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Development of a Technique for Mitigating Four-Wave Mixing Effect in Dense Wavelength Division Multiplexing System Using DP-QPSK with Channel Spacing

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Abstract: A Dense Wavelength Division Multiplexing (DWDM) system is a vital component in the optical network for the transmission of high data over a long distance. However, the non-linear effect of Four-Wave Mixing (FWM), one of the critical non-linear effects, limits the channel capacity and the amount of data that the DWDM system transmits. Intensity Modulation formats and Channel Shuffling algorithms being used to overcome the impact of FWM in DWDM are unable to sufficiently suppress the FWM effect due to limited capacity. This research, therefore, examined the mitigation of the FWM effect in the DWDM system using Dual Polarization Quadrature Phase Shift Keying (DP-QPSK) and channel arrangement. The DP-QPSK was designed and implemented using 100 GHz for both Equal Space Channel Allocation (ESCA) and Unequal Space Channel Allocation (USCA). It was analysed on a 64-channel DWDM system operating at 100 Gbps capacity over a transmission distance of 1000 km. The DP-QPSK-based ESCA and USCA techniques were simulated using OptiSystem 17 simulation software and Python for data analysis. The performance of the system was evaluated using bit error rate (BER), optical signal-to-noise ratio (OSNR) and Electrical Constellation Diagram. Validation was done with other advanced modulation formats: Quadrature Phase Shift Keying (QPSK) and Differential-Quadrature Phase Shift Keying (D-QPSK). The DWDM system using DP-QPSK gave better performance due to the highest OSNR and BER values obtained when compared with ESCA-based QPSK and D-QPSK techniques. The technique can be used to suppress the effect of FWM in optical communication systems.

Keywords: Coherent Detection, Dense Wavelength Division Multiplexing, Dual Polarization Quadrature Phase Shift Keying, Four-Wave Mixing, Optical Communication System

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1. INTRODUCTION

A good communication system transmits as much information as possible with as low as possible bandwidth. In recent times, network traffic has increased geometrically with the deployment of new technologies such as the fifth generation (5G) network and increasing data center traffic. The demand for higher bandwidth was also compounded by the exponential growth of internet traffic [1]. Enhancing the capacity of a telecommunication system to accommodate the ever-increasing demand for long-distance and high-capacity data services necessitated the deployment of an Optical Communication System (OCS). However, it suffers from nonlinear effects [2-3]. OCS development, using optical fibre cable, picked up pace after the discovery of the total internal reflection principle. Optical communication is the transmission of communication signals in the form of light over a thin glass or plastic (fiber) guided through glass fibers to move huge blocks of data over long or short distances [3].

In, OCS Wavelength Division Multiplexing (WDM) system enhances multiple uses of transmission fibre, coupling several wavelengths into the fibre through optical filters. The WDM standards are coarse WDM (CWDM) and dense WDM (DWDM) with the International Telecommunication Union-Telecommunication (ITU-T) Standards; G.694.2 and G.694.1, respectively [4]. The DWDM is equidistant in frequency whereas CWDM is equidistant in the wavelength domain [3].

Propagation of light inside an optical fibre, most especially single-mode fibre, is subjected to linear and nonlinear effects that must be considered when designing optical transmission equipment such as DWDM. Linear impairment of light occurs when spectral and spatial components of light do not affect each other in a medium [1]. These are caused by fibre loss and dispersion. Optical power loss due to linear impairments inside fibre, is compensated for with the use of optical amplifiers and dispersion-compensating optical fibre [3].

On the other hand, the nonlinear attributes of optical fiber play a negative role in the information-carrying capacity since it degrades the performance and reduces the bandwidth capacity of optical transmission equipment [5].

The limitation of nonlinear effects in DWDM cannot be compensated instead, it accumulates. Nonlinear impairments are the fundamental limiting mechanisms to the amount of data that can be transmitted in fibre optics communication. The nonlinear effects that occur in optical systems are Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS), Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and FWM [1]. In DWDM, FWM is the most critical of nonlinear effects. It is caused by the nonlinear nature of the refractive index of the optical fiber interacting among different DWDM channels to create sidebands that can cause inter-channel interference. The major effect of FWM is to limit the DWDM's channel capacity. The FWM effect occurs when two co-propagating waves produce two new optical sideband waves at different wavelengths.

A fibre optic system has been found sufficient to solve the problem. However, nonlinear effects on optical fibre networks pose serious limitations to the existing carrier technologies. In principle, the capacity of optical communication systems can exceed 10 Tbps (Tera byte Per second) to enable service providers to accommodate consumers' demand for ever-increasing bandwidth. However, in practice, the bit rate of 100 Gbps (Giga Bits Per Seconds) is hard to come by with DWDM transmission equipment due to limitations imposed by the nonlinearity attributes on an optical fibre link [2]. Researchers have proposed measures to overcome the impact of nonlinear effects in DWDM, such as intensity modulation formats [6], Channel Spacing [7], Shuffling Algorithm [8], Electro-Optic Phase Modulation [9], and Differential Quaternary Phase-Shift Keying [10].

Understanding nonlinear effects is vital to the efficient design of an optical communication system. This research tends towards significantly reducing the channel's spacing to accommodate clients for more data access while also working towards reducing FWM that arises as a result of the reduction in channel spacing on the long-haul transmission system. The two opposing aspects need a fundamental trade-off while also guaranteeing the system's efficiency. Therefore, this research focused on how to mitigate the harmful attributes of FWM in DWDM systems. There are a number of nonlinearities in light propagation; but this research concentrated on the most destructive of them all, FWM. This nonlinearity is weak, but its effects accumulate due to the long propagation distances involved in fibre communication.

In this paper, we propose a new technique for mitigating FWM, and the remaining part of this paper is organized as follows. Section 2 reviewed the methods and results of other researchers in relation to FWM mitigation. Section 3 was based on how the objectives of the paper were realized was discussed. In Section 4, the results were extensively discussed while also making comparisons with existing methods. We concluded the work in Section 5.

2. RELATED WORKS

This paper reviewed different methods employed by researchers to mitigate the effect and complexity of FWM on the DWDM system. This work highlighted, in chronological order, the methods proposed by researchers, their results, strengths, and limitations.

In the work of [11], the relationship between modulation format and the performance of Multi-Channel Digital Back-Propagation (MC-DBP), in ideal optical fibre communication systems was investigated. Numerical simulation and analytical modeling were carried out on a WDM system of nine channels of 32 GHz spacing. It was observed from the results obtained that the nonlinear distortions, FWM, show considerable dependence on modulation format. They failed to establish the category of the modulation scheme used, whether it is intensity or advanced-based.

Ref [12] theoretically explored the limitations imposed by nonlinear effects on the optimum power in a multi-span DWDM system. Optimum power transmission per channel was evaluated for the different number of channels or inter-channel spacing. It was discovered from the work, conditions under which FWM and SRS limit the performance of the DWDM system. The limitation of the research is that it is practically impossible to transmit an optical signal over a 700 km distance without a repeater. An end-to-end deep learning technique for designing optical fiber communication transceivers with focus on supervised offline training. In the research, a fiber-optic system was modeled using a deep fully connected feedforward Artificial Neural Network (ANN). The simulation results obtained from the end-to-end deep learning IM/DD system operating at 42 Gbps were validated experimentally [12].

An analytical model to compensate for the FWM effect using a managerial approach in the long-haul and high-capacity optical transmission network was presented by [13 -14]. The researchers considered a fixed transmission distance of 500 km. The work was anchored on two techniques, with/without dispersion variation, at various launched power and channel spacing. In the proposed transmission performance model, it was observed that the effect of FWM increases with an increase in launch power. It was further noticed that the bit-error-rate (BER) decreases with an increase in the launched optical power. The researchers considered an intensity modulation scheme for the reduction of FMW but failed to explore advanced modulation formats to mitigate the FWM effect.

An end-to-end (E2E) learning method to minimize the error between the transmitted and received bits was proposed by [15]. In the approach, multilayer neural networks were placed at the transmitting and the receiving ends, to represent an encoder and decoder, respectively. The transmitter and the receiver neural networks were jointly optimized to learn the encoding and decoding strategies that minimize the error between the transmitted and received bits. The fiber optic channel is nonlinear, and maximizing the achievable information rate requires operating in a nonlinear regime, making the techniques for linear channels ineffective.

Also presented is a theoretical model of cascaded noise of SRS, XPM, and FMW and their influence on the performance of the Quantum Key Distribution (QKD) system; putting into consideration modulation frequency over multicore fibre [2]. The researchers, while experimentally measuring the noise of quantum channels at varying modulation techniques and symbol rates of classical signals; discovered that optical power and symbol rate of data signals increase. However, the secure key rate of the QKD system decreases in the proposed method. Also, the transmission distance of 40 km considered for the effect of FWM is short to notice the nonlinear effect of FWM. The effect of equalization-enhanced phase noise (EEPN) on coherent optical systems performance was explored [16] using numerical simulation. The researchers aimed at reducing distortions of signal, caused by the nonlinear effect to enhance signal quality. In the work, the researcher used an analytical model in coherent optical transmission systems to predict the signal-to-noise ratio, in the presence of EEPN and electronic dispersion compensation (EDC). Although an adequate distance of 2000 km was considered with the DP-16QAM modulation scheme; only five channels were used in the implementation. The designed capacity is small to accommodate more clients.

Ref [2] analysed the system performance in terms of the BER, OSNR, and Error Vector Magnitude penalties. Wavelength Conversion for dual users Coherent Optical Orthogonal Frequency Division Multiplexing system based on FWM in a cascaded high nonlinear fibre. According to the researcher, results obtained show that wavelength-converted signals are of high quality. The scheme proved to be useful in the short-distance transmission of 500 m. This makes the solution unsuitable for mitigating FWM in the long-haul link. A review of the application of Artificial intelligence (AI) based techniques in improving the performance of optical communication systems and networks [17]. The enumerated AI-based approaches cover optical transmission given the characterization and operation of network components to performance monitoring, quality of transmission, and mitigation of nonlinearities. The authors also highlighted subdivisions of AI that have been successfully engaged in optical networking, stating the motivation behind their choice.

It was noticed the proposed methods are inadequate to suppress the FWM. Due to these limitations, this paper explored the use of an advanced modulation format, DP-QPSK, under Equal Space Channel Allocation (ESCA) and Unequal Space Channel Allocation (USCA) to suppress the FWM and enhance DWDM performance.

3. METHODOLOGY

This research aims to reduce the channel's spacing to accommodate clients for more data access. Simultaneously, working towards reducing FWM that arises as a result of the reduction in channel spacing on the long-haul transmission system. The method used in developing the technique to achieve the aim and objectives of this research are presented in the subsequent sections.

3.1 Design of Dual Polarization-Quadrature Phase Shift Keying

This paper employed dual polarization-quadrature phase shift keying (DP-QPSK), an advanced modulation technique. This modulation scheme involves a coherent detection method and digital signal processing (DSP) unit. The system setup for the DP-QPSK is shown in Figure 1. The source of the 100 Gbps signal was the light amplification by stimulated emission of radiation (LASER). At the transmit end, the optical signal from a continuous wavelength (CW) LASER diode was equally divided into even and odd bits and fed into two parallel QPSK modulators using the serial-to-parallel (S/P) converter. To form a DP-QPSK signal, a Polarization Beam Combiner was used to combine the two independent pseudo-random bit sequences (PRBS). The DP-QPSK signal has two (x and y) polarization components in tandem with the polarization of pumps 1 and 2, respectively. The power of the two CW pumps is set to 10 dBm. An amplified spontaneous emission (ASE) noise was added to the two components of the DP-QPSK signals to measure BER performance. The DWDM system is of 64 channels, carrying combined 64 DP-QPSK signals using a multiplexer (MUX) and transmitted via 10 spans of 100 km of fibre.

At the receiver end, the inverse operation at the transmitter was performed. The receiver structure used is coherent detection (homodyne). Coherent detection is preferred to direct detection because it gives better sensitivity to the phase and amplitude of the optical wave and intrinsic narrow optical filtering capability. The receiver section comprises a demultiplexer (DEMUX), which acts as an optical bandpass filter, a Polarization Beam Splitter, a LASER diode acting as a local oscillator, two 90^0 optical hybrids, and photodetectors. The outputs of the photodetectors are Low Pass Filter; which was sampled at the integer multiple of a fraction of the symbol period with the aid of an Analog-to-Digital converter for DSP.

3.2 Implementation of DP-QPSK Modulation Formats with ESCA and USCA

The MUX and the DEMUX act as 64:1 wavelength combiner and 1:64 wavelength-selective splitters, respectively. The transmitter was built around a direct LASER consisting of a PRBS Generator which sends the bit sequence to the Non-Return-to-Zero (NRZ) Pulse Generator. The NRZ encoding scheme is preferred to RZ since it requires only one transition per symbol. The MUX combined all 64 signals referred to as composite signals.

The transmitter section consists of 64-ESCA, with each containing a data source, a CW LASER source, and a modulator. The pulses modulate the measured laser. The DWDM channel propagates along a 1000 km link made of six spans of standard Single-mode fibre, at 100km/span

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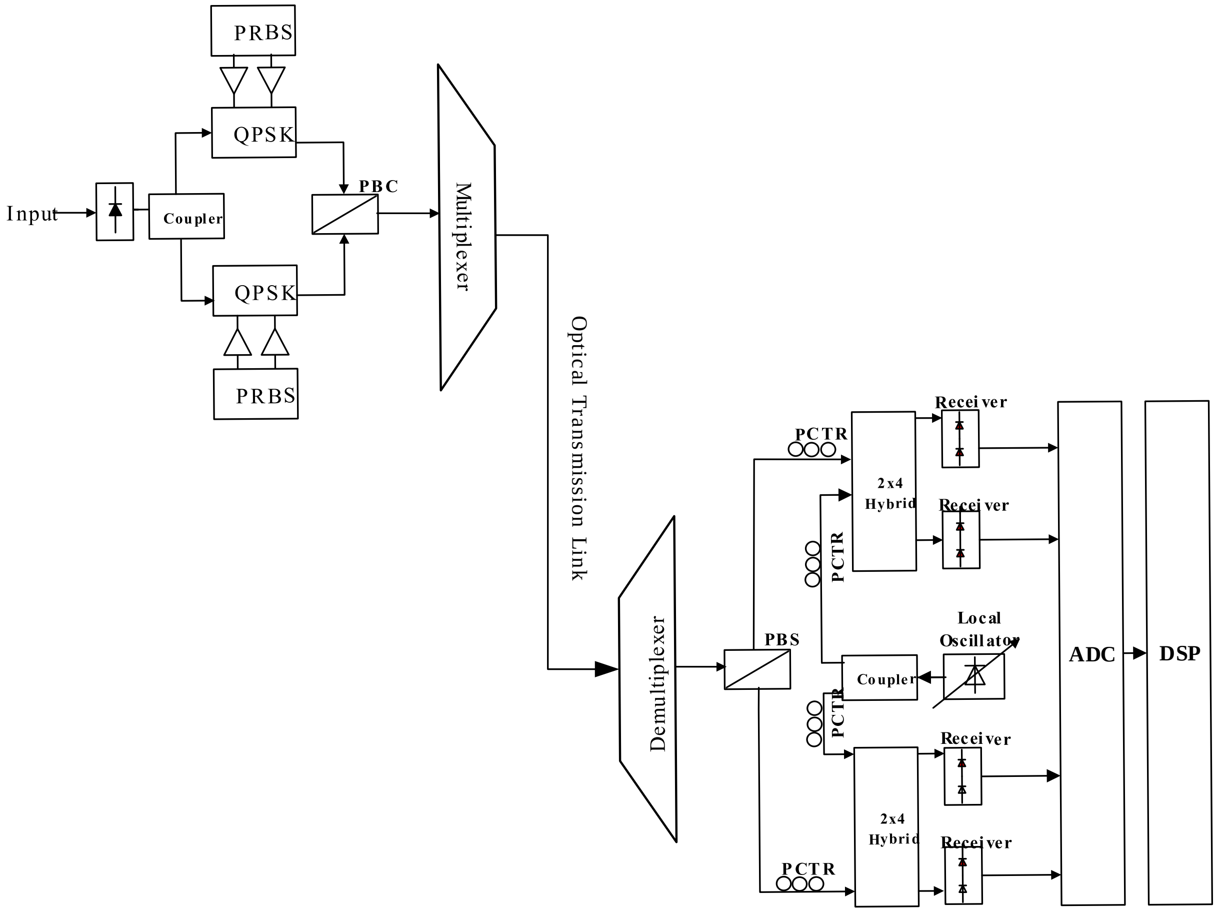

Figure 1. Designed DP-QPSK Based DWDM System

and four spans of Dispersion Shifted Fiber (DSF), at 100 km/span each. The DSF was used to compensate for dispersion. The data source generated 100 Gbps for 100 GHz ESCA over a 1000 km transmission distance. The relatively long 1000 km fibre link length was chosen to allow more light interaction and the realization of the nonlinear effect of FWM. The DP-QPSK signals are amplified by the Erbium-Doped Fibre Amplifiers (EDFAs) with a 20 dB gain/amplifier over a 100 km span at a fibre attenuation constant of 0.2 dB/km.

The DEMUX split the received signal into 64 individual wavelengths of the composite signal out to individual fibres for the 90^0 hybrids. The photodetector PIN receives the optical signal. The Low Pass Bessel Filter filters the electrical signals. Optical Spectrum Analyzer (OSA) was used to display the modulated optical signal in the frequency domain. For ESCA, the frequencies were anchored at 193.1 THz, C-band (196.1 -192.1 THz), which was extended to 185.9 THz of L-band (191.4-185.9 THz). This is also in alignment with the ITU-T (2020) standard. The transmission window of the 1550-nm band was used. This is preferred to other transmission windows (operating windows) of 850 nm and 1310 nm because it is the most effective for DWDM applications. Also, based on the low attenuation characteristics of a glass of 0.25 dB/km at 1550 nm and EDFA operates within this window. Optical Line Amplifiers are introduced at every 100 km of the 1000 km link to maintain ASE noise and to achieve a longer transmission distance. In this design 3 dB power margin was reserved to ensure the system's reliability against unexpected events and system aging over the lifetime. The flowchart for this work is shown in Figure 2.

3.3 Channel Arrangement for ESCA and USCA Systems

The arrangement of channels on the DWDM system, ECSA, and USCA, was adopted to check the better suit for minimizing FWM. For the ESCA system, channel spacing of 100 and 50 GHz for 100 Gbps DWDM capacity was considered for the three advanced modulation formats: QPSK, DQPSK, and DP-QPSK. Similarly, for USCA, a channel with a mix of 100/50/25 GHz allocation was considered in the channel arrangement. The design was carried out from a transmission distance of 100 km to a maximum distance of 1000 km.

3.4 Research Technical Specifications

The FWM imposes limitations on the maximum transmit power per channel. FWM has severe effects in DWDM systems, which use dispersion-shifted fiber. For this reason, Non-Zero Dispersion-Shifted Fibers were used in the system design. FWM presents a severe problem in

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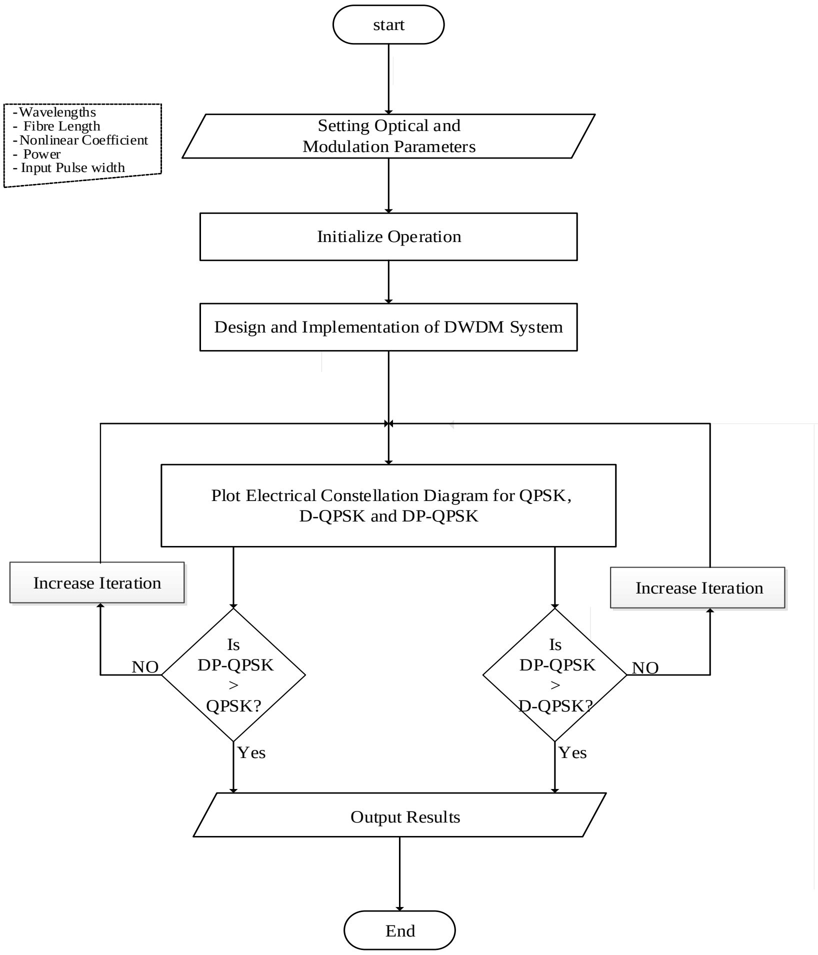

Figure 2. Research Flowchart

DWDM systems using G.653; hence NZDSF (G.655) was deployed to compensate for dispersion. Although, it may introduce nonlinear effects at higher optical power but is better for constraining FWM. The OCS parameters are shown in Table 1.

3.5 System Simulation

Research on OCS is better carried out with the aid of advanced software tools. The advanced modulation formats, QPSK, D-QPSK, and DP-QPSK, which are under consideration in this paper; were modeled on an OCS design software package, OptiSystem 17. This OCS simulation package was used to design, test, and optimize optical links in the physical layer of a broad spectrum of optical networks for long-haul systems. This application is a simulator that is based on the modeling of OCS.

3.6 Evaluation of System Performance

Ideally, in an optical communication system, it is desired to transmit an optical signal for long length of fiber at high bit rates. Understanding the source of errors is essential in order to be able to reduce them and improve the performance of the system. Evaluation of signal is one of the most important tasks in optical networks. The most fundamental method for evaluating the Quality of Transmission (QoT) of any digital communication system is the Bit Error Rate (BER). It is expressed as the ratio of incorrectly received bits to the total number of received bits. Hence, the system's performance was measured based

Table 1. Optical Transmission System Parameters

S/N	Parameters	Values
1	Input Power	10 dBm
2	Fibre Attenuation Constant	0.2 dB/km
3	Fiber Dispersion Coefficient	17 ps/nm/km
4	Effective fibre Core Area	70
5	Reference Wavelength	1550 nm
6	Maximum Transmission Distance	1000 km
7	Numbers of Channels	64
8	EDFA gain	20 dB/100 km Fibre
9	EDFA Noise Figure	6 dB
10	Laser Initial Phase	0
11	Channel Spacing	100, 50, 25 GHz
12	Bit Rate	100 Gbps
13	Receiver Responsivity	1 A/W

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on BER, Optical Signal-to-Noise Ratio (OSNR) and Electrical Constellation Diagram (ECD). The OSNR parameter was used to measure the quality of transmission.

3.6.1 Optical Signal-to-Noise Ratio

The OSNR is the ratio of the energy signal to the noise variance. It was used to measure how much signal has been corrupted by noise. The predominant source of OSNR is noise inserted by optical amplifiers. This is expressed in the discrete-time domain as,

$$OSNR = \frac{E_S}{\sigma^2} \quad (1)$$

where Es is the signal energy and σ^2 is the noise variance. The Es is defined as the mean of the square of the symbol.

3.6.2 Bit Error Rate

The BER specifies the ratio of bit errors to the total number of transmitted bits. Therefore, a lower BER indicates a better performance. The performance of an optical communication system based on BER depends on attenuation, noise, dispersion, crosstalk between adjacent channels, nonlinear phenomena and bit synchronization challenges. The system performance was improved by launching a strong signal into a transmission system.

BER depends on both the modulation scheme and the OSNR. The BER was used to determine the integrity of the communication system, what degrades the digital signal and how to improve on the optical fiber communication system. In general, the BER decreases as the Q-factor increases. Q-factor specifies the minimum required OSNR to obtain a certain value of BER.

In the presence of Gaussian noise and in the complete absence of phase noise and Inter Symbol Interference, the bit error probability of QPSK was analytically derived as

$$BER = \frac{1}{2} erfc\left[\frac{Q}{\sqrt{2}}\right] \quad (2)$$

where Q is the Q-factor and *erfc* is the error function defined as

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-\mu^2} d\mu \quad (3)$$

The bit errors were counted by the BER tester on the Optisystem 17.
The relationship between BER and OSNR is given by the expression,

$$BER = \frac{1}{2}\left[1 - erfc\left(\frac{\sqrt{OSNR}}{2\sqrt{2}}\right)\right] \quad (4)$$

The Error function, *erfc*, is defined in Equation (3)

In order to determine BPSK and QPSK Bit Error Rate and Symbol Error Rate; it was established that

$$P_{BE} = Q\left[\sqrt{\frac{2E_b}{N_0}}\right] = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (5)$$

E_b = Energy/Bit; Es = Energy/Symbol;
P_{BE} = Probability of Bit Error;
P_{SE} = Probability of Symbol error;
N_0 = Noise Power Density (W/Hz)

The symbol error is equal to Bit error rate in BPSK since one bit per symbol can be transmitted at a time. Under QPSK it is expected that the probability of bit error is the same; but QPSK makes of twice the power of BPSK since two bits were transmitted at a time. Hence the symbol error rate is given as

$$P_{SE} = 1 - (1 - P_{EE})^2 = 1 - \left(1 - P_{BE} + P_{EE}{}^2\right) = 2P_{EE} - P_{EE}{}^2 \quad (6)$$

$$P_{SE} = 2Q\left[\sqrt{\frac{E_S}{N_0}}\right] - Q^2\left[\sqrt{\frac{E_S}{N_0}}\right] = Q\left[\sqrt{\frac{E_S}{N_0}}\right][2 - Q] \quad (7)$$

The Probability of symbol error P_{SE}, was approximated as

$$P_{SE} \approx \left[\sqrt{\frac{E_S}{N_0}}\right] \quad (8)$$

3.6.3 Electrical Constellation Diagram

A suitable way to represent QPSK based modulation scheme is the ECD to show the point in the complex plane; that is the real and imaginary components (In-phase and Q-quadrature). The constellation diagrams were used to visualize the different states and symbols for a given modulation scheme, QPSK, D-QPSK, and DP-QPSK. The constellation diagram was preferred to the vector diagram because of its usefulness in troubleshooting modulation accuracy, to determine the cause(s) of deviations from ideal referenced points. The signal type for I and Q are electrical signals, the two signals were orthogonal to each other. When the symbol error was activated, the estimated symbol error is calculated according to Equation (9)

$$S_e = \sum_{h=1}^{N} S_n(h)\left[\sum_{l=1,l=h}^{N} \frac{1}{2} erfc\left[\frac{Q_{hl}}{\sqrt{2}}\right]\right] \quad (9)$$

where N is the number of total received symbols, $S_n(h)$ is the probability of occurrence of symbol h (that fall within the target region defined for symbol h divided by the total number of symbols received (N), and Q_{hl} is calculated according to Equation (10)

$$Q_{hl=} \frac{d_{hl}}{Q_{hl} + Q_{lh}} \quad (10)$$

where

$$d_{hl} = \sqrt{(I_{av}, Q_{av})_h{}^2 + (I_{av}, Q_{av})_l{}^2} \quad (11)$$

$$\sigma_{hl} = \sqrt{[SD(I)]_h^{\ 2} + [SD(Q)]_h^{\ 2}} \quad (12)$$

$$\sigma_{lh} = \sqrt{[SD(I)]_l^{\ 2} + [SD(Q)]_l^{\ 2}} \quad (13)$$

From (10), I_{av} and Q_{av} represent the average values of all received I and Q amplitudes, respectively; that fall within the target region defined for a given symbol. The SD represents the standard deviation of amplitudes I or Q and was calculated as follows

$$SD(I) = \sqrt{[I - I_{av}]^2} \quad (14)$$

$$SD(Q) = \sqrt{[Q - Q_{av}]^2} \quad (15)$$

where the values for I and Q include all received symbols that fall within the target region.

4. RESULTS AND DISCUSSION

In the system operating at 100 Gbps, the values of BER obtained were used to determine the number of bits transmitted in error to the number of transmitted bits while the OSNR values determine the energy signal to the noise variance. The results were obtained at different transmission distance at a multiple of 100 km to a maximum distance of 1000 km to check the system tolerance to FWM at different modulation schemes of Quadrature Phase Shift Keying (QPSK), Differential Quadrature Phase Shift Keying (D-QPSK) and DP-QPSK; under ESCA and USCA.

4.1 Transmission Results under ESCA

Under ESCA of 100 GHz and channel capacity of 100 Gbps for the three modulation formats (QPSK, D-QPSK and DP-QPSK). The Log values of BER with the OSNR values varies from 23.06 to 14.02 dB, 25.06 to 15.32 dB and 28.40 to 18.30 dB for QPSK, D-QPSK and DP-QPSK, respectively. The results obtained revealed that higher OSNR shows better BER performance. DP-QPSK has a slight degradation when compared with QPSK and D-QPSK strong degradation in ascending order. Hence, a channel of 100 GHz ESCA and 100 Gbps FWM is slightly suppressed from the values obtained from the results. The slight degradation obtained from DP-QPSK can be attributed to the wide channel spacing and the coherent property of the receiver which incorporated the DSP unit into the design. Besides, the wide channel spacing decreases the interference between the adjacent channels and consequently, reduces the FWM effect. The results obtained is as shown in Table 2.

4.2 Transmission Results under USCA

Under the USCA system with a channel capacity of 100 Gbps, the Log values of BER with the OSNR values varying from 24.06 to 16.02 dB, 26.06 to 19.22 dB and 30.37.80 to 21.00 dB were obtained respectively. The obtained is as shown in Table 3. The better performance of USCA under DP-QPSK is attributed to the OSNR tolerance. The result obtained did not fall below the OSNR threshold of 15 dB. This threshold is the minimum ITU-T standard required for a signal to be detected at the receiver. In addition, other methods of USCA, under QPSK and D-QPSK, shows better performance in contrast to any of the ESCA because of unequal channel spacing.

4.3 Response of BER to Increase in Transmission Distance

This sub-section discussed results obtained from the response of BER to increase in fibre length and the dependence of the FWM nonlinear effect on the fiber length. The Figure shows the response of the proposed technique over different lengths of fiber ranging from 100 to 1000 km. Figures 3 shows the plot of Log (BER) against the Transmission Distance for the modulation formats. The values for the plotted graph were obtained under the 100 GHz ESCA at 100 Gbps capacities. Considering BER values from 400 to 1000 km, it can be seen that increase in the fiber lengths can cause the BER to decrease. Figure 4 shows the variation of BER with respect to the transmission distance. The stated values were under USCA.

Table 2. Results Obtained from 100 Gbps Capacity at 100 GHz ESCA

Distance (km)	QPSK		D-QPSK		DP-QPSK	
	Log (BER)	OSNR (dB)	Log (BER)	OSNR (dB)	Log (BER)	OSNR (dB)
100	-4.5	23.06	-3.5	25.06	-3	28.4
200	-4	22.4	-2.95	24	-2.75	27.23
300	-3.25	21.48	-2.6	23	-2.5	26.4
400	-2.5	20.51	-2.43	22.51	-2.25	25.1
500	-2.2	19.77	-2.1	21.83	-1.9	24.05
600	-1.9	19.2	-1.8	21.2	-1.7	23.66
700	-1.6	18.32	-1.52	20.02	-1.42	22.27
800	-1.3	17.73	-1.2	19.63	-1	21.15
900	-0.9	15.52	-0.61	17.52	-0.5	20.62
1000	-0.5	14.02	-0.5	15.32	-0.5	18.3

Table 3. Results Obtained from 100 Gbps Capacity under USCA

Distance (km)	QPSK		D-QPSK		DP-QPSK	
	Log (BER)	OSNR	Log (BER)	OSNR (dB)	Log	OSNR
100	-3.4	24.06	-3	26.06	-2.5	30.37
200	-2.91	23.4	-2.6	25.07	-2.25	29.51
300	-2.61	22.78	-2.4	24.11	-2	28.23
400	-2.45	21.83	-2.1	23.51	-1.8	27.28
500	-2	20.83	-1.9	22.83	-1.6	26.53
600	-1.7	19.5	-1.55	21.76	-1.4	25.44
700	-1.42	19	-1.22	21.02	-0.9	24.64
800	-1	18.22	-0.8	20.53	-0.5	23.7
900	-0.6	17.52	-0.4	20	-0.3	22.3
1000	-0.3	16.02	-0.25	19.22	-0.21	21

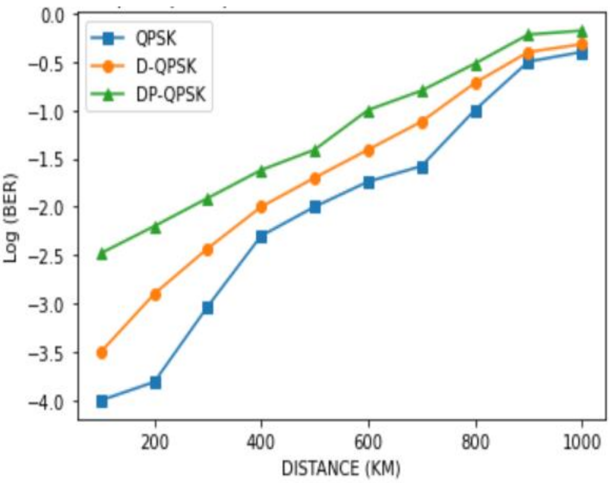

Figure 3. Log (BER) versus Transmission Distance of 100 Gbps ESCA

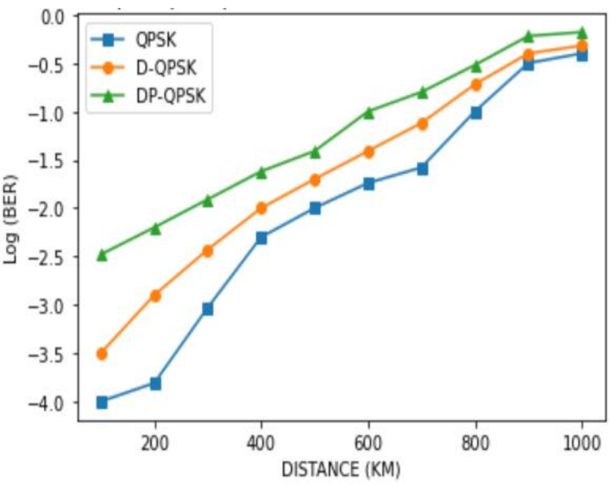

Figure 4. Log (BER) versus Transmission Distance for 100 Gbps under USCA

4.4 Results Obtained from Electrical Constellation Diagram

Results obtained from ECD under ESCA are shown in Figure 5 is for 100 Gbps capacity for the 100 GHz ESCA system. It is found that the signals at the receiver have lightly squeezed constellation diagrams. This defect can be attributed to amplitude error, as the point moved away from the origin, causing the points to spread out. The amount of distortion is proportional to the deviation from 90^0 separations. Results obtained from ECD under USCA are shown in Figure 6 shows the electrical constellation diagram obtained from the USCA system. The diagram showed that the IQ components were shifted by 90^0. The I and Q channels have equal gains. The results showed that the geometry of the constellation diagrams was not altered.

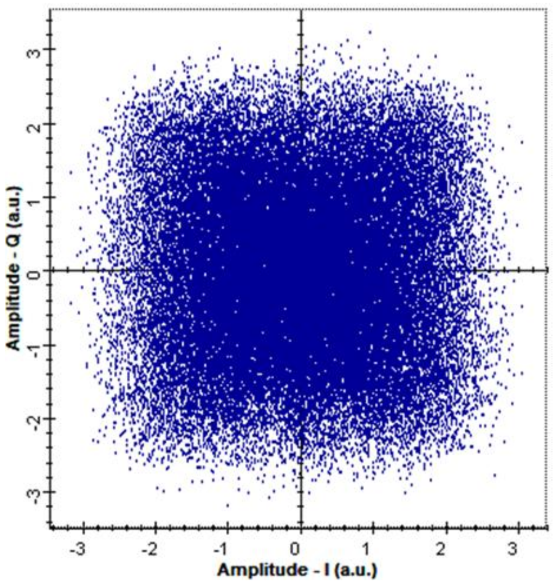

Figure 5. Electrical Constellation Diagram of 100 Gbps for 100 GHz ESCA

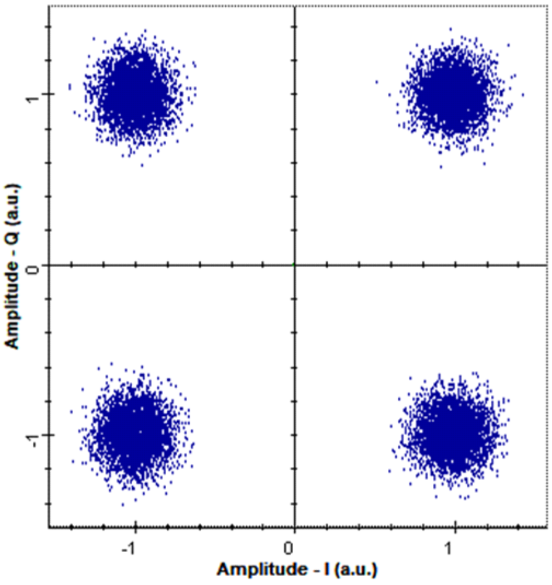

Figure 6. Electrical Constellation Diagram for USCA

5. CONCLUSION

In this paper, the technique for the mitigation of FWM effect was developed. The effectiveness of using the advanced modulation format of DP-QPSK to suppress nonlinear attributes of FWM for data at 100 Gbps in a 64-channel DWDM over a transmission distance of 1000 km under ESCA and USCA was established. The system gives better transmission results in terms of tolerance to FWM and transmission distances. A capacity of 100 Gbps was achieved in the simulation platform. The DWDM system with USCA performed better than ESCA with superior nonlinear tolerance when compared with QPSK and D-QPSK.

Consequently, the developed technique of USCA-DP-QPSK successfully suppressed the nonlinear effect of FWM, hereby increasing the channel capacity, better transmission performance, and spectral efficiency. The developed technique is a viable alternative for suppressing the nonlinear effect of FWM on the DWDM system.

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