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Performance investigation of different optical filter on the OFDM system with QAM modulations

Rusul Hameed Kahdum[a,*], Ali H. Khidhir[a], Thanaa Hussein Abd[b]

[a] *Collage of Science, University of Baghdad, Baghdad, Iraq*

[b] *Ministries of Science and Technology, Baghdad, Iraq*

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Abstract

In this article, we present new research on the impact of various optical filters on the functionality of an Orthogonal optical Frequency Division Duplexing (OFDM) system for the first time. This paper focused on long-haul optical systems using four Quadrature Amplitude Modulation (4-QAM) methods for OFDM systems. The analysis demonstrates the impact of choosing a Gaussian, Rectangular, or Trapezoidal optical Filter on the effectiveness of the optical system used for long-distance high data rate transmission. Compared with other systems for long-distance transmission using various filter types, 4-QAM OFDM showed a high Bit Error Rate (BER) performance. Significant findings like transmitting Power received Power, and Error Vector Magnitude (EVM) is compared with the system's propagation length.

Keywords: 4-QAM OFDM system, Bit Error Rate (BER), Error Vector Magnitude (EVM), Gaussian, Rectangular, Trapezoidal optical Filter
2020 MSC: 60G15, 78A60

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1 Introduction

Using the OFDM method of multicarrier modulation, a high level of the information of the modulating stream is divided into the symbols, with each symbol modulating a subcarrier [17, 10]. OFDM is used in high data rate optical transmission systems and long-haul because of the incorporation of a cyclic prefix that ICI and ISI [4, 5, 18]. The quadrature amplitude modulation (QAM) with the OFDM approach increases the capacity and effectiveness of optical networks to accommodate large data rates and low BER. The efficient and inexpensive optical communication system known as intensity modulation/direct detection (IM/DD) can be utilized for a wide variety of purposes, including communication of visible light, free-space optical, optical wireless OFDM, and light-based underwater wireless [2, 11, 7].

The two most important components of the IM/DD system are the Mach-Zehnder Modulator (MZM) located at the transmitter, and the photodetector, also known as a PD, located at the receiver [16]. This system is extremely simple and easy to put into action, and it is believed to be more (CO-OFDM), which employs a distinct optical source (local oscillator) at the receiver. This system is very basic and easy to put into action [17, 6]. In contrast to non-optical

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[*] Corresponding author

Email addresses: `rusul.h444@gmail.com` (Rusul Hameed Kahdum), `alzurfialiali@gmail.com` (Ali H. Khidhir), `eng_thanaa@yahoo.com` (Thanaa Hussein Abd)

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OFDM systems, in which the information is carried on the electrical field, and the signal will have both positive and negative values (bipolar), IM/DD optical systems can carry information that is positive (unipolar) due to the intensity of the optical signal. This is in contrast to non-optical OFDM systems, in which the information is carried on the electrical field, and the signal will have both positive and negative values (bipolar) [13]. Simulations were performed using 16-QAM OFDM, wavelength-division-multiplexing, passive optical network, and direct detection at speeds (10) Gbps, upstream data rates of 2.5 Gbps, and propagation lengths of 70 kilometers [9]. The simulation was used to compare the performances of long-haul 100-Gb/s DDO-OFDM [3] and CO-OFDM WDM systems. System variables like laser linewidth launched power and system dispersion tolerances were a low-cost WDM OFDM system and high performance [15].

It was shown in [12] how successful Radio over Fiber (RoF) systems could be by using the IM/DD approach. These systems' simulation results with MB-OFDM signals and direct and external modulations were described. Asymmetrically clipped optical orthogonal frequency division multiplexing and DCO-OFDM are two other systems that were presented and compared with PO-OFDM, which is considered to be a new type of intensity optical OFDM modulations. Both of these other systems were compared with PO-OFDM, considered a new type of intensity optical (ACO-OFDM). The Hermitian symmetry can convert the complicated signal into a real and positive signal is used [14]. The OFDM IM/DD system with many techniques (QAM and Phase Shift Keying) was illustrated in [1]. (PSK) To achieve the best (BER) performance, 16-PSK and 16-QAM were applied to the IM/DD system. Based on the best BER, it was decided that the transmission distance and the downstream data rate would be 100 Gbps and 10 km, respectively. IM/DD system gave the greatest BER performance than in 16-QAM and 128 sub-carriers. In this article, we provide fresh research on the effectiveness of the 4-QAM OFDM system using direct modulation technology. This study examined the results of using three distinct kinds of optical filters, including trapezoidal, rectangular, and gaussian filters.

The remainder of this work is structured as follows, with the system design of the 4-QAM OFDM being presented in the second part. The retrieved findings and an assessment of the system's performance were presented in the third section. In the end, we get to the conclusion in the fourth and last segments.

2 Mathematical Model of Optical Filter

At the receiver end, the quality of the signal may be improved by the use of a variety of filters. In this study, we evaluate the effectiveness of three different shapes of optical filters: Rectangular, Trapezoidal, and Gaussian. The following is a representation of what each Filter's structure and numerical model stand for:

1. **Gaussian Filter:**
   The transfer function of an optical Gaussian filter may be expressed in the following way [8]:

$$H\left(f\right) = \propto e^{-\ln\sqrt{2}\left(\frac{2(f-f_c)^{2N}}{B}\right)} \tag{2.1}$$

   where $H(f)$ is the transfer function of the Filter, α is the parameter for the insertion loss, fc is the center frequency of the Filter, which is specified by the parameter Frequency, B is the parameter for the bandwidth, N is the parameter for the order, and f is the frequency.
2. **Rectangular Filter:**
   The rectangular Filter is the most basic kind of linear Filter; the purpose of this Filter is often to smooth out the input signal. The arithmetic mean of the input values that correspond to the moments of time near the current time is what the rectangular Filter will produce as its output when it is applied to the data at the time instant.

$$y\left(t\right) = \left(\frac{1-R}{1-R*e^{2\pi j\left(\frac{f-f_0}{B}\right)}}\right) \tag{2.2}$$

   where $y(t)$ is the transfer function of the Filter, J is the parameter for the insertion loss, $f0$ is the center frequency of the Filter, which is set by the parameter Frequency, B is the parameter for the bandwidth, N is the parameter for the order, and f is the frequency.
3. **Trapezoidal Filter:**
   One of the signal processing methods that are used in digitizers is called the trapezoid filter. The trapezoid filter employs a linear transformation. In the Filter, there are few parameters; the "shaping" parameters are
   - trapezoid rise time
   - It has to be longer than the rise time of the signal.

- Trapezoid flat top

$$k\left(n\right) = \propto 10^{\left(\frac{1-A}{10B-B_{0dB}}\right)}\left(f-f_0\right) \tag{2.3}$$

where $k(n)$ is the transfer function of the Filter, $\propto$ is the parameter for the insertion loss, f_0 is the center frequency of the Filter, which is set by the parameter Frequency, B is the parameter for the bandwidth, N is the parameter for the order, and f is the frequency.

3 System Design of the 4-QAM OFDM

The component breakdown of our system is depicted in Figure 1. The software known as Optisystem v.18 was utilized in the process of designing and simulating the system architecture and the results of the simulation. The digital bits are produced using a set of BER (100) Gbps. The BER test set came to the conclusion that the produced bit rate is 50 Gbps since there are 512 subcarriers and 1024 FFT points.

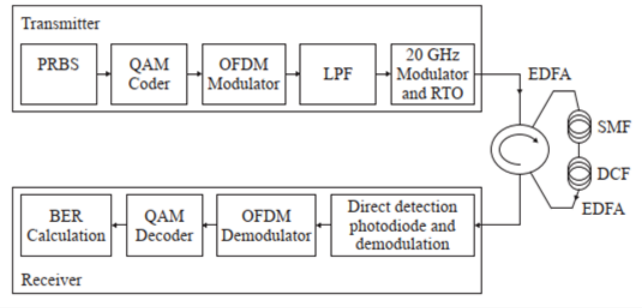


Figure 1: System block diagram for OFDM IM/DD

This is because the bit rate can be divided by 1024. The primary Optisystem v.18 simulation parameters and OFDM modulator parameters are listed in Tables 1 and 2, respectively.

Table 1: Main parameters of OFDM modulator

PARAMETER Name	**Value**
Subcarrier numbers	512
FFT points	1024
Position array	256
Cyclic prefix	100 symbol
DAC interpolation	extension
Number of training OFDM	Cubic
symbols	2

Table 2: Main simulation parameters

Optisystem global parameters	**Value**
Bit rate	100Gbps
Sequence length	32768 to 65536
Samples per bit	2 to 8
Number of samples	65536 to 262144

After the IFFT in each OFDM symbol, a cyclic prefix with the value 100 is appended to prevent ISI from occurring between OFDM symbols. This is done. Using a QAM sequence generator, the created bits are translated into symbols with the required amount of bits. After the symbols are formed, they are sent through an M-ary sequence generator, which transforms them into pulses with a variety of levels. In order to convert QAM symbols into a significant number of orthogonal sub-carriers, an OFDM modulator is employed. However, the number of subcarriers must match fifty percent of the total FFT points in order to be considered acceptable. Lower-rate subcarrier tones will be sent and received between 0 and 12.5 gigahertz frequencies. In order to precisely pinpoint the positions of the subcarriers that are now being used, the position array included inside the OFDM modulator has to be twice as big as the entire number of subcarriers that are currently in use. After that, I-Q OFDM signals will low pass filter which has a cutoff frequency (0.65) times the symbol rate. This Filter will be used to further process the signals. It is possible to boost the frequency of OFDM signals up to a maximum of 20 GHz by using a quadrature modulator in the transmission chain. To modulate the radio frequency (RF) electrical signal, a Mach-Zehnder modulator (MZM) is deployed. The use of a continuous-wave laser with a power of 2 dBm and a frequency of 193.1 THz is what is required to achieve this result. The MZM is functioning at the quadrature point because the voltage that is provided to its arms is only half of the RF switching voltage. This causes the MZM to operate in the quadrature mode. The complete explanations of the capabilities of the CW laser and the PIN photodetector may be found in Tables 3 and 4, respectively. After MZM, the optical signal is next amplified by using an optical amplifier with the major parameters of a gain of 10 dB and a noise floor of 4 dBm. These characteristics are in contrast to the primary specifications of the MZM process. Figure 2 depicts the block diagram that is associated with the simulation of 4-QAM OFDM.

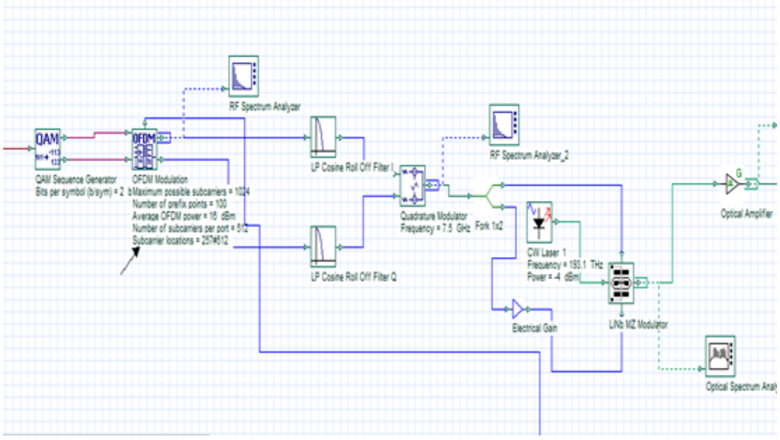


Figure 2: Block diagram of the transmitter of the 4-QAM OFDM System

The optical signal that was generated is then sent over a distance of (50+20Number of loops) kilometers using an SMF that has the following specifications: a dispersion of 16 ps/nm/km, an attenuation of 0.2 dB/Km, a nonlinearity coefficient of 2.6, and a dispersion slope of 0.08 ps/nm2/km. The transmission section of the investigated 4QAM OFDM system presenting in Figure 3.

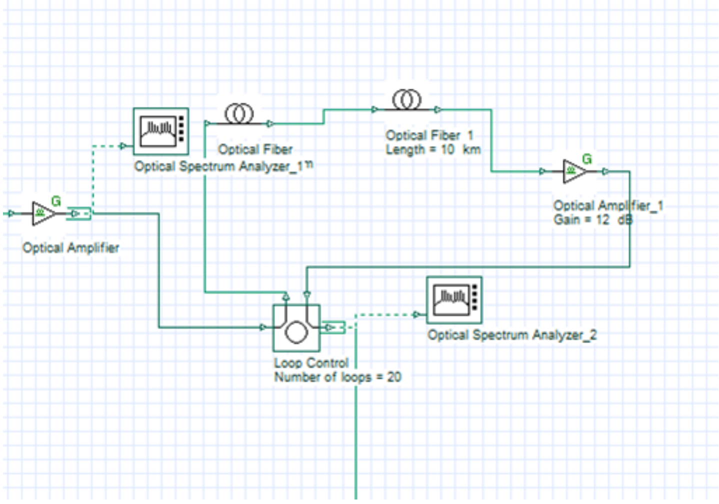
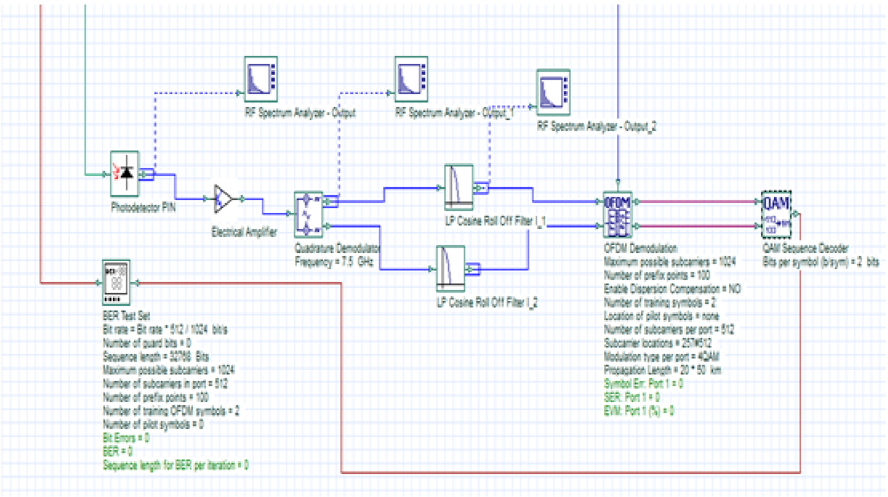


Figure 3: Transmission part of the 4-QAM OFDM system

With the aid of DCF, the performance of the transmission may be increased, and it can also correct for the dispersion that was brought on by the primary optical fiber. Based on the calculation of the DCF value using the main optical fiber's length of 50 kilometers, the length of the DCF within the loop has been decided to be 10 kilometers, and its dispersion has been set to 83.75 picoseconds per kilometer (ps/nm/km). A second amplifier is utilized within the loop so that the optical signal can be amplified, and the loss can be compensated for. The optical signal that has been amplified is then filtered with the assistance of a Gaussian, Rectangular, and Trapezoidal optical Filter that has 193 as frequency.1 THz and a bandwidth of 70 GHz. In the receiver section, a PIN photodetector is responsible for converting the optical signal into an electrical signal. Figure 4. represent the receiver side of the 4-QAM OFDM system.



Quadrature Demodulator
Frequency = 7.5 GHz

OFDM Demodulation
Maximum possible subcarriers = 1024
Number of prefix points = 100
Enable Dispersion Compensation = NO
Number of training symbols = 2
Location of pilot symbols = none
Number of subcarriers per port = 512
Subcarrier locations = 257#512
Modulation type per port = 4QAM
Propagation Length = 20 * 50 km
Symbol Err. Port 1 = 0
SER: Port 1 = 0
EVM: Port 1 (%) = 0

QAM Sequence Decoder
Bits per symbol (b/sym) = 2 bits

BER Test Set
Bit rate = Bit rate * 512 / 1024 bit/s
Number of guard bits = 0
Sequence length = 32768 Bits
Maximum possible subcarriers = 1024
Number of subcarriers in port = 512
Number of prefix points = 100
Number of training OFDM symbols = 2
Number of pilot symbols = 0
Bit Errors = 0
BER = 0
Sequence length for BER per iteration = 0

Figure 4: Block diagram of the 4-QAM OFDM System

The PIN photodetector has a center frequency of 193.1 THz, a current of 10 nA (dark), and a thermal power density of 15 and 1024 W/Hz. Additionally, the photodetector has a dark current of 10 nA. Using the electrical amplifier to amplify the electrical signal received after it has been received. Using a quadrature demodulator, the amplified signal is down-converted, and its original frequency, which was between 0 and 12.5 GHz, is recovered.

It is necessary for the parameters of the OFDM modulator and the demodulator to be identical for recovering QAM symbols that were transmitted. The sequence of the QAM detector uses the number of bits that are associated with each symbol to convert the received symbols into bits. The BER test set is utilized to evaluate BER and its log.

4 Simulation Result

This section presents the simulation results of the investigated system (4-QAM OFDM) based on the presence of different optical filter effects. However, to reduce the linear noise effects on the 4-QAM OFDM, the Gaussian Filter, Rectangular Filter, and Trapezoidal Filter are utilized.

The results show that the system of 4-QAM OFDM with 10dBm as transmitted Power can receive a signal with a power of -2 dBm with a data rate of 10Gb/s as transmitting data when implementing Gaussian Filter. The Gaussian Filter with a 4th filter order can achieve a long haul transmission distance of 100km. Figure.5 depicts different transmitted power values varied from -10 dBm to 10 dBm with respect to received Power for the 4-QAM OFDM system without implementing the Gaussian Filter. The depicted results show that the received Power of 1 dBm can be detected. As well, the received Power at 100km is equal to -2dBm when implementing the Gaussian Filter.

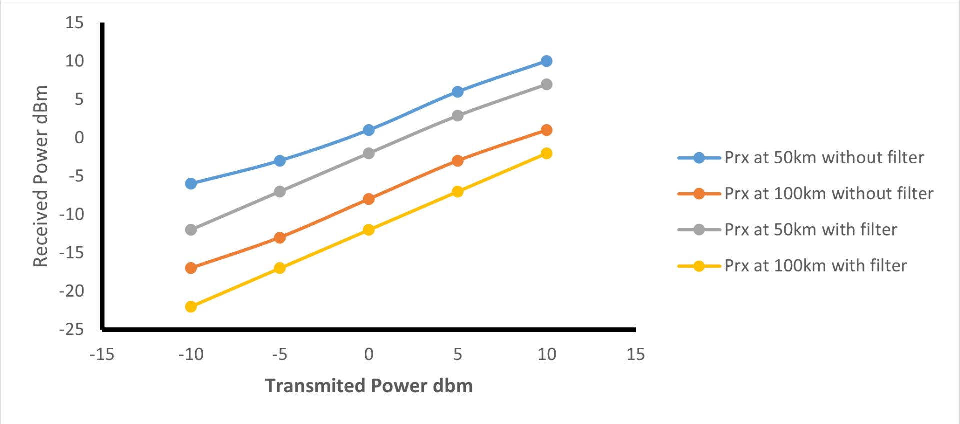
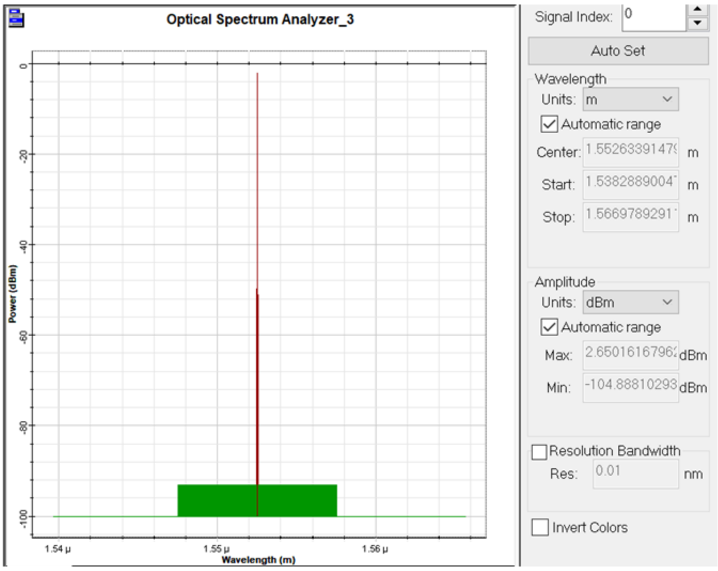


Figure 5: Transmitted Power versus Received Power for System with Gaussian Filter

Table 3: Transmitted and Received Power with /without presenting the Gaussian Filter

Transmitted Power (dBm)	Filter receiver power (dBm) at 50km		Filter receiver Power (dBm) at 100km	
	without	with	without	with
-10	-6	-17	-12	-22
-5	-3	-13	-7	-17
0	1	-8	-2	-12
5	6	-3	2.9	-7
10	10	1	7	-2

The transmitted and received optical spectrum of the investigated system is presented in Figure 6 and Figure 7 for the system with/without Gaussian optical Filter. It is clear to observe that the system, when implementing the optical Gaussian Filter can eliminate the effect of noise on the received signal.



Signal Index: 0

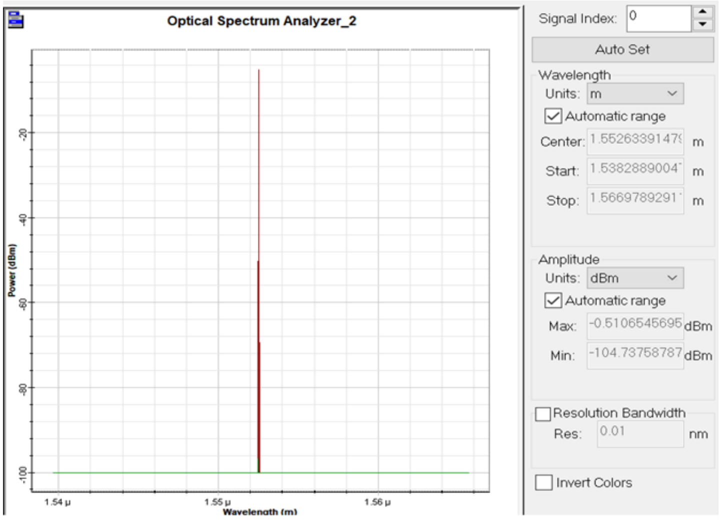
Wavelength
Units: m
☑ Automatic range
Center: 1.5526339147 m
Start: 1.5382889004 m
Stop: 1.5669789291 m

Amplitude
Units: dBm
☑ Automatic range
Max: 2.6501616796 dBm
Min: -104.88810293 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

☐ Invert Colors

Figure 6: Optical Spectrum Analyzer before Adding Gaussian Filter



Signal Index: 0

Wavelength
Units: m
☑ Automatic range
Center: 1.5526339147 m
Start: 1.5382889004 m
Stop: 1.5669789291 m

Amplitude
Units: dBm
☑ Automatic range
Max: -0.5106545695 dBm
Min: -104.73758787 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

☐ Invert Colors

Figure 7: Optical Spectrum Analyzer after Adding Gaussian Filter

The system performance comparison based on the transmitted and received Power based on utilizing the rectangular Filter is presenting in Figure 8. The presenting result shows that the received Power at 100km when transmitting 10dBm is equal to -2dBm. Table 4, shows the system comparison based on transmitted and received Power with /without presenting the rectangular Filter for different transmission distance.

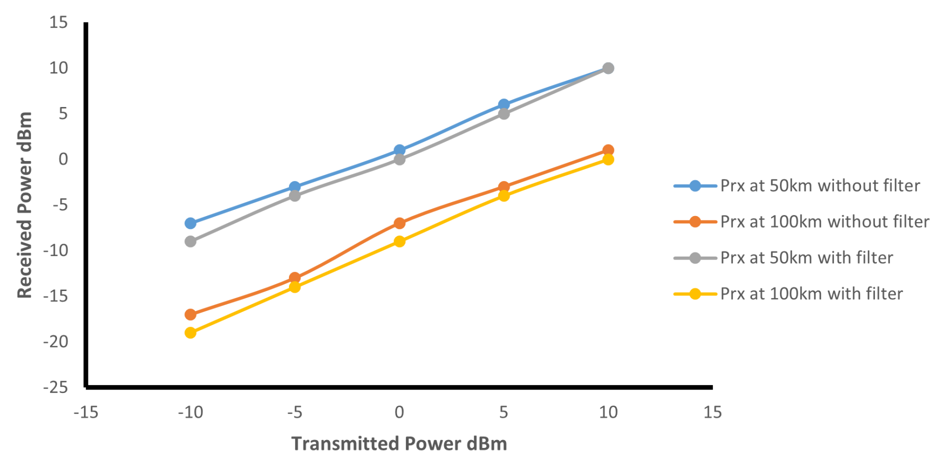
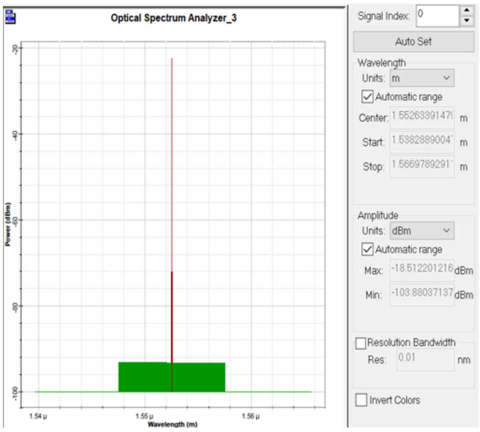


Figure 8: Transmitted Power versus Received Power for System with Rectangular Filter

Table 4: Transmitted and Received Power with /without presenting the Rectangular Filter

Transmitted Power (dBm)	Filter receiver power (dBm) at 50km		Filter receiver Power (dBm) at 100km	
	without	with	without	with
-10	-7	-17	-9	-19
-5	-3	-13	-4	-14
0	1	-7	0	-9
5	6	-3	5	-4
10	10	1	10	0

The investigated system's transmitted and received optical spectrum is presented in Figure 9 and Figure 10 for the system with/without rectangular optical Filter. It is clear to observe that the system, when implementing the optical rectangular Filter can reduce the effect of noise on the received signal.



Signal Index: 0

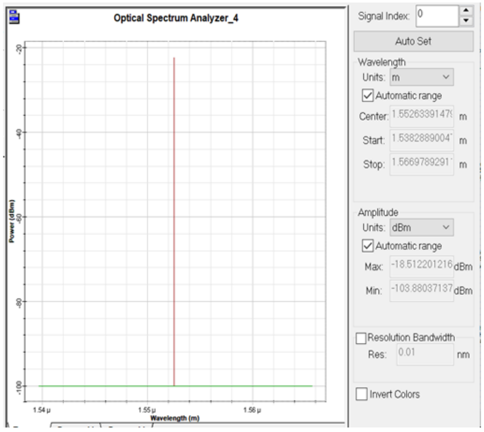
Wavelength
Units: m
☑ Automatic range
Center: 1.5526339147 m
Start: 1.5382889004 m
Stop: 1.5669789291 m

Amplitude
Units: dBm
☑ Automatic range
Max: -18.512201216 dBm
Min: -103.88037137 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

☐ Invert Colors

Figure 9: Optical Spectrum Analyzer before Adding Rectangular Filter



Signal Index: 0

Wavelength
Units: m
☑ Automatic range
Center: 1.5526339147 m
Start: 1.5382889004 m
Stop: 1.5669789291 m

Amplitude
Units: dBm
☑ Automatic range
Max: -18.512201216 dBm
Min: -103.88037137 dBm

☐ Resolution Bandwidth
Res: 0.01 nm

☐ Invert Colors

Figure 10: Optical Spectrum Analyzer after Adding Rectangular Filter

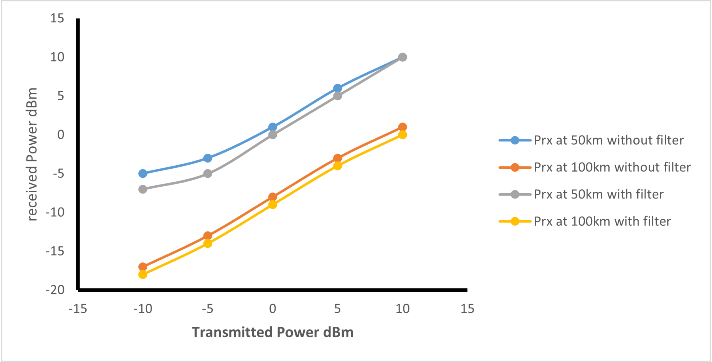
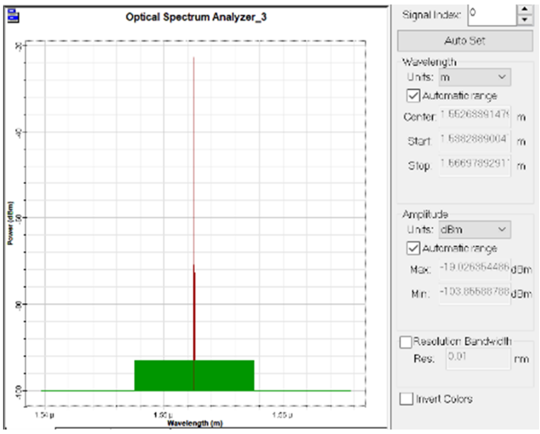


Figure 11: Transmitted Power versus Received Power for System with Trapezoidal Filter



Signal Index: 0

Units: m

☑ Automatic range

Center: 1.5526339147 m

Start: 1.5382889004 m

Stop: 1.5669789291 m

Units: dBm

☑ Automatic range

Max: -19.026354486 dBm

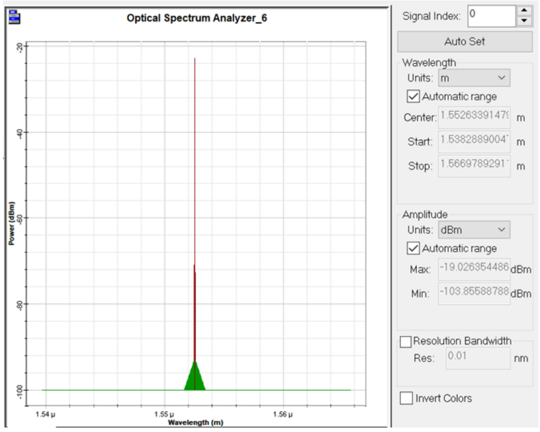
Min: -103.85588788 dBm

☐ Resolution Bandwidth

Res: 0.01 nm

☐ Invert Colors

Figure 12: Optical spectrum analyzer after doubling optical amplifier & before adding Filter



Signal Index: 0

Units: m

☑ Automatic range

Center: 1.5526339147 m

Start: 1.5382889004 m

Stop: 1.5669789291 m

Units: dBm

☑ Automatic range

Max: -19.026354486 dBm

Min: -103.85588788 dBm

☐ Resolution Bandwidth

Res: 0.01 nm

☐ Invert Colors

Figure 13: Optical spectrum analyzer after adding Filter

To perform the system investigation in terms of BER, we designed a direct detection 4-QAM OFDM system with a transmitter of -5 dBm and 10 Gb/s as transmitted data. The system performed for different transmitted distances varied from 40 km to 180 km. Table 5 compares the optical system with implementing different optical Filters. As well as Figure 14 depicts the variation of BER for different transmitted distances. It is found that the Gaussian Filter has a lower BER value than system

Table 5: Fiber Distance versus BER for Different Optical Filter

Fiber Distance (km)	BER of Gaussian Filter	BER of Rectangular Filter	BER of Trapezoidal Filter
40	0	0	0
50	0	0	0
60	0	0	0
70	0	2×10^{-5}	3×10^{-5}
80	0	0	0
110	0.015	0.0085	0.002
120	0.087	0.0545	0.022
140	0.33	0.25	0.17
160	0.46	0.425	0.39
180	0.49	0.48	0.47

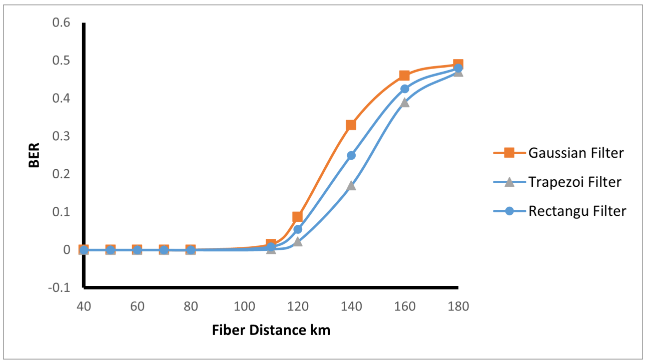


Figure 14: Comparison of BER for Different Optical Filter

The accuracy of the transmit Filter and the digital-to-analog converter (D/A) and the nonlinearity of the high-power amplifier (HPA) may be estimated with the help of error vector magnitude, also known as EVM. The error value measured by the EVM is the difference between the complex voltage of a demodulated signal and the symbol that was predicted. However, Table 6 presents the result of the investigated system for a different type of optical Filters with transmitting data of 10 Gb/s, -5dBm lunched Power, and 5 Gb/s as symbol rate. The results show that the system employing a gaussian Filter has the lowest EVM value as it increases the transmission distance. The EVM value concerning increasing the transmission distance is depicted in Figure 15; the investigated system deployed different filter type (Gaussian Filter, Rectangular Filter, and Trapezoidal Filter). It is clear that the EVM value of 811.81 has been achieved by the rectangular Filter, while the Gaussian Filter achieved the lowest value of 395.55.

Table 6: Compere EVM between the filters

Fiber distance	EVM for Gaussian filter	EVM for trapezoidal filter	EVM for rectangular Filter
40	15.3	8.3	15.14
50	7.09	8.5	15.59
60	7.9	8.8	16.7
70	9.59	9.5	19.09
80	9.46	11.2	20.66
110	25.05	31.3	56.35
120	35.17	49.2	84.37
140	110.67	143.08	253.75
160	240.06	266.12	506.18
180	395.55	416.26	811.81

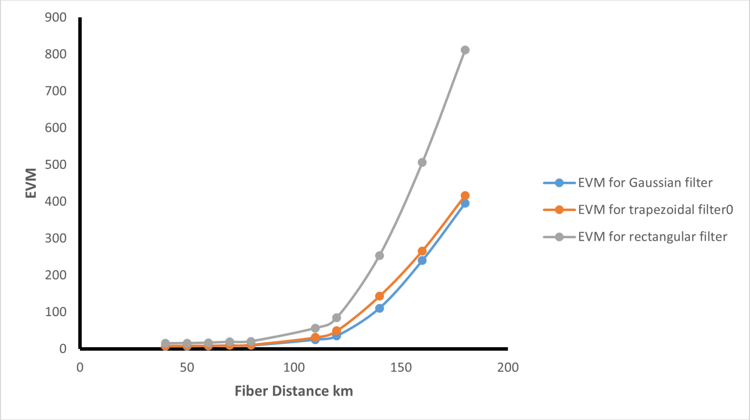


Figure 15: Comparison of EVM for Different Optical Filter

5 Conclusion

In this paper, we investigate the effect of implementing different optical Filter on the performance of the 4-QAM OFDM system. the extracted results show that the optical 4-QAM OFDM system has a lower BER value of less than 3×10^{-3} when utilizing the Gaussian optical Filter. A 10 Gb/s 4-QAM OFDM with direct detection techniques has been transmitted over 180 km single mode fiber, achieving BER less than 10^{-3}. Also, EVM demonstrated the transmitting length for Gaussian, rectangular, and Trapezoidal optical Filters. These systems have cost effective and high-performance long-haul 10-Gb/s.

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