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Original Research

Performance Optimization for (NG-RoF) Systems: Mitigating Nonlinear Effects in Long-Distance Transmission

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ABSTRACT

In the past decade, numerous modern technologies have been invented, and various services have been subscribed to and used in daily life. All of these require high data rates and wide coverage in terms of mobile communication, necessitating an advanced generation to meet these performance demands set by end users. This paper aims to promote the radio-over-fiber technique in 5G systems, enhancing the standards of techniques to ensure effective wireless communication coverage. However, a significant issue arises due to nonlinear effects causing system performance failures, particularly at a transmission distance of 400km and the data rate impact at fifth generation, where data downloads reach up to 100 GBps. The approach utilizes a key concept from signal processing within NG5 RoF for transmission and reception. The flaws begin with the use of the transmitted signal during the initial modulation of 16QAM, progressing through power allocation to bit error rate (BER) filtering, which is crucial for long-distance transmissions, ranging from 100 km right up to a distance of 400 km.

Keywords: RoF, fifth generation, invers gaussian filter.

1. Introduction

An exponential growth in demand for mobile services with a high data rate, followed by an upsurge in mobile users, has led to the development of fifth-generation (5G) wireless technologies. A survey by Cisco predicts a more than 100-fold increase in 5G connections between 2019 and 2023 [1]. To meet the requirements of this emergence, next-generation wireless communication technologies are expected to operate at ultra-high unlicensed millimeter wave (mmWave) frequencies [2]. However, the insufficiency of available wireless frequency spectrum to support the growing number of mobile devices, combined with the use of radio frequencies by both government and private sector entities within the existing spectrum allocation, has led to spectrum congestion. Using millimeter-wave (mmWave) bands in wireless communications represents a critical fundamental change in addressing the spectral dilemma. Yet, the penetration level combined with atmospheric attenuation creates a challenge in terms of coverage range for such bands [3]. The radio-over-fiber (RoF) technology is one of the most promising wireless access technologies in congested metropolitan regions in terms of enhanced capacity, mobility, and energy consumption [4-6]. Since most modulation methods in wireless structures adopted the Orthogonal frequency-division Multiplexing (OFDM) principle of data transmission, the requisites for future wideband wireless communication systems attainment become ambitious [7-10]. Therefore, the integration of OFDM with RoF is introduced as a means to efficiently transmit millimeter-waves in mobile communication environments. This integration may also help to effectively cope with the delay spread of multipath propagation, increase robustness in frequency-selective fading channels, in addition to narrowband photonic quantum entanglement [11, 12].

The optical fiber networks exhibit low noise and do not endure radio interference. Furthermore, they are considered a separate medium, and several technologies have been developed for the purpose of providing bandwidth with a range of one terabit per second (Ts) in optical networks, such as the dense wavelength-division multiplexing (DWDM) [13, 14]. This technology features promising solutions for increasing bandwidth rates, so that it could have low maintenance costs. The DWDM of multi-density is utilized between the channels, where the frequency range of each channel fluctuates between 0.1 to 0.8 nanometers, which gives the DWDM the ability to transmit multiple optical channels using a single fiber [15, 16].

It is important to note that the deployment of DWDM is primarily due to two reasons. Firstly, DWDM utilizes multiple wavelengths, which can increase the number of stations. Secondly, the use of multiple wavelengths can help create a transmission spectrum. This transmission spectrum can allocate one wavelength for each transmission station, resulting in a receiving wavelength. With these capabilities, a DWDM-RoF system can be established. Therefore, the effectiveness of this system relies on distributing antennas along the transmission distance, connecting the distributed antennas to other antennas that are linked to optical fiber cables [17, 18].

However, there will be two drawbacks: signal dispersion and refraction. The signal will endure dispersion and refraction, resulting in the emergence of nonlinear effects, namely the Raman scattering (SRS), Brillouin Scattering (SBS), Four Wave Mixing (FWM), Self-Phase modulation (SPM), and Cross-Phase Modulation (XPM). It is worth noting that the emergence of these effects is due to the use of high power in transmission and the type of optic fiber used in transmitting signals [11, 19].

For an improved overview of recent trends in research on Radio-over-Fiber (RoF) systems based on OFDM and WDM methods, a comparative study of relevant works is provided. The works compare different architectures, modulation methods, and compensation methods with the aim of improving transmission quality, minimizing bit error rate, and managing nonlinearities and dispersion in fiber links. The collective findings are presented as a broad overview of technological progress and restrictions in this area. Table 1 shows an organized comparison of major contributions and outcomes of recent publications between 2012 and 2022.

Table 1. Summary of Related Works on OFDM-WDM-RoF Systems and Performance Optimization Techniques

Ref.	Year	System Proposed	Key Techniques & Features	Main Findings / Performance
[20]	2012	WDM-RoF System	OFDM-CPM and OOK modulation; 40 GHz carrier; 2.5 Gbps; Carrier regeneration	Achieved BER ≈ 10^{-9} using OFDM-CPM and centralized light source
[21]	2013	OFDM-RoF with RA Code	RA (Repeat Accumulate) Code, LLR on Chi-square & Gaussian channels	Reduced BER to ≈ 10^{-4} over 150 km; Improved FEC coding guidance
[22]	2015	OOFDM/WDM Overview	Dispersion/nonlinearity compensation techniques	No universal solution found; suggested adaptive compensation per system
[23]	2016	OFDM-WDM Architecture	4x10 Gbps OFDM for 40 Gbps; WDM Design	Achieved BER evaluation over 240 km; Analyzed constellation performance

[24]	2017	28 GHz OFDM-RoF using FBG	4-QAM/16-QAM; DD-MZM; SSB generation; No optical amplifier	BER ≈ 10^{-4} at 4.56 Gbps between 50–70 km; SSB improves spectral use
[25]	2019	All-optical modulation conversion	SOA-based format conversion between OOK, QPSK, 8-QAM	Evaluated OSNR, optical strength, dispersion via simulations
[26]	2020	IM/DD Fast-OFDM-CDMA OCDMA-PON	Hybrid FastOFDM-CDMA for access networks	Analytical study on BER/Q-factor vs. users, fiber length, power
[27]	2021	40/40 Gbps TWDM-PON with OFDM	Full-duplex, 4-ary QAM, DSP-based, VLC	Transmitted 40 Gbps bidirectional over 200 km at BER = 3.8×10^{-3}
[28]	2022	SCM-OFDM Radio-over-Fiber	DSP-16QAM Filter for nonlinear compensation	Better performance at 10 Gbps; DSP mitigates nonlinear effects

Five such structures that based on above literature operates by compensating the effects, includes Gaussian, RC, Raised-cosine, Root-raised-cosine and Bessel filters. Based on nonlinear effect, in the present study a system modeling would be carried out. A few technologies would be adopted. These are OFDM orthogonal frequency division technologies that can divide frequency in an orthogonal manner for the purpose of minimizing power to the least needed and for the purpose of utilizing frequency in an optimal manner, and the technology of Digital Signal Processing in the form of Gaussian Filter. Moreover, the function of each of the five compensation techniques is analyzed and a comparison is realized in terms of their performance for the same data conversion rates over different channel distances. The behavior of these models is assessed based on the presence of non-linear effects, namely XPM and SPM, and the outcome is inspected with the quality elements: BER, SNR, and transmitted data rate.

2. System Model

The DWDM-OFDM-RoF network anatomy of the proposed system anatomy (see Figure 1) is an optical architecture that encompasses three components: Optical Line Terminal (OLT), Optical Distribution Network (ODN), and Optical Network Unit (ONU). Linear and non-linear distortions, such as: Amplitude Modulation, Polarization Mode Dispersion (PMD), linear scattering, and non-linear effects within the confines of the proposed system.

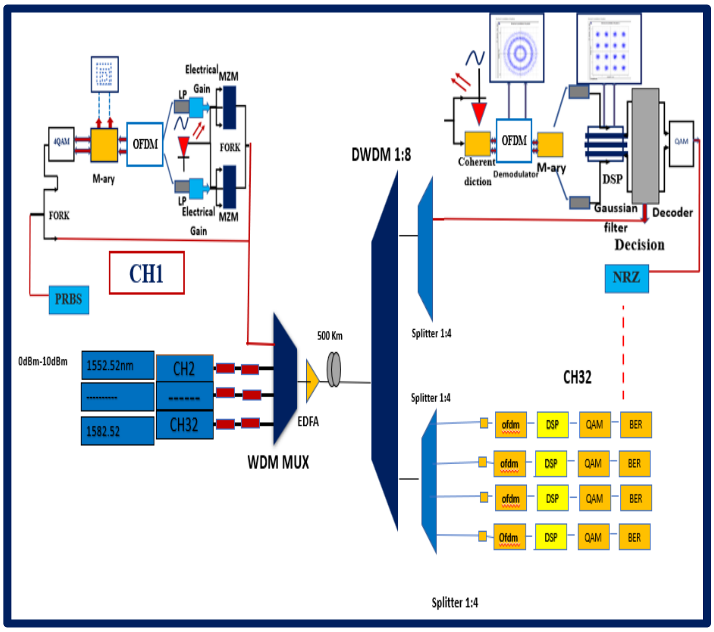

Figure 1. The proposed NG-DWDM-OFDM-RoF system

The first building block of the proposed architecture, optical line terminal (OLT), accommodates a TX transmitter (see Figure 2, and 3) whose function is to send power sequencing signals to test the proposed model's ability. The TX transmitter has thirty-two channels of wavelengths ranging from 1596.339-THz to 1596.411-THz, whereby the gap between any two wavelengths appears less than or equal to 100-GHz. The aim, however, is to guarantee Dense Wavelength-division Multiplexing (DWDM), as well as to provide assurance of channel spacing. Additionally, thirty-two Pseudo-Random Binary Sequence Generators (PRBSGs) were incorporated into the TX transmitter. (PRBSG) creates random encoded data without this pulse generator (RZ) clocking zero. Within the proposed system, each of those thirty-two channels was converted from electrical-to-optical. Hence, thirty-two 16-ary Quadrature Amplitude Modulators (16-QAM) were used, as the output yielded (I). The (I), is then linked with the Quadrature Amplitude Modulation (QAM) to give birth to a sequence of rays. Finally, each component of the TX circuit links with the Mach-Zehnder Modulator (MZM) and with CW laser.

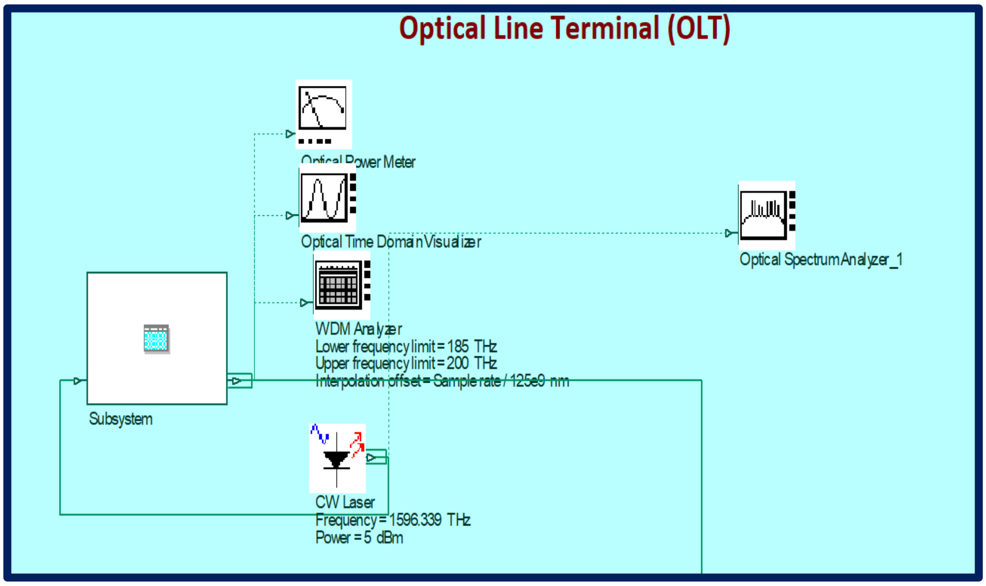

Figure 2. Optical Line Terminal (OLT)

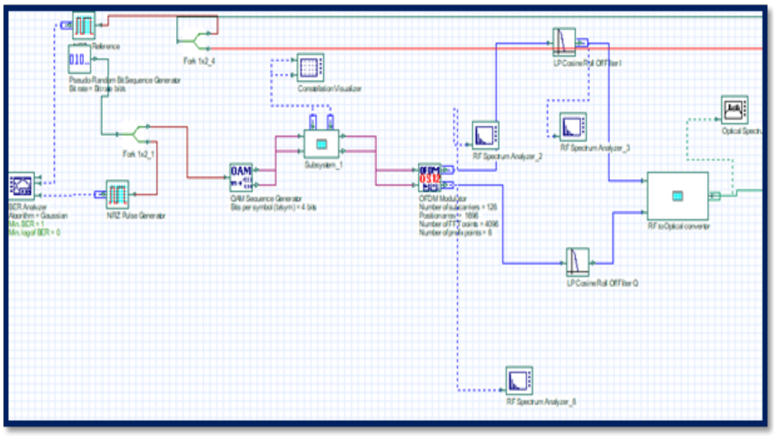

Figure 3. Optical Line Terminal Opti system (OLT)

The second component, Optical Distribution Network (ODN), is composed of two units: a transmission medium, which is an optical fiber with a length of 20 km to 500 km, and an Erbium-Doped Fiber Amplifier (EDFA), as illustrated in Figure 4.

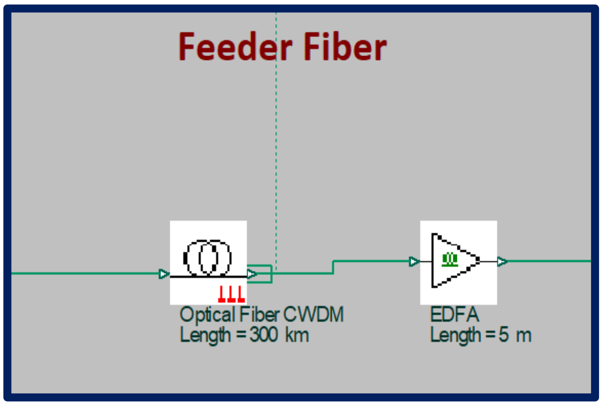

Figure 4. Optical Distribution Network (ODN)

The third component, Optical Network Unit (ONU), contains thirty-two PIN Photodiodes, which decrease light intensity within long-range networks. The unit also hauls thirty-two Quadratic Modulators, a DSP-16-QAM filter (Gaussian, RC, Raised-cosine, Root-Raised-cosine, and Bessel), in addition to QAM decoders, M-ray detectors, a pulse generator (RZ), and a Quadratic Demodulator. See Figure 5:

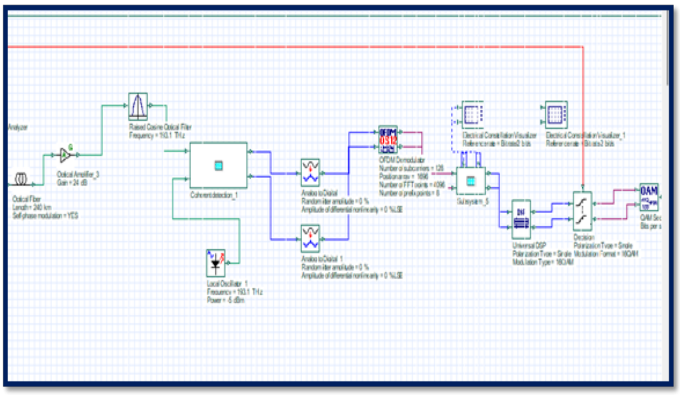

Figure 5. Optical Network Unit (ONU)

3. Results and discussion

For achieving the objectives of this study, proposed DWDM system performance was simulated based on two different approaches. The first simulation was carried out invoking the DCF-SOA (dispersion compensating fiber (DCF) and semiconductor optical amplifier (SOA)) technology, whereas in the consequent simulation, DSP-16-QAM filter (Gaussian, Raised-cosine, Root-Raised-cosine, RC, and Bessel) was used in order to reduce non-linearity's impact to minimum extents. It must be noted that simulated behavior, with respect to duration of two simulations, was analyzed with non-linearity effects present. The major purpose of above procedures was to see what happens to the light spectrum when it is transmitted over a large distance. To this end, measurement of wavelengths density was taken at the transmission of 20 km-500 km, where wavelengths were associated with 10-GBps second with non-linearity effects present.
The light spectrum's form will take this appearance in Figure 6 when using the DWDM approach as a result of transmitting thirty-two wavelengths between 1596.339-THz and 1596.411-THz.

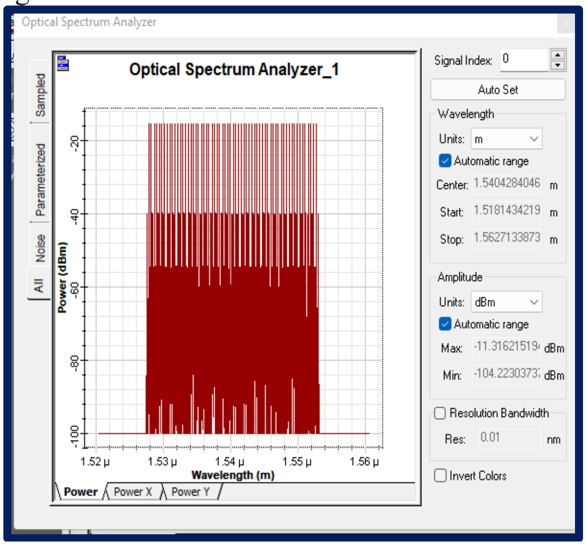

Figure 6. Optical Spectrum Analyzer input

The gross transmission of the optical fibers was evaluated at varying distances ranging from 20 km to 500 km. The non-linear effects: SBS, SRS, SPM, XPM, and FWM were found, in the DWDM-RoF optical system, to be in equally spaced channels. According to this finding, the non-linear effects take the form of second-order harmonics at the output signals. This non-linear process, in consonance with transmission distance, demonstrates that second-order harmonics have the greatest impact on the proposed system performance **Figure 7**.

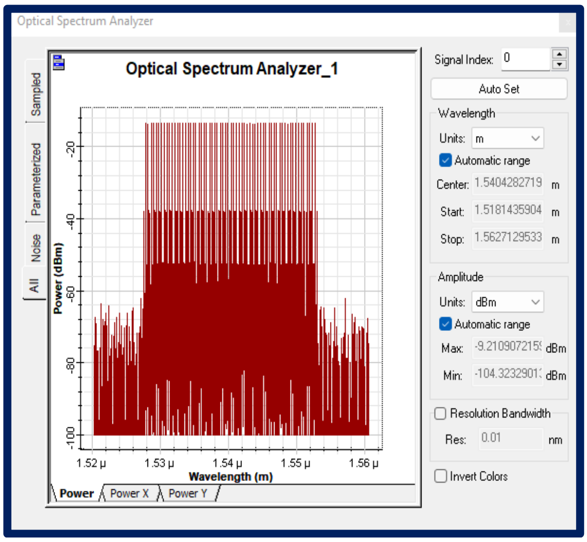

Figure 7. Optical Spectrum Analyzer output

The optical signal quality, in this suggested system, was also analyzed at a distance of 500 km under non-linearity effects by using the constellation map of chaos-embedded message.

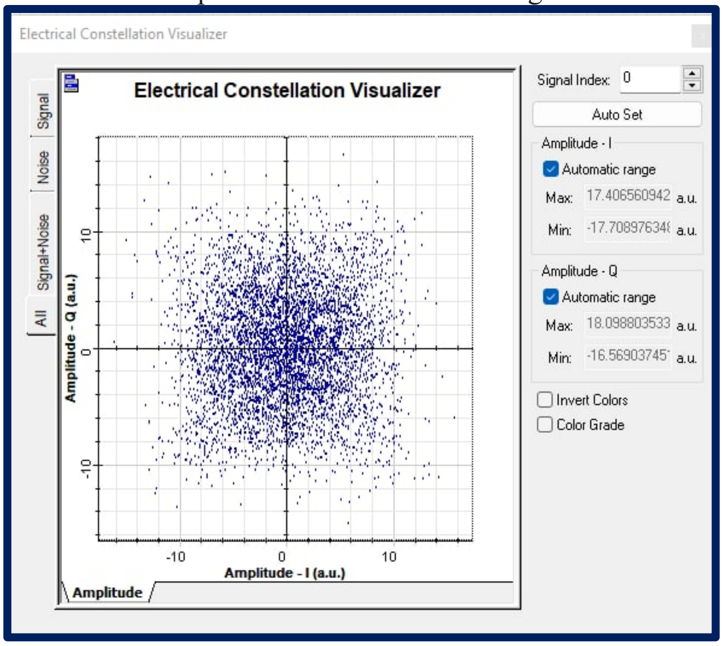

Figure 8. Electrical Constellation diagram at a distance of 500 km in the presence of non-linear effects

It was concluded, by observing nonlinearity's impact on system performance, that by not utilizing the (DSP) technology, overall quality of this structure becomes poor; and signal becomes dim visibly because of generating second-order harmonics. To counter this system performance depression, the DSP-16-QAM (Gaussian, RC, Raised-cosine, Root-Raised-cosine, and Bessel) structure was employed. The operation of this filter is based on Digital Signal Processing (DSP) principles to achieve the same data conversion rate over a large distance, without utilizing a semiconductor optical amplifier (SOA). The operation of every single one of these five filters was evaluated against each other based on SNR measures. While plying with DSP (Gaussian) filter, each of input and output light spectrum's forms are as illustrated in Figure 11. which implies significantly suppressed generation of second-order harmonics.

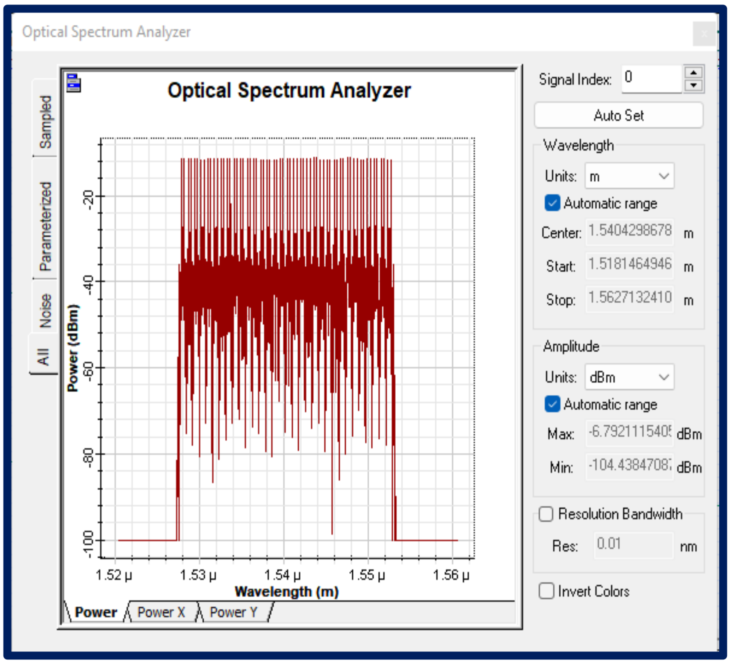

Figure 9. Optical spectrum at the input and the output after plying the DSP-16-QAM-GAI (Gaussian) filter

Following the inclusion of the DSP-16-QAM-GAI (Gaussian) filter the quality of the optical signal, in the proposed system, was again evaluated at the 500 km distance in the presence of non-linear effects using the constellation diagram of message-embedded chaos.

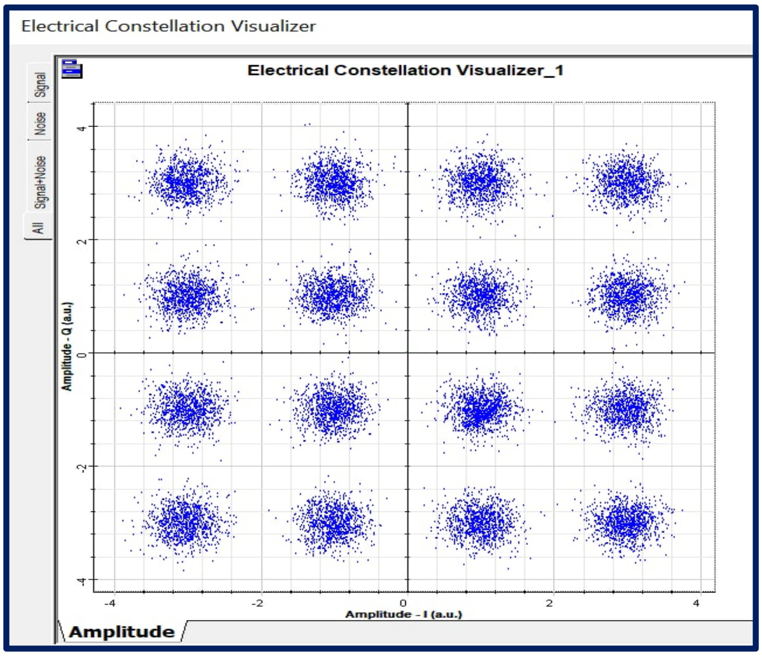

Figure 10. Constellation diagram at the 500 km distance with adopting Gaussian filter

The below BER vs transmission distance plot illustrates the relationship between bit-error rate to distance of transmission of how system performance is affected by non-linear effects with and without the presence of those models functioning based on compensation of effects of nonlinearity.

It was found that using the DSP-Gaussian filter assisted in having an acceptable BER of E-0.0000008683 when transmitted over a distance of 400 km. As compared to, BER attained in the absence of Digital Signal Processing (DSP) over the same distance of 400 km was BER of E-0.01, and this is an unacceptable BER and has a significant impact on system performance.

For measurement of BER values of non-linear effects: SPM, XPM, FWM, SRS, and SBS, after applying the DSP-Gaussian filter, all values were satisfactory. It was discovered that the cause of maximum degradation to system quality is the Stimulated Brillouin scattering (SBS), an inflexible non-linearity, because of high compatibility having its effect on system operation at a distance of 300 km. The BER value, for this non-linearity (SBS), was E-0.25003677 when measured at a distance of 300 km, and it was an acceptable measurement. While BER value, for flexible non-linearity (SPM), was 4.44E-22 when measured at 300 km, and it was the optimum measurement taken by proposed system with a transmission reach of 300 km.

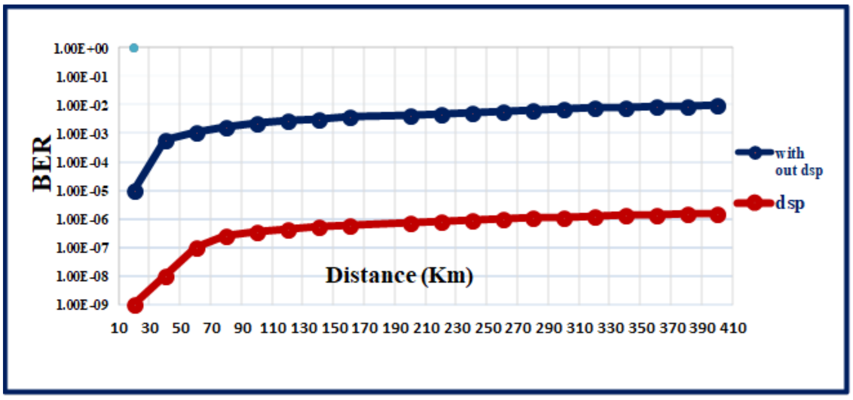

Figure 11. BER to Distance in the presence of non-linear effects at a transmission distance of 400 km with the (DSP) technology.

The BER graph below demonstrates the relation between the Bit-error rate to SNR with and without the attendance of the models that operate by compensating for the effect of non-linear effects.
The SNR value, at a distance of 400 km, reached 18-dB without the (DSP) technology and realized 28-dB, at the same distance of 400 km, with the (DSP) technology. The value of 18-dB indicates that the system is not working properly and displays losses when transmitting and receiving.

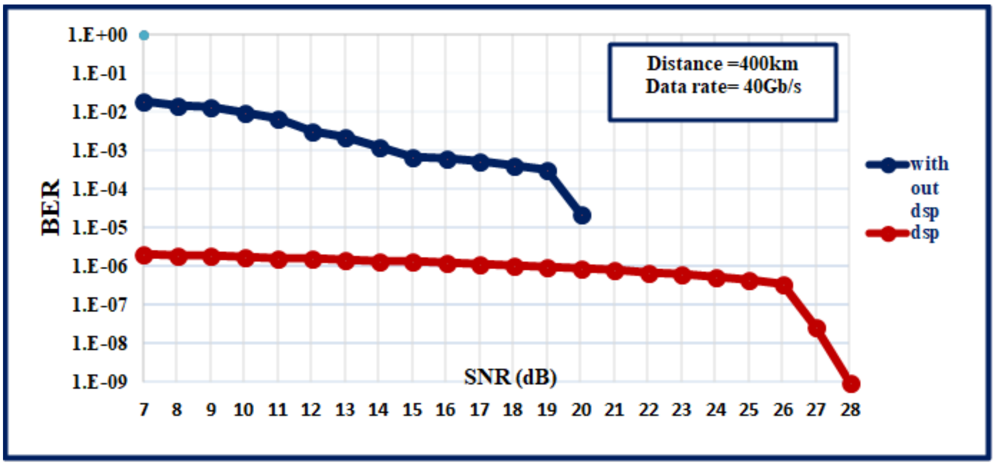

Figure 12. BER vs. SNR of the received signal using the DWDM-RoF-DSP-16-QAM system at a transmission distance of 400 km; the proposed system operated without noise and delivered satisfactory results.

The BER graph below demonstrates the correlation between the Bit-error rate to data rate with and without the inclusion of the models that operate by compensating for the effects of nonlinearity.
The BER value is 0.1E, at a data transfer speed of 80-GBps and transmission distance of 400 km, without the (DSP) technology. This value indicates poor system function and display of losses at each of the transmission and reception. While the BER totaled a value of E-0.0000008683, at the same data transfer speed and transmission distance, when using the proposed DWDM-RoF-DSP-16-QAM system.

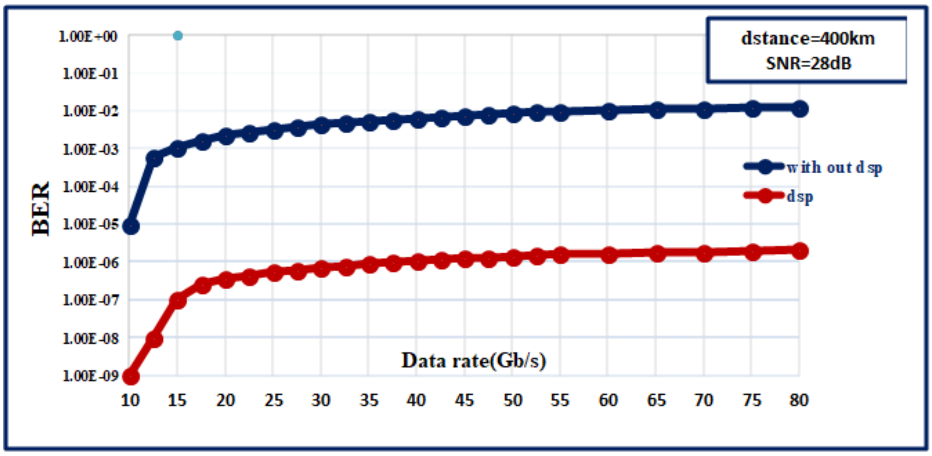

Figure 13. BER to data rate of the power

Note. BER value at E-0.0000008683, at a transfer speed of 80-GB per second and transmission distance of 400 km, when using the proposed DWDM-RoF-DSP-16QAM system.
Figure 14 demonstrates the process of comparison through the values of SNR between the five filters: Gaussian, RC, Raised-cosine, Root-Raised-cosine, and Bessel.
The SNR value reached 20 dB when operating with the DSP-Bessel filter at a transmission distance of 400 km. Whereas the value realized 28 dB using the DSP-Gaussian filter at the same transmission distance. The results evinced that the DSP-Gaussian filter is the finest among the five filters at the 400 km transmission range.

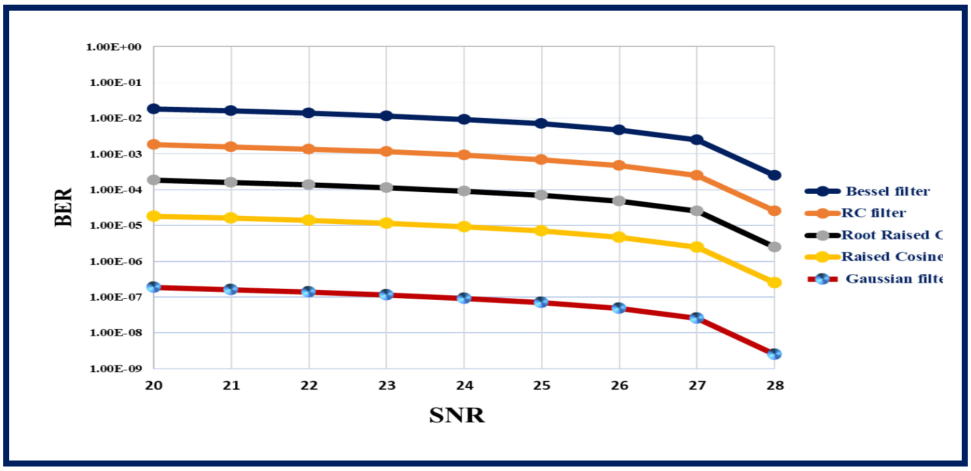

Figure 14. BER vs. SNR performance of the filters

Note. The SNR value reached 20-dB when operating with the DSP-Bessel filter at a transmission distance of 400 km. Whereas the value realized 28-dB using the DSP-Gaussian filter at the same transmission range.

Conclusion

The conduct was successful based on the following considerations:

In the proposed DWDM system, it was discovered that implementing of the DSP (Gaussian) filter effectively reduced second-order harmonics and significantly minimized the impact of SRS, SBS, SPM, XPM, and FWM nonlinear effects. This was achieved without the need for costly compensation technology, which would require complex maintenance. The DSP-Gaussian filter also eliminated signal interferences by quickly avoiding delays caused by the interaction between light and the medium. Furthermore, incorporating the DSP-16-QAM-GAI (Gaussian) filter in the system notably improved performance, as evidenced by increased SNR values. Optimal SNR values of 28 dB were achieved with the DSP filter at a transmission distance of 400 km, compared to 19dB without it.

The results of the study deemed the proposed DWDM-OFSM-RoF system as one of the top technologies tested in optical fiber communication. It was suggested that investments in distances exceeding 1000 km could be made to achieve high data rates of 500 Gb per second. This could be accomplished by integrating a DSP-512-QAM structure with a Raised Cosine roll-off filter to enhance versatility.

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