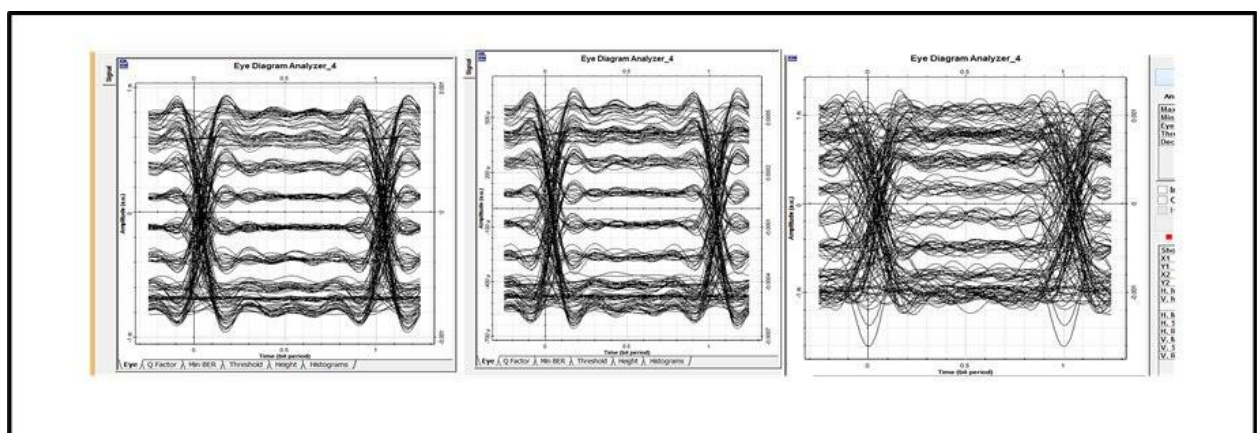
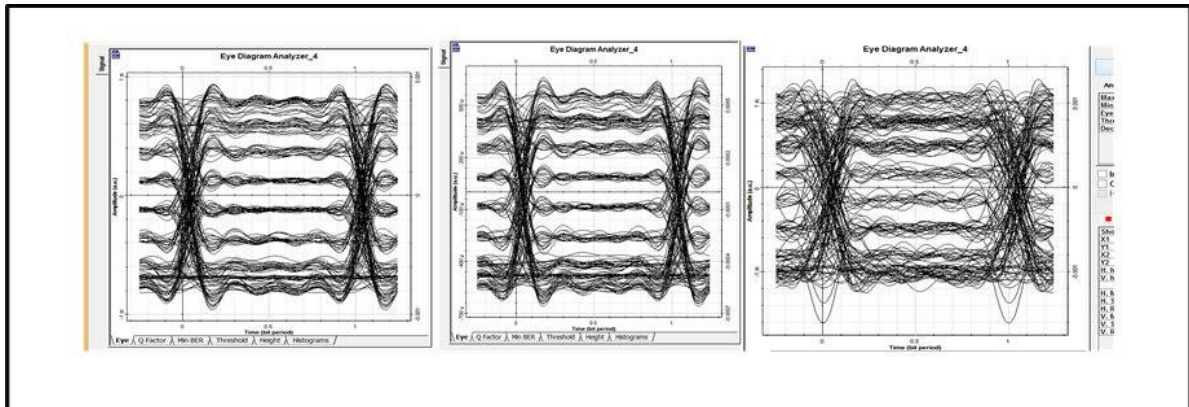Fig. 16 Eye-Diagram without the nonlinear effects (Downlink)

Fig. 17 Eye-Diagram without the nonlinear effects (Uplink)

The quality optical signal was also evaluated of the proposed system in the presence of the nonlinear effects using a graphical representation. The representation was carried out at transmission distances of 20 Km, 50 Km, and 100 Km. The Eye-Diagrams (figure 18), and (figure 19) below illustrate the quality of the signal for the download and upload processes.
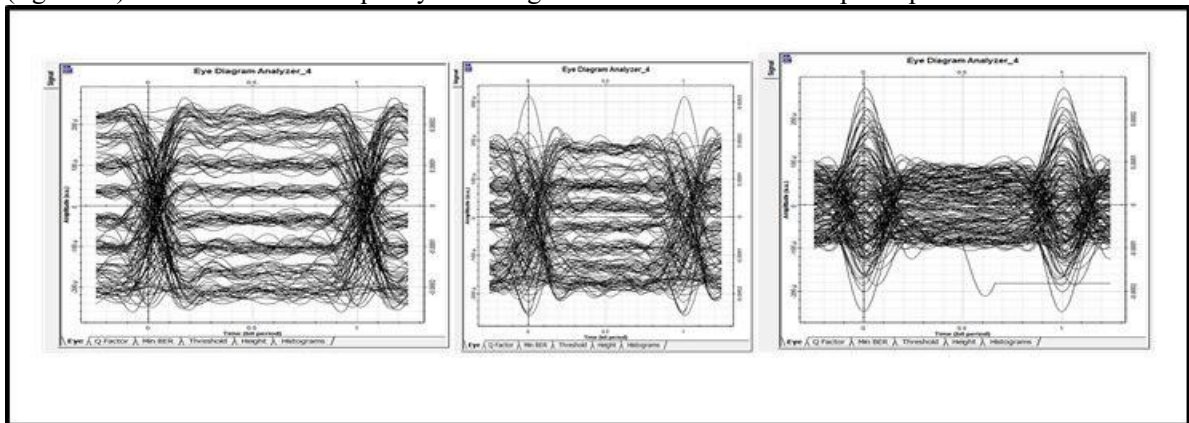

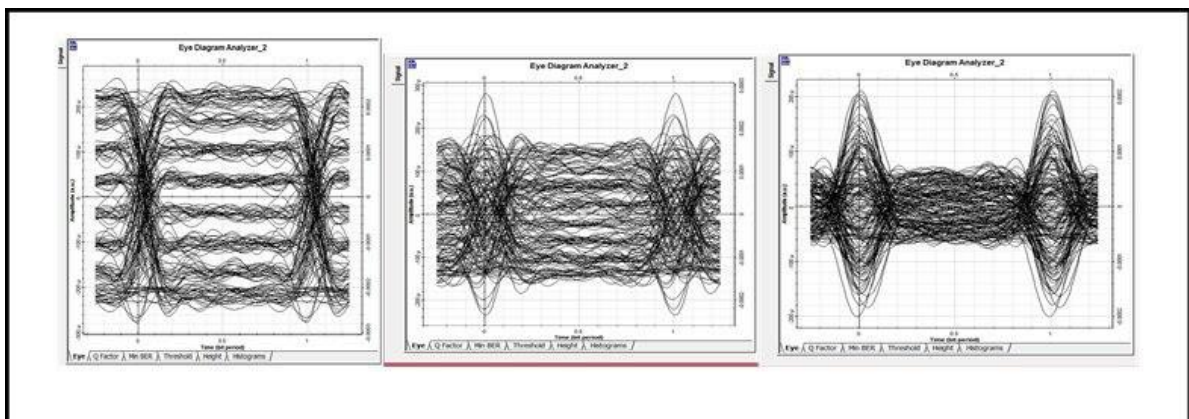Fig. 18 Eye-Diagram in presence of the nonlinear effects (Downlink)

Fig. 19 Eye-Diagram in presence of the nonlinear effects (Uplink)

4- conclusion

In light of the findings of this paper, few remarks could be drawn.

The first remark is that the performance of the system is successful when the NG-PON2 is matched with RoF with data rate of 40 Gbps using four wavelengths of radio frequency that equal 40 GHz for four channels. Also, an optical sound amplifier type EDFA is used in the system. Optimal results are obtained at the distance of 55 Km where the Q factor values are up to 6.22 which is within the acceptable range.

The second assertion is that the best value of Q factor at the distance of 37.77 in the presence of the nonlinear effects is 6.38, and Q factor is 4.39 at the distance of 55.55. This indicates that the performance of the system degrades due to the nonlinear effects.

The third obervartion is that, in the absence of the nonlinear effects, the simulation of the NG-PON2-RoF show that the value of the BER is 1.00E-30. This is the minimum value which falls within the acceptable range.

In addition, it also could be noted that, in the presence of the nonlinear effects, the simulation of the NG-PON2-RoF show that the value of BER varies depending on the type of the nonlinear effects. For the SPM effect, the BER is 1.62E-07. For the XPM effect, the BER is 3.35E-06. For the FWM effect, the BER is 3.35E-04. All of these results are at the 1597.18 nm wavelength. And all the values fall within the acceptable values of system performance. It could concluded that the most degrading effect on the performance of the system is the FWM

Furthermore, and as illustrated in Fig. (15) where the received power to the BER, the losses of the system are more than -30 dPm due to the nonlinear effects.

The last remark is that the Inter-Symbol Interference (ISI) as illustrated in the Eye-Diagram is relatively clear without the presence of the nonlinear effects; yet, in the presence of the nonlinear effects, there is significant interference

In conclusion, the proposed system operates effectively when there are no nonlinear effects at transmission distance of 55 Km. Nonetheless, it only operates effectively in the presence of the nonlinear effects at the transmission distance of 37 Km. Therefore, to increase the capacity of the system for transmission distance more than 37 Km, further studies are recommended to optimize and mitigate such systems.

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