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Enhanced thresholding-based wavelet noise filtering in optical fiber communications

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ABSTRACT

Nowadays, the growing requirement of higher data transmission rates for real-time applications of communication systems. The capacity of data transmission increased with the higher carrier frequency. Optical Fiber Communication (OFC) systems gained a significant interest of researchers due to its capability of enhancing the data-carrying capacity. The optical waves in OFC systems operate in the range of THz those results in the increased capacity of data-carrying. The OFC systems achieved a high data rate, however, suffered from the challenges of various noises. The presence of noises in OFC may degrade the transmitting signal quality & increases the error rates. The OFC systems design by considering the noise in optical communication links recently received great interest from researchers. In this paper, we first presented the OFC design with noises such as white Gaussian noise, shot noise, & thermal noise. Secondly, the impact of noises in OFC analyzed through simulation results by performing optical communications with & without noises. Third, to suppress the noise effects on optical communications, we propose the enhanced thresholding-based wavelet Denoising approach called Wavelet Denoising using Enhanced Thresholding (WDET). The aim of WDET for optical communications is to improve the signal quality & minimize the signal errors effectively in the presence of various noises. The design of WDET is based on the properties of hard & soft thresholding of wavelet Denoising. The simulation results show that the proposed Denoising approach improves the signal quality factor with reduced Bit Error Rate (BER) & Mean Square Error (MSE) compared to existing filtering methods.

Keywords: Bessel filtering, bit error rate, Gaussian filtering, optical communications, noise, wavelet thresholding, signal quality.

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1 Introduction

In general, communication is the process of transferring data from one location to another. To communicate over a long distance, communication systems are required [1]. In these communication systems, information is being transferred over the wide distance range by the process of modulation. The information is carried by high-frequency electromagnetic waves in the modulation process. Particularly, in optical fiber communication systems, the visible optical carrier waves are required & these are in the optical range. These optical carrier waves are of high frequencies of around 100 THz. The recent 5th generation optical systems focused on the conventional C band. These systems focused on increasing the wavelength range in Wavelength Division Multiplexing (WDM) [2] [3]. Optical communications systems also made use of Solitons. Solitons are pulses of specific shape that preserves its shape while counteracting the dispersion & non-linearity in the fiber. The goal of 5th generation systems was to utilize the bandwidth of fiber efficiently by the techniques of Dense WDM (DWDM). DWDM is the variant technology of WDM [4].

Figure 1 demonstrates the general block diagram of the OFC system which is consisting of three main components such as a transmitter, transmission channel, & receiver. The optical signal connected to optical fiber using fibber fly lead. The block regards transmission channel known as cable that delivers environment & mechanical security to optical fibers. Every optical fiber represents itself as a channel. Two optical fibers joined by using optical splice, furthermore, optical connector introduced for temporary non-fixed joints among two optical fibers. The received signal provided by optical coupler to other devices. The repeater used to convert the optical signal to an electrical signal exploiting the optical receiver & transmit it to the electronic circuit. The electrical signal reshaped & amplified at an electronic circuit due to distortion, attenuation, & noises caused by long-distance communications. The signal furthermore converted into an optical signal using an optical transmitter. Finally, the receiver block consists of a photo detector, amplifier, & signal restorer. The optical signal converted into an electrical signal using a photo detector. The blocks amplifiers & signal restorers used to enhance the received signal quality which is degraded due to the possibility of noise insertion. The noises in signals introduced because of photo detectors [5]. LED & LASER diode has been commonly used as a source for short & long-distance communications respectively. Similarly, P-I-N (PIN) & Advance Photo Diode (APD) diodes used commonly for short & long-distance communications respectively in OFC systems.

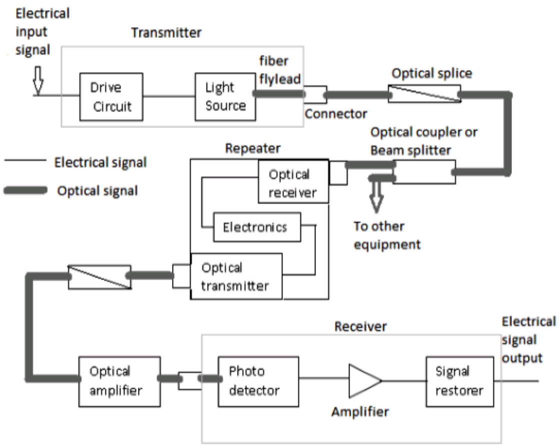

Figure 1. OFC system block diagram

The presence of noises in received signal degrades the signal quality & affects significantly of performance in terms of quality factor & BER. In the case of the OFC system, noises such as voltage noise, current noise, thermal noise, Gaussian white noise, shot noise, & optical intensity noise. Noise can be classified in several ways such as (i) intrinsic or extrinsic, (ii) coherent or random, (iii) additive or multiplicative, (iv) Ergodic, & (v) stationary. As discussed earlier, in optical communications noise will be signal distortion/attenuation caused by long-distance communications & limiting in electronics, interaction among fibber dispersion & laser chirp, nonlinear effects in electro-optics.

This paper presents the method to reduce the noise from the received signal in OFC systems. We present the Enhanced thresholding approach of wavelet Denoising property to effectively suppress different types of noise to improve the signal quality & minimize the BER performance. The enhanced thresholding technique designed using properties of hard & soft thresholding of Discrete Wavelet Transform (DWT). The received signal decomposed by DWT into approximation & detailed coefficients, the enhanced thresholding applied on coefficients to filter out noisy parts, & then reconstruct the de-noised signal using Inverse DWT (IDWT). Section II presents a brief study of related works. Section III presents the proposed system design for noise reduction. Section IV presents the simulation results for long-distance optical communications in presence of different noises. Section V presents summarizes the methodology & results of this paper.

1.1 Related works

Recently for 5th generation optical communications, very rare methods introduced for noise reduction of OFC systems. This section presents the review of related to noises in optical communications & their reduction techniques.

In [6], author introduced the advances, Dispersion Managed (DM) arrangements and waveform reshaping in the paper. For DM Soliton transmission, the author depicted 1 Tb/s WDM Soliton transmission more than 1500 km. The dispersion managed Solitons have enormous forces edge and dispersion resistance.
In [7], concentrate on nonlinear impact and effect of Polarization Mode Dispersion (PMD) on DWDM introduced. Transmission condition of DWDM framework comprises of PMD, SPM, XPM and FWM were inferred. In light of the equations, numerical simulation of an 8 x 40 GB/s DWDM framework has been completed.
In [8], author acquainted strategy with actualize electronically post repay fibber non-linearity in long stretch, WDM transmission frameworks with bit rate over 40 Gb/s. The authors approved the strategy by playing out the simulations of a 42.7 GB/s RZ and CSRZ regulated WDM framework. The author examined the proposed strategy for come back to zero and bearer stifled come back to zero balance group utilizing two diverse dispersion maps.
In [9] impact of filter bandwidth and flank steepness of both multiplexing and de-multiplexing filters in DWDM framework within the sight of sound frequency division multiplexing crosstalk examined. Utilizing the simulation, author decided the ideal estimations of bandwidth and states of MUX and DEMUX filters in DWDM framework.
In [10] DWDM communication framework examined dependent on the Fibber Optical Parametric Amplifier (FOPA) as inline amplifier and contrasted it and EDFA. Parametric intensification depended on a viable four wave blending process that happens in profoundly nonlinear fibber.
In [11], author utilized EDC (Electronic Dispersion Compensation) in light of least mean square blunder enhancement to improve the presentation of 32 channels, long stretch DWDM optical Soliton connect. In spite of the fact that DCF (Dispersion Compensated Fibber) was a valuable strategy to nullify the collected dispersion yet it needs flexibility.
In [12], author introduced the correlation of different dispersion compensation procedures on the base of Q factor and BER. The authors examined the OPC, FBG, DCF, CDM and AIO (All-In-One) as dispersion repaying methods.
In [13], author presented the different dispersion compensation strategies like DCF, EDC, FBG and computerized filters. The computerized filters were favored over FBG, as FBG had a mind-boggling design. Advanced filters when utilized alongside computerized handling can remunerate chromatic dispersion. All pares lossless optical filters are utilized for dispersion compensation. Lossless all pares filter can surmised any ideal stage reaction in spite of the fact that keeping up a steady solidarity sufficiency reaction. The author likewise talked about different filters like Band Pass filter, Super Gaussian filters, Butterworth filters and Fabre Perot filters.
In [14], as of late author introduced the examination on accessible acknowledgment of long stretch DWDM frameworks with ultra-broadband optical amplifiers. They investigated the half breed plans with the EDFA and Raman amplifiers.
In [15], multi-channel-good and balance group free long stretch transmission interface with in-line stage touchy amplifiers introduced. They showed an arrive at progress of 5.6 occasions at ideal dispatch powers with the stage delicately intensified connection working at an all-out amassed nonlinear stage move of 6.2 rad.
In [16], author proposed the noise reduction technique for PIN & APD using the different filters such as Butterworth filter, Bessel filter, & Gaussian filter in optical communications.
From above literature, we noticed that 95 % works reported on amplification & modulation-based signal quality improvement & only couple of attempts introduced that uses the filtering methods to reduce the noises at receiver end like in [17] where Bessel filtering shows the effective performances. The amplifier & modulation approaches cannot effectively address the distortions & attenuations caused by the long-distance communications; hence it is required to design the effective filtering technique to filter out the noise from received signal in optical communications. This paper proposed the DWT Denoising technique where we designed the enhanced thresholding approach to reduce the BER & improve the quality factor performance.

2 Methodology

Figure 2 demonstrates the proposed OFC system using the enhanced thresholding-based DWT signal Denoising approach. The transmitter information generated is transmitted into the electrical form first. At the optical signal conversion block (which is also called as optical source), received electrical data converted into an optical signal. As discussed earlier, the optical source in optical communications at transmitter either LED or LASER diode. In this work, we used a continuous-wave LASER diode with operating frequency 1550 nm & 1310 to continuously pump & emit light. This diode operates at 10mW power. The optical signal at transmitter block is further transmitted towards the receiver block via the transmission channel i.e. glass fiber. The detailed components of the transmission channel or glass fiber are shown in figure 1. Due to long-distance communications, the optical signals get attenuated or distorted during the transmission towards the receiver block. Figure 2 shows that after optical signal transmission via fiber cable using different components, the distorted/attenuated/noisy optical signal received at the receiver end. At the receiver end, the photo detector APD used to convert the optical signal into the electrical signal. In this paper, we used APD due to its ability to achieve improved performances for both short & long-distance communications compared to PIN [21]. APDs are especially introduced for reverse breakdown areas which are having severed sensitivity. Due to multiplication effects, APD provides higher gain. The received electrical signals using APD are noisy or distorted, hence to suppress such signal distortions to we applied the proposed WDET to improve received signal quality.

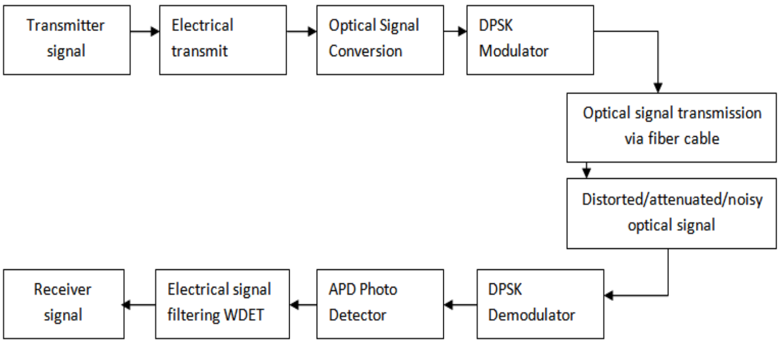

Figure 2. Proposed OFC design using the WDET filtering approach

Modulation is another important component of the OFC system. In this paper, we used the DPSK (Differential Phase-Shift Keying) as it delivered the best results for ultra-high-speed & long-distance optical communication technology in all-optical networks [22]. In general, for OFC systems, Electra-Absorption Modulator (EAM) & Mach-Zehnder Modulator (MZM) as DSPK modulators are used. These modulators appropriate for 40 Gbit/s optical communications. In this paper, we used MZM to deliver the optical DPSK signals. The optical signal modulated using the DPSK encoder followed by the electro-optic (E/O) phase modulator. The output of the DPSK modulator block is DPSK optical signal which is further transmitted over the transmission channel. Once the DPSK optical signal received at the receiver, Mach-Zehnder interferometer (MZI) is used for phase demodulation, furthermore, a balanced detector used to enhance the Optical Signal-to-Noise Ratio (OSNR). The MZM controls the optical wave amplitude effectively compared to EAM.
The key part of this proposed design is WDET block which is used to perform the received distorted/noisy electrical signal filtering in this paper. Before presenting the DWT based filtering of electrical signals at receiver end, we presented the wavelet transform & its mathematical representation in section A. Section B presents the design of WDET consist of DWT decomposition, Denoising, & Inverse DWT operations.

2.1 Wavelet transform

The DWT is the wavelet transform technique which is widely adopted across different domains such as image processing, signal processing, wireless communications etc. The achievement of the DWT lies in ease of computation (minimum time & energy requirements) & its decomposition of a signal into spatial sub-packs that allows the Denoising operations.
Wavelets are functions generated by dilation & translation of a single mother wavelet function Ψ (t) as given by:

$$\Psi_{a,b}(t)=\frac{1}{\sqrt{a}}\ \Psi(\frac{t-b}{a}) \qquad (1)$$

Where, a & b represents wavelet coefficients. The Ψ (t) has to satisfy the following conditions:
Admissibility condition: $\int |\ \Psi(\omega)|^2|\ \omega|^{-1}d\omega$

Discrete wavelet transform function given by Eq. (1) is obtained by putting $a = 2^{-j}$ & $b = k2^{-j}$ in this equation. Where $\Psi(\omega)$ is the Fourier transform of $\Psi(t)$? It implies that $|\Psi(\omega)|_{\omega=0}=0$ i.e.$\int \Psi(t)dt = 0$, which means that $\Psi(t)$ is zero mean & must be a wave.

Regularity conditions: That the wavelet function ought to have some smoothness & concentration in both time & frequency domains:

$\Psi_{j,k}(t) = 2^{j/2}\,\Psi(2^{j}t - k).$ (2)

Where the $\Psi_{j,k}$ constitute ortho-normal basis, i.e., wavelet coefficients of function $f(t)$ is:

$W_{j,k}=\int f(t)^{j/2}(2^{j}t - k)\,dt$ (Analysis equation) (3)

The function $f(t)$ can be reconstructed from wavelet coefficients as

$f(t) = \sum_{j}\sum_{k} W_{j,k}2^{j/2}\,\Psi(2^{j}t - k)$ (Synthesis equation) (4)

The above Eq. (3) & (4) shows analysis & synthesis equation of DWT. DWT is implemented using filter banks.

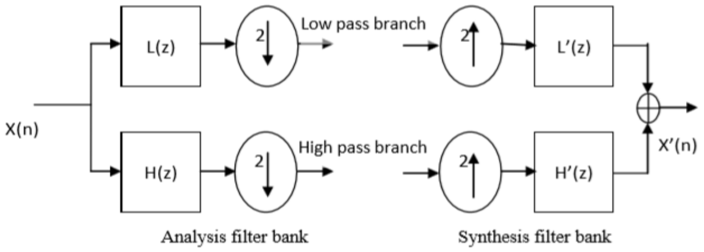

Figure 3. Wavelet represenation with basic two-channel filter bank structure

2.2 WDET Filtering

The noise removal or distortion removal from received optical communication signal in electrical form is performed by WDET technique in this paper. This process consists of three key steps decomposition, Denoising, & reconstruction.

1.Decomposition*:* In communication systems, the effective filtering technique required with minimum information misfortune probabilities. In the design of WDET, we decomposed the input electrical signal *ES* using 2D-DWT.

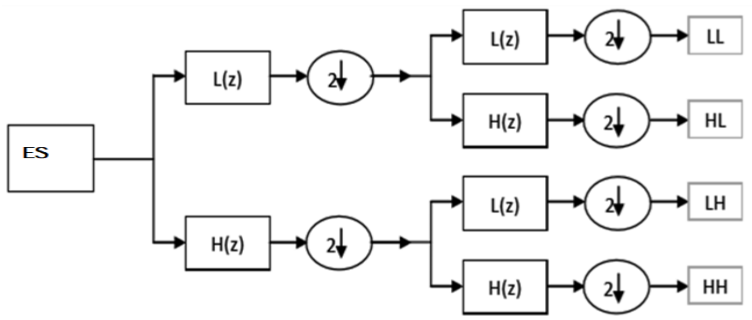

Figure 4. Electrical signal decomposition using 2D-DWT

As showing in figure 4, the distorted/noisy signal *ES* decomposed into low-frequency & high-frequency bands at first level. The 2^{nd} level DWT decomposition produces four coefficients consist of one low-frequency LL (approximation) coefficient & three high-frequency coefficients such as HL (horizontal), LH (vertical), & HH (Diagonal).

2.Denoising: As discussed earlier, the noise/distortions in the received signal lead to poor signal quality & higher BER performance. We used the DWT Denoising function to suppress the noise or distortion components from the decomposed coefficients. DWT Denoising property supports thresholding-based noise removal. Two types of thresholding techniques commonly used such as soft & hard thresholding. The limitations of hard & soft thresholding methods are: the hard threshold method is irregular & the soft threshold method induces consistent variation. To overcome the problems of hard & soft thresholding, we introduce the enhanced thresholding function which is applied to all high-level coefficients such as HL, LH, & HH. The hybrid thresholding based on properties of hard & soft thresholding techniques to achieve effective Denoising. The three high-frequency coefficients are filtered using proposed enhanced thresholding functions in Eq. (5), Eq. (6), & Eq. (7).

$$\widehat{\mathrm{HL}} = \begin{cases} \mathrm{sng}\,(\mathrm{HL})) * (|\mathrm{HL}| - \alpha), & \text{if } (\mathrm{HL} > \varepsilon\alpha) \\ 0 & \text{else} \end{cases} \quad (5)$$

$$\widehat{\mathrm{LH}} = \begin{cases} \mathrm{sng}\,(\mathrm{LH})) * (|\mathrm{LH}| - \alpha), & \text{if } (\mathrm{LH} > \varepsilon\alpha) \\ 0 & \text{else} \end{cases} \quad (6)$$

$$\widehat{\mathrm{HH}} = \begin{cases} \mathrm{sng}\,(\mathrm{HH})) * (|\mathrm{HH}| - \alpha), & \text{if } (\mathrm{HH} > \varepsilon\alpha) \\ 0 & \text{else} \end{cases} \quad (7)$$

Where, α denotes the minimum threshold value to remove the noise, ε represents the additional adjustment parameter in range$(0 < \varepsilon < 1)$. The$\widehat{\mathrm{HL}}$,$\widehat{\mathrm{LH}}$ & $\widehat{\mathrm{HH}}$ are the filtered DWT coefficients of original high-frequency coefficients HL, LH, & HH respectively. We applied the enhanced thresholding only on high-frequency coefficients as it contains the detailed electrical signal information as compared to the low-frequency coefficient.
3.Reconstruction**:** After Denoising the wavelet coefficients, we required to reconstruct the original received electrical signal using de-noised high-frequency coefficient ($\widehat{\mathrm{HL}}$,$\widehat{\mathrm{LH}}$ &$\widehat{\mathrm{HH}}$) & low-frequency coefficient LL. This can be done by using the Inverse DWT (IDWT). The de-noised electrical signal $\widehat{ES}$ received at receiver end by:

$$\widehat{ES} = IDWT\ (LL, \widehat{HL}, \widehat{LH}, \widehat{HH}) \quad (8)$$

3 Simulation results

This section presents the simulation results using proposed filtering approach & compared its performances with state-of-art filtering techniques such as Butterworth [21] & Bessel filter [21,22]. The methods are implemented & evaluated in MATLAB tool. To claim the efficiency of proposed technique, we introduced three types of noises such as Gaussian white noise, short noise (also called as Poisson noise), & thermal noise. These noises commonly appeared in optical communications. Table 1 shows the other simulation parameters used to design OFC system in this work.

Table 1: Simulation parameters

Communication distance	0-30 Km
Transmitter	2
Receiver	2
Optical source type	LASER diode
Photo-dector	APD
Optical source power	10mW
Continuous wave wavelengths	1550nm
SNR	0:5:50dB

The evaluation of filtering techniques used in OFC system is performed using the three metrics such as BER, MSE, & Q-factor (i.e. quality factor). The BER & MSE are computed using the standard MATLAB functions by passing the two signals original transmitted signal from transmitter TS & filtered signal$\widehat{ES}$. The Q-factor is computed by first measuring the OSNR followed by the estimating the higher SNR for each method. The noise is inserted into the optical signal received at APD. The results presented for each noise in below sections.

3.1 White Gaussian Noise

This is mothering but the Additive white Gaussian noise (AWGN) is a basic noise model used in information theory to mimic the effect of many random processes that occur in nature. This noise is commonly occurred into the communication channels. The results of BER, MSE, & Q-Factor are showing in figures 5, 6, & 7 respectively.

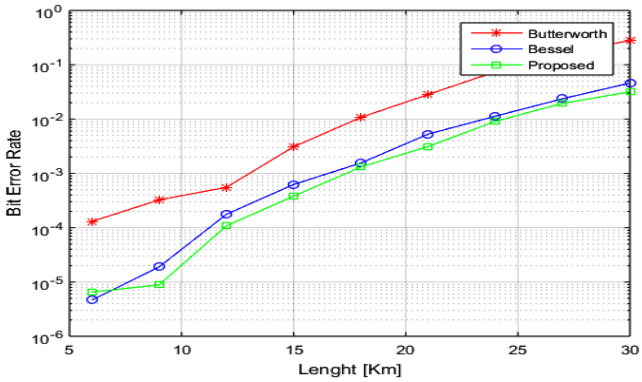

Figure 5. BER performance analysis for white Gaussian noise

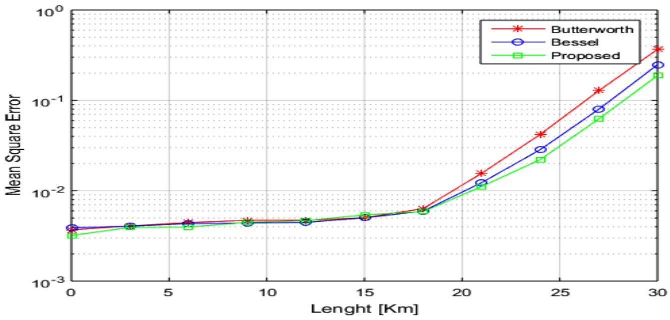

Figure 6. MSE performance analysis for white Gaussian noise

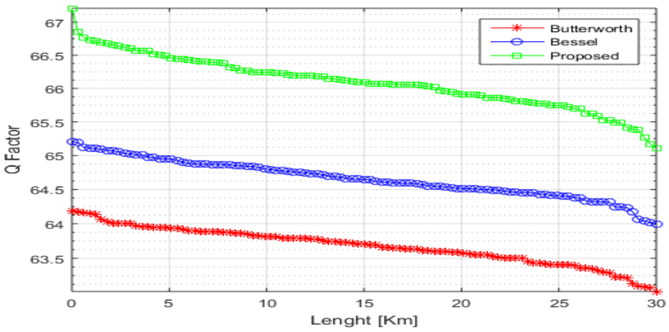

Figure 7. Q Factor performance analysis for white Gaussian noise

As showing in figures above, the proposed WDET technique effectively suppresses the white Gaussian noise in received optical signals at the receiver end as compared to existing filters. The results of BER, MSE, & Q-factor show that as the communication distance or fibber length increases, the performances become worst i.e. BER & MSE increase, & Q-factor decreases. It means that longer communication distances prone to higher signal disturbances. The proposed approach achieved minimum signal errors (BER & MSE) & higher signal quality (Q-factor) over the Butterworth & Bessel filters.

3.2 Shot Noise

This is another kind of noise that is frequently introduced in OFC systems. The shot noise is caused by unavoidable random statistical fluctuations in optical transmission channels electronic devices such as coupler, amplifier. In the evaluation of short noise, we apply all filtering methods individually to minimize its effects on the received optical signal. The simulation results demonstrate the outcomes of using each method in terms of BER, MSE, & Q-factor in figures 8, 9, & 10 respectively. The results are expressive using proposed enhanced thresholding-based wavelet Denoising function in optical communications over the existing filtering methods.

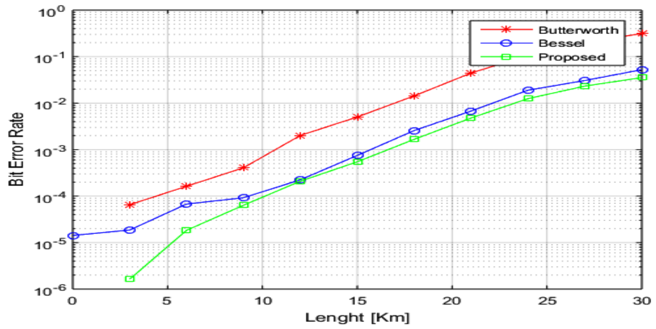

Figure 8. BER performance analysis for shot noise

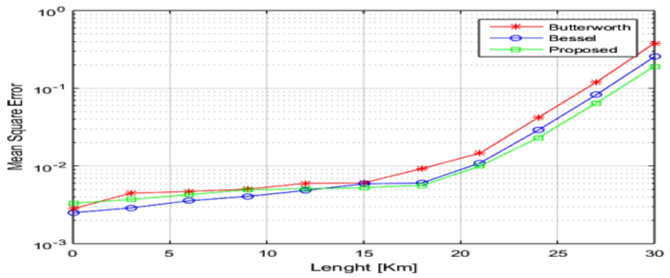

Figure 9. MSE performance analysis for shot noise

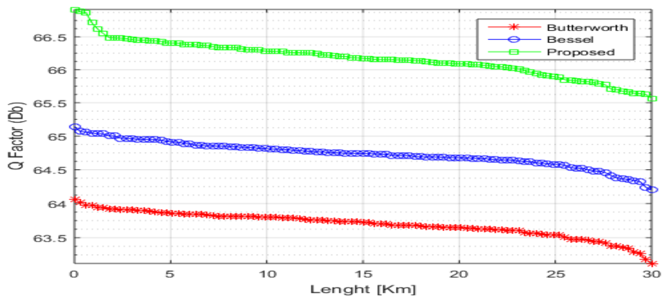

Figure 10. Q-Factor performance analysis for shot noise

The Bessel filtering shows the second-best Denoising technique in these evaluations. Among all the previous filters, Bessel filtering showed an efficient technique so far for optical communications; however, the wavelet Denoising technique not yet applied for the same. In this paper, we designed the wavelet Denoising property by defining the enhanced thresholding technique to enhance the signal quality further. The BER & MSE show a significant reduction in signal error approach & improved signal quality using WDET compared to other filtering methods.

3.3 Thermal Noise

In optical communications, the thermal noise is caused by electrons random motion which is frequently present at any finite temperature. In these simulations, we created the thermal noise with having 290 K noise temperature & 5 MHz sample rate. The simulation results of BER, MSE, & Q-factor presented in figures 11, 12, & 13 respectively. The BER & MSE for 30 km length using proposed method shows error reduction in received signals. The Butterworth filter shows the worst performance for all parameters & noises investigations.

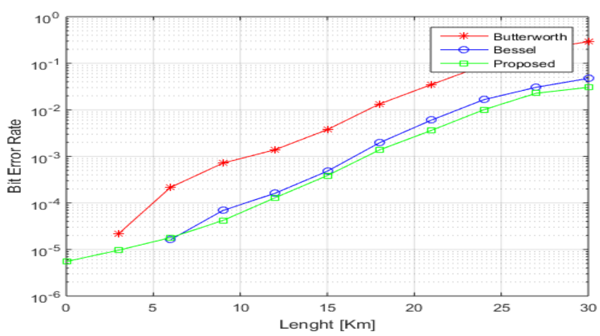

Figure 11. BER performance analysis for thermal

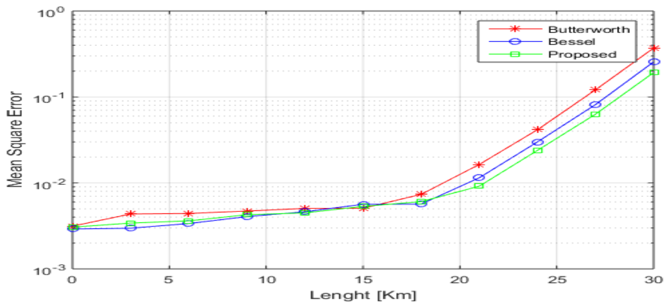

Figure 12. MSE performance analysis for thermal noise

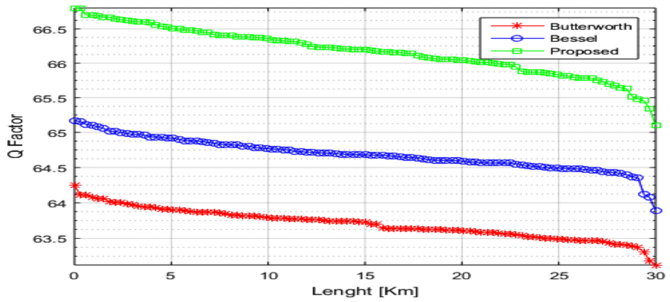

Figure 13. Q-factor performance analysis for thermal noise

The uses of filtering using DWT achieved further improved results in de-noised electronic signal & assure the higher signal quality by suppressing the thermal noise.

3.4 Average Evaluations

Table 2, 3, & 4 shows the average BER, MSE, & Q-Factors results in presence of white Gaussian, shot, & thermal noises respectively. From these results it shown that BER results reduced by approximately 0.003 compared to recent best Bessel filter. The MSE results reduced by approximately by 0.008 compared to Bessel filtering. The Q-factor results show the improvement by 1.5 dB compared to Bessel filtering.

Table 2. Average BER, MSE, & Q-Factor results using white Gaussian noise

	BER	MSE	Q-Factor
Butterworth	0.0512	0.0533	63.67
Bessel	0.0081	0.0364	64.65
Proposed	0.0059	0.0287	66.09

Table 3. Average BER, MSE, & Q-Factor results using shot noise

	BER	MSE	Q-Factor
Butterworth	0.0625	0.0541	63.69
Bessel	0.0102	0.0370	64.73
Proposed	0.0071	0.0292	66.17

Table 4. Average BER, MSE, & Q-Factor results using white thermal noise

	BER	MSE	Q-Factor
Butterworth	0.0571	0.0531	63.70
Bessel	0.0094	0.0371	64.68
Proposed	0.0062	0.0290	66.17

4 Conclusions and future work

This paper presented the simulation & analysis of proposed OFC system Denoising using the APD photo detector & 30 Km long communication fibber cable. We proposed a wavelet-based Denoising function in which the enhanced thresholding designed to effectively reduce the impact of different kinds of noises. Paper presented the complete design of the OFC system using WDET. The proposed model is simulated using three types of noises such as white Gaussian, shot, & thermal. The performance of the proposed Denoising approach compared with state-of-art filtering methods. The results show a significant improvement in results for 30Km distances. For future work, we suggest working on other short & long communication fibber distances.

Abbreviations and acronyms

OFC-Optical Fiber Communication
WDET-Wavelet Denoising using Enhanced Thresholding
BER-Bit Error Rate
Q-Factor-Quality Factor
MSE-Mean Square Error
WDM-Wavelength Division Multiplexing
DWDM-Dense Wavelength Division Multiplexing
LED-Light Emitting Diode
LASER-Light Amplification by Stimulated Emission of Radiation
PIN-Positive-Intrinsic-Negative
APD-Advance Photo Diode
IDWT-Inverse Wavelength Division Multiplexing
DM-Dispersion Managed
PMD-Polarization Mode Dispersion
SPM-Self-Phase Modulation
XPM-cross-phase modulation
FWM-Four-Wave Mixing
RZ- Return to Zero
CSRZ-Carrier Suppressed Return to Zero
MUX-Multiplexer
DEMUX-Demultiplexer
FOPA-Fibber Optical Parametric Amplifier
EDFA-Erbium-Doped Fiber Amplifier
EDC-Electronic Dispersion Compensation
DCF-Dispersion Compensated Fibber
OPC-Optical Phase Conjugation
FBG-Fiber Bragg Grating
DCF-Dispersion Compensating Fiber
CDM-Chromatic Dispersion Map
AIO-All-In-One
EDC-Electronic Dispersion Compensation
DPSK-Differential Phase-Shift Keying
EAM-Electra-Absorption Modulator

MZM-Mach Zehnder Modulator ()
E/O-Electro Optic
MZI-Mach-Zehnder interferometer
OSNR-Optical Signal-to-Noise Ratio
AWGN-Additive white Gaussian noise

References

[1] N. AL-Janaby and A. AL-Dergazly, “Fabrication of multi-mode tip fiber sensor based on surface plasmon resonance (SPR)”, Sustainable Engineering and Innovation, vol. 2, no. 1, pp. 10-17,

[2] K. Singh, N. Singh & G. Dhaliwal, (2012), “Performance Analysis of different WDM systems”, International Journal of Engineering Science & Technology, Vol. 4, No. 3, pp. 1140-1144.

[3] J. Li, E. Tipsuwannakul, T. Eriksson, M. Karlsson & P. Andrekson, (2012), “Approaching Nyquist Limit in WDM Systems by Low-Complexity Receiver-Side Duobinary Shaping”, Journal of light wave technology, Vol. 30, No. 11, pp. 1664-1676.

[4] H. Tan, Q. Nguyen, M. Matsuura & N. Kishi, (2012), “Reconfigurable All-Optical OTDM-to-WDM conversion Using a Multi Wavelength Ultra shot pulse Source Based on Raman Compression”, Journal of Light wave Technology, Vol. 30, No. 6, pp. 853-863.

[5] R. Randhawa & J. Sohal, (2010), “Comparison of optical network topologies for wavelength division multiplexed transport networks”, International Journal For light & Electron Optics, Vol. 121, No. 12, pp. 1096-1110.

[6] M. Nakazawa, (2000), “Solitons for Breaking Barriers to Terabit/Second WDM & OTDM Transmission in the next Millennium”, IEEE Journal of selected topics in Quantum Electronics, Vol. 6, No. 6, pp.1332-1342.

[7] S. Ming, Z. Hui, Z. Meng, G. Yi & X. Xiong, (2006), “Impact of polarization mode dispersion & nonlinear effect on 40 Gb/s dense wavelength division multiplexing system”, Frontier of Electrical & Electronics Engineering in China, Vol. 1, No. 3, pp. 361-366.

[8] N. Ahmed, M. Hayee & Q. Zhang, (2010), “Electronic Post-compensation of Fiber Nonlinearity for 40Gbit/s WDM Systems”, Journal of Optical Communications Networks, Vol. 2, No. 7, pp. 456-462.

[9] M. Pfennigbauer & P. Winzer, (2006), “Choice of MUX/DEMUX Filter Characteristics for NRZ, RZ & CSRZ DWDM Systems”, Journal of Light wave Technology, Vol. 24, No. 4, pp. 1689-1696.

[10] M. Jazayerfar, S. Warm, R. Elschner, I. Sackey, C. Meuer, C. Schubert & K. Petermann, (2013), “Performance Evaluation of DWDM communications systems with Fiber Optical Parametric Amplifier”, Journal of Light wave Technology, Vol. 31, No. 9, pp. 1454-1461.

[11] J. Malhotra, M. Kumar & A. Sharma, (2012), “Performance Enhancement of 32 Channel Long Haul DWDM Soliton Link using Electronic Dispersion Compensation”, International Journal of Electronics, Communication & Instrumentation Engineering, Vol. 2, No. 4, pp. 11-15

[12] P. Singh & R. Chahar, (2014), “Performance Analysis of Dispersion Compensation in long haul Optical Fiber using DCF”, International Journal of Engineering & Science, Vol. 3, No. 8, pp. 235-238.

[13] N. Kahlon & G. Kaur, (2014), “Various Dispersion Compensation Techniques for Optical System: A Survey”, Journal of Communication & Software, Vol. 1, No. 1, pp. 64-73.

[14] R. Z. Ibragimov (2019), "Evaluation of DWDM systems design with ultra broadband optical amplifiers," Proc. SPIE 11146, Optical Technologies for Telecommunications 2018, 1114603 (24 June 2019); https://doi.org/10.1117/12.2526557

[15] Olsson, S. L. I., Elias son, H., Astra, E., Karlsson, M., & Andrekson, P. A. (2018). Long-haul optical transmission link using low-noise phase-sensitive amplifiers. Nature Communications, 9(1). Doi: 10.1038/s41467-018-04956-5.

[16] Gunman, Ghanendra Kumar, & Chakresh Kumar (2019), “Noise Reduction in Optical Communication System,” Int. J. Advanced Networking & Applications, Volume: 10 Issue: 06 Pages: 4065-4069 (2019) ISSN: 0975-0290.

[17] Shuai, R., Guijin, X., Yinghui, X., Weihu, Z., Xuejun, R., & Xiaoshuang, W. (2018). Research on Performance of Optical DPSK Modulation Format in All Optical Networks. 2018 10th International Conference on Communication Software & Networks (ICCSN). doi:10.1109/iccsn.2018.8488317.

[18] N. Kahlon and G. Kaur, (2014), “Various Dispersion Compensation Techniques for Optical System: A Survey”, Journal of Communication and Software, Vol. 1, No. 1, pp. 64-73.

[19] R. Z. Ibragimov (2019), "Evaluation of DWDM systems design with ultrabroadband optical amplifiers," Proc. SPIE 11146, Optical Technologies for Telecommunications 2018, 1114603 (24 June 2019); https://doi.org/10.1117/12.2526557

[20] Olsson, S. L. I., Eliasson, H., Astra, E., Karlsson, M., & Andrekson, P. A. (2018). Long-haul optical transmission link using low-noise phase-sensitive amplifiers. Nature Communications, 9(1). doi:10.1038/s41467-018-04956-5.

[21] Gunjan, Ghanendra Kumar, & Chakresh Kumar (2019), "Noise Reduction in Optical Communication System," Int. J. Advanced Networking and Applications, Volume: 10 Issue: 06 Pages: 4065-4069 (2019) ISSN: 0975-0290.

[22] A. Aldergazly, "Investigation of dispersion and nonlinear characteristics of liquid core optical fiber filled with olive oil", Sustainable Engineering and Innovation, vol. 2, no. 1, pp. 34-40, 2020.

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