Journal of Engineering and Applied Sciences 12 (Special Issue 10): 8802-8808, 2017
ISSN: 1816-949X

Performance Enhancement of Ultra Dense Inter-Satellite Optical Wireless Communication System Incorporating Polarization Diversity

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Abstract: Inter-satellite Communication reliant on Laser (LIC) is a promising technology for future satellite networks ascribed to ultra high capacity and high speed systems that can be accomplished with compact, light weight and lower power consumption optical equipments. This research explores the performance enhancement of 64×40 GB/sec optical wireless system incorporating polarization diversity for dense WDM. The high speed system is attained to fulfill the wide bandwidth requirements of data services in satellites by employing DWDM system at channel spacing of 50 GHz. In order to suppress the polarization crosstalk and nonlinearities among adjacent channels of WDM, a polarization diversity technique is included in the system. Moreover, comparative analysis is carried out for the polarization interleaved and conventional DWDM-OWC system. Also, it has been found that system carrying different state of polarization among adjacent channels, shows enhanced performance as compared to conventional systems in terms of Q-factor, BER and SNR.

Key words: Optical Wireless Channel (OWC), Polarization Interleaving (PI), State of Polarization (SOP), Differential Quadrature Phase Shift Keying (DQPSK), Bit Error Rate (BER), diversity

INTRODUCTION

Optical wireless communication is the engaging technology in the field of communication and provides us with the fastest transmission than microwave and RF technology (Alipour *et al*., 2016). Optical wireless communication is the special kind of optical communication that uses wireless medium to transmit the information to the destination. It basically uses the same concept as the laser communication technology (Wang *et al*., 2013). Laser communication sends the data or signal at several data rates over long distances using laser. As the numbers of users are increasing, the demand for bandwidth and high speed is also increasing and there is a wide research in this forte (Patnaik and Sahu, 2013). Therefore, optical wireless communication is the only way to meet these demands because of high bandwidth and high transmission capacity (Zhu *et al*., 2016). Infrared light region is widely operational for transmission of data over long distances. Use of optical wireless communication in space is termed as inter-satellite optical wireless communication (Liu *et al*., 2016). Is OWC offers high bit rate, high quality and more security (Kumar, 2014). Although, the optical communication that works in vacuum is considered to be loss less but the transmitted signal suffers different path losses that increases with the communication distance (Zhu *et al*., 2015). Integration of Dense Wavelength Division Multiplexing (DWDM) with intersatellite communication provides high capacity and high speed network. The concept of free space communication reaches up to several Tbps with incorporation of DWDM which is the necessity of inter-satellite communication.

Figure 1 shows the basic block diagram of IsOWC system (Vinod *et al*., 2017). Transmitter, OWC channel and receiver are the main blocks of this system. The transmitter section consist of Pseudo Random Bit Sequence (PRBS) generator that generates the binary data, Non Return to Zero (NRZ) pulse generator that converts binary data into electrical signal, CW laser used to carry information and Mach-Zehnder modulator that modulates the intensity of light according to our desire whereas the receiver section includes a photodetector and low pass filter. The photodetector gives the ouput in electrical form and low pass filter performs the function of filtering the undesired high frequencies. The optical antenna are attached at the both ends of the OWC channel, one at the transmitter side and other at the receiver side. OWC channel is generally outer space surrounding the satellites (Fig. 1). The received signal power for LOS system is shown as (Arnon, 2005):

$$P_R = P_T \eta_T \eta_R \left(\frac{\lambda}{4\pi z}\right)^2 G_T G_R L_T L_R \qquad (1)$$

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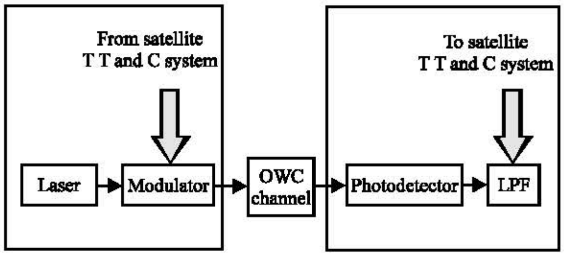

Fig. 1: Basic block diagram of IsOWC system

Where:

G_T, G_R = The gain of transmitter and receiver antenna

L_T, L_R = The pointing errors, respectively

Z, λ are distance and wavelength, respectively, along with η_T, η_R which are optical efficiencies of T_X and R_X Beam divergence should be less and only then link can be of longer distances. The gain of transmitter and receiver antenna is given by Arnon (2005):

$$G_T = \left(\frac{\pi D_T}{\lambda}\right)^2 \tag{2}$$

$$G_R = \left(\frac{\pi D_R}{\lambda}\right)^2 \tag{3}$$

where, D_T, D_R represents the Diameter of transmitter and receiver antenna here, loss of pointing is given by Arnon (2005):

$$L_T = \exp\left(-G_T\theta_T^2\right) \tag{4}$$

$$L_R = \exp\left(-G_R\theta_R^2\right) \tag{5}$$

θ_T, θ_R are the azimuth pointing error of transmitter and receiver, respectively. Numerous researches has been reported on intersatellite optical communication systems employing different modulations (Singh and Kumar, 2013), wavelengths (Zaki *et al*., 2014), polarization states (Pradhan *et al*., 2015), etc. Comparison of phase shift keying reported by Bindushree *et al*. (2014) and results revealed that quadrature phase shift keying is superior to differential phase shift keying in terms of long haul transmission. Analysis for line codings such as Non Return to Zero (NRZ) and Return to Zero (RZ) in high speed system is presented by Supinder and Simarpreet (2016). Major limitation of reported systems are less speed data carrying ability, low number of WDM channels, more channel spacing 100-200 GHz, high cost, bandwidth inefficient modulation formats. However, to suppress crosstalk among WDM channels, techniques are proposed several times in the past such as low power system, unequal channel spacings (Kwong and Yang, 1997), transceiver diversity (Aggarwal *et al*., 2013), hybrid modulation (Robinson *et al*., 2015) but are not very much efficient to quell effects of interference and demonstrate ultra high speed IsOWC system.

In this research, an enhanced performance ultra dense inter-satellite optical wireless communication system is presented by incorporating polarization diversity. Differential quadrature phase-shift keying modulation is considered in proposed architecture due to its advantages such as reliable data transfer, robust against transmitter/receiver frequency discrepancies and non-coherent detection. Moreover, comparison is established between proposed DWDM OWC system (with polarization diversity) and conventional (without polarization diversity) DWDM OWC system.

Differential quadrature phase shift keying: In order to ameliorate the system endurance to nonlinearities to attain a prolonged transmission reach, differential quadrature phase shift keying is appropriate technology. In recent year, DQPSK attracted much attention of researchers due to numerous advantages and also, referred as true multilevel modulation. In this higher modulation, it generate four phase shifts ($0, +\pi/2, -\pi/2, \pi$) at symbol rate of half the total data rate. A DQPSK is most appropriately and suitably implemented with convenience by two parallel Mach-Zehnder modulators function as phase modulators.

Figure 2 shows a transmitter consisting of a continuous laser source, a power divider with two paths of identical energy, two Mach-Zehnder modulators, 90° phase shifter in one arm or path and power combiners to accumulate signals. This depiction represents the schematic of parallel MZM generation of the multilevel modulation. However, serial MZMs are also included in place of parallel configuration for DQPSK generation. In diagram, signal transition and constellations of upper/lower arms or paths is also represented. Aforementioned arrangement exhibit the π phase shifts by modulators irrespective of the drive signal over shoot. Subsequently, this architecture needs binary bits only and is easy to generate at high speeds rather than waveforms. A pulse carver is also incorporated in the system to generate return to zero DQPSK. Due to compressed spectrum, it provides numerous advantages such as useful for attaining high spectral efficiencies in wavelength division multiplexing systems, improved tolerance to Chromatic Dispersion (CD), the longer symbol period compared to binary modulation formats makes DQPSK more robust to Polarization Mode

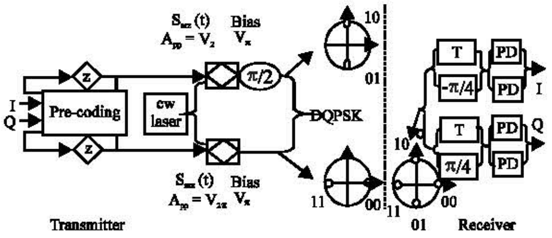

Fig. 2: Depiction of differential quadrature phase shift keying transmitter and receiver

Dispersion (PMD). Reception of the signals is carried out by splitting input signal and fed to balanced receivers.

Different biasing in delay interferometers is provided to demodulate binary data and delay is two time the duration of bit. Figure 3a illustrates the optical spectrum of modulation and represents the carrier frequency with respect to power of the signal. Optical spectrum of DQPSK signal is narrow thus suitable for DWDM systems.

Polarization diversity: In a lot of systems but not all, the laser intensity is polarized. This means a state of linear polarization where the electric field oscillates in a particular path orthogonal to the propagation of the laser intensity. However, fiber lasers do not generate a stable directional electrical field. But not necessarily the laser output is unpolarized, having same powers in two polarizations simultaneously, not including any correlation of the consequent amplitudes. Due to several reasons, state of polarization is not stable such as temperature drifts, randomly switches between diverse directions.

In order to generate the pure single direction variation of electrical field vector, some kind of polarization fixing devices are generally needed. Degree of specific state of polarization is generally quantified with Polarization Extinction Ratio (PER), stated as the ratio of powers in the diverse polarization directions and calculated by recording the orientation-reliant power transmission of a polarizer. Polarization diversity is an effective approach to suppress the impact of inter-channel nonlinear effects by fixing the adjacent channels polarization. Approach is extended to design WDM systems such that the bit streams in two adjacent channels are orthogonally polarized. The Jones matrix describes the transfer function of polarization and this matrix is defined by:

$$P_\theta = \begin{bmatrix} \cos^2(\theta) \\ \cos(\theta)\times\sin(\theta) \end{bmatrix} \begin{bmatrix} \cos(\theta)\times\sin(\theta) \\ \sin^2(\theta) \end{bmatrix} \qquad (6)$$

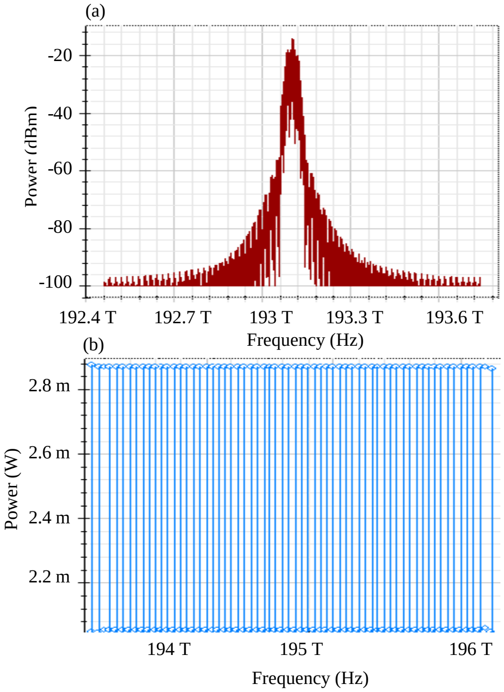

Fig. 3: Optical spectrum analyzer representations for: a) Single DQPSK transmitter and b) 64 DQPSK WDM transmitters

The even and odd number channels are multiplexed mutually into different branches that have orthogonal States of Polarization (SOPs). Polarizations are adjusted using linear polarization controllers to keep channels orthogonal. Basic method of suppression is that both cross phase modulation and four wave mixing are completely reliant on state of polarization of adjacent channels and SOPs are orthogonal in polarization diversity based systems. As a result, inter channel collisions generates smaller shifts of phase and direct to very less jitter and jitter amplitudes.

MATERIALS AND METHODS

Proposed architecture: For the accomplishment of proposed architecture, a leading and compendious simulation tool that facilitates users to implement, investigate and simulate communication system in optical domain, optiwave's optisystem^{TM} is used. In this research study, a 64×40 GB/sec WDM system is demonstrated at ultra dense spacing 50 GHz among adjacent channels to realize a bandwidth efficient system. A continuous wave laser array signals with starting frequency 193.1 THz and power 30 dBm are fed to a DQPSK modulation as depicted in Fig. 4. DQPSK modulation consisting of pseudo random bit sequence generator and MZMs as elaborated in study 2 for phase shifts.

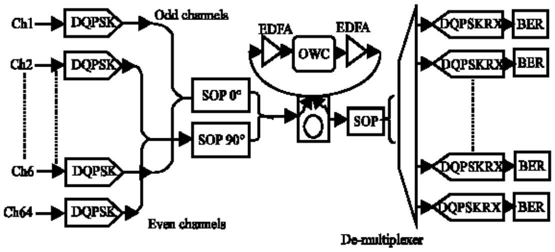

Fig. 4: Proposed system of 64 channels DWDM with polarization diversity

The polarization of even and odd channels is changed in order to analyze effects of nonlinear degradations on system. The linear polarizer transmits the linear polarization component that coincides with the transmission axis of the polarizer and eliminates the orthogonal component. Odd channels from λ_1-λ_{63} carry same polarization and State of Polarization (SOP) is fixed to 0° in linear polarizer. Even channels λ_2-λ_{64} have the state of polarization orthogonal to odd channels, i.e., 90°. The investigated range for the proposed link is 1250 km with two Erbium Doped Fiber Amplifiers (EDFA), one is in pre and other in post configuration. An optical wireless channel with 250 km link reach is considered for each loop and total loops are set to 5 to get 1250 km distance. An EDFA gain is set to 25 with 4 dB noise figure in order to realize a practical system as shown in Table 1.

An optical wireless channel with 250 km link reach is considered for each loop and total loops are set to 5. Power amplitude degradation for OWC is fixed to 0.14 dB/km (Singh and Kumar, 2013) and transmitter, receiver aperture diameter are 20 and 25 cm, respectively. A 1:64 demultiplexer route the specific frequency to their respective output port with the help of reference frequency and filtering of Gaussian filter. Receiver section consisting of optical couplers with coupling ratio of 50:50 and divide signal for two pairs of photodetectors that receives drive with time delay and phase shift to input signal as shown in Fig. 2.

A p-i-n photodetector with 100%, responsivity and 10 nA dark current is placed in the receiver by considering shot, thermal and ASE (Amplified Spontaneous Emission) distortions. Electrical bias is provided to electrically subtracted output of balanced photodetectors followed by 3-R regenerator. A 3-R regenerator is employed for re-sampling, re-shaping and re-amplification of the received data. Bit error rate analyzer is decision making component which calculate the final received quality factor, Bit Error Rate (BER) and Signal to Noise Ratio (SNR) of the received signals.

Table 1: Proposed architecture specification

Parameters	Values
CW laser array power	30 dBm
Frequency range	193.1-196.25 THz
Frequency spacing	50 GHz
SOP_1	0°
SOP_2	90°
Data rate	40 GB/sec per wavelength
Sequence length	256
Sample per bit	64
EDFA gain and noise figure	25 and 4 dB
OWC channel attenuation	0.14 dB/km

RESULTS AND DISCUSSION

Figure 4 depicts the proposed architecture of 64 channel DWDM system over optical wireless channel with non-coherent detection and polarization diversity. Investigation has been carried out at 40 GB/sec data rate for two DWDM OWC system, proposed polarization diversity based system conventional system at 50 GHz dense spacing in WDM system. Mainly, the regions that affect or influence the transmitting beams are troposphere and ionosphere. Reach of troposphere is 10-15 km with respect to ground and ionosphere spreads up to 60-1000 km. The influence of atmospheric instabilities is less till the height of 2 km on free space communication channel. All the research is considered for clear weather and attenuation corresponding to it is fixed as 0.14 dB/km. DWDM system over optical wireless channel is analyzed for both conventional and proposed system in terms of Q-factor, Bit Error Rate (BER) and Signal to Noise Ratio (SNR). First and foremost, a loop length that consists of EDFA-OWC-EDFA is varied and Q-factor is observed at 250-1250 km.

Figure 5 represents the graphical depiction of Q-factor with respect to distance for proposed Fig. 5 represents the graphical depiction of Q-factor with respect to distance for proposed polarization interleaved system and conventional DWDM OWC system and it is observed that when we increase the distance (250-1250 km) in both the systems (proposed and conventional), Q-factor decreases gradually due to attenuation and adjacent channel crosstalk as increase in distance introduces more attenuation and crosstalk. It is seen in Fig. 5 that maximum Q-factor is reported for polarization interleaved channels in comparison to conventional DWDM OWC system. The maximum Q factor is observed at the distance of 250 km and minimum at the distance of 1250 km.

Figure 6 shows the performance of the system in terms of bit error rate at different distances and it is found that there is significant increase in the BER with increase in link distance. Comparison of DQPSK-DWDM system

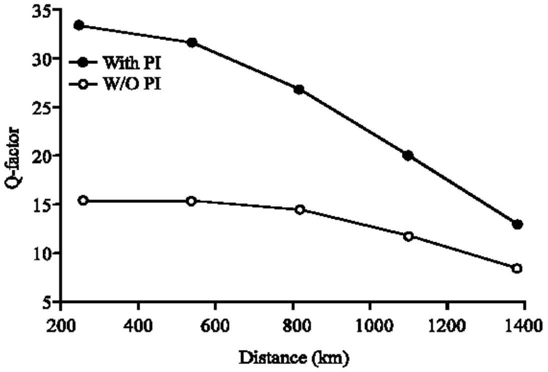

Fig. 5: Graphical representations of Q factor and distance for proposed and conventional DWDM OWC system

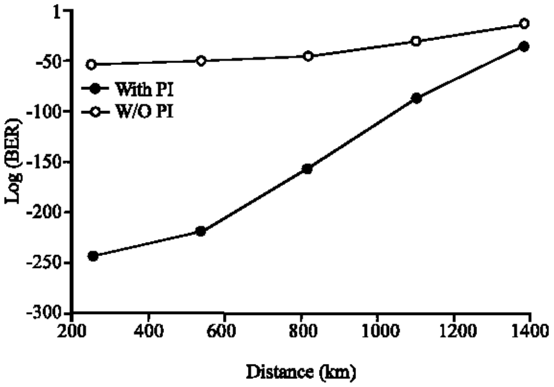

Fig. 6: Values of BER with respect to distance for proposed and conventional DWDM OWC system

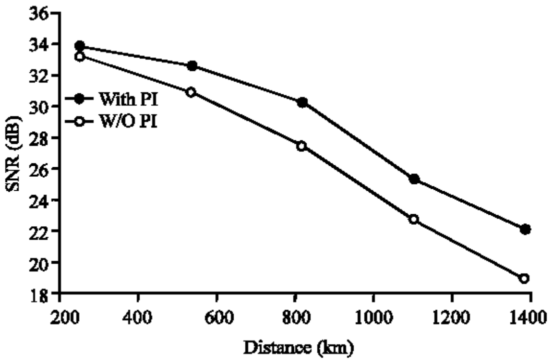

Fig. 7: Signal to noise ratio versus distance for DWDM OWC system with and without polarization interleaving

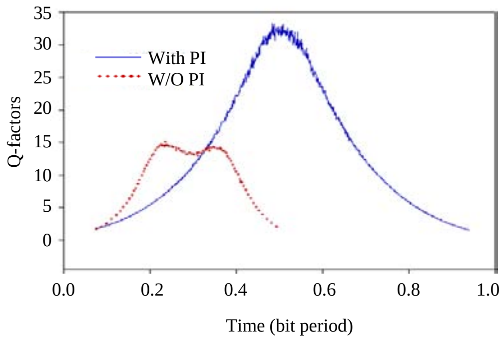

Fig. 8: Maximum Q factor versus time (bit period) for DWDM OWC system with and without polarization interleaving

with polarization interleaving and conventional system is established and minimum BER is obtained at 250 km and for polarization interleaved system.

Figure 7 illustrates the signal to noise ratio values for DQPSK-DWDM system with and without PI at different distances. Signal to noise ratio is an important factor to consider for assessment of signal and noise power at receiver. Basically, SNR is ratio of light power that impinges a detector to the noises that are introduced due to quantum and amplified spontaneous emission noise. SNR of 33.75 dB for PI system is reported as shown in Table 2 and conventional system exhibits SNR of 33.22 dB at 250 km. It is seen that proposed system exhibits better performance in comparision to conventional DWDM OWC system due to less adjacent channel noises. Increase in link length introduces more noises and as a result SNR degrades with the link reach.

Figure 8 shows the comparative analysis of Q-factor versus bit period that is time of any transmitter bit for two proposed cases. This comparison is carried out for conventional system and polarization diversity system. It is prominently observed that maximum Q-factor for PI system are 33.28, 31.49, 26.72, 19.9 and 12.86 at distances of 250, 500, 750, 1000 and 1250 km whereas the values of Q-factor for conventional system are 15.26, 15.19, 14.29, 11.53 and 8.16. The proposed polarization diversity based system exhibits enhanced performance and curve is far better than conventional DQPSK-DWDM OWC system.

The value of Q-factor, BER and SNR for proposed and conventional DWDM OWC system are given in Table 2.

Figure 9 depicts the eye diagram of polarization diversity incorporated system and conventional DWDM. Fig. 9a and b represents eye diagrams of DWDM OWC system using the concept of polarization diversity at 250 and 1250 km which allow user to calculate Q-factor, BER, eye opening and eye closer, etc. Eye diagram depicts the eye opening of received signal and Q-factor. BER is less when eye opening is more and in case of polarization diverse system, the eye is widely open which results into

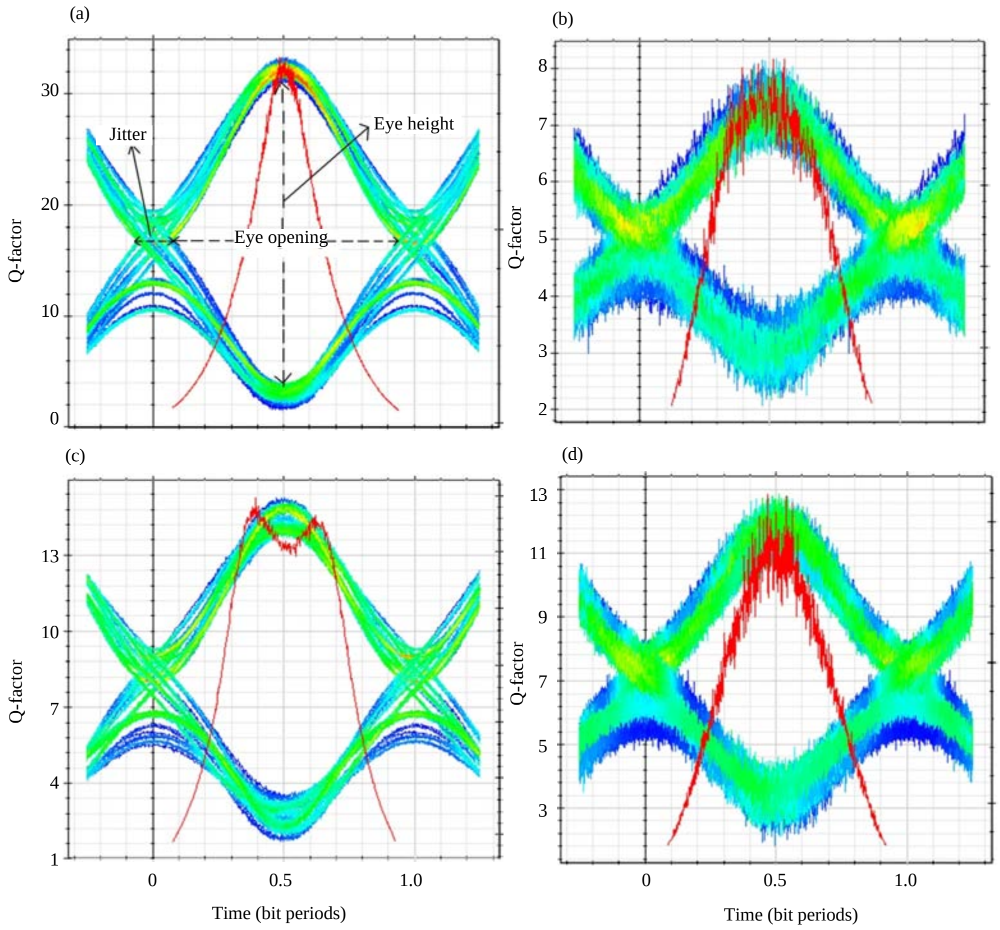

Fig. 9: Eye diagram of DWDM OWC system at 250 and 1250 km, respectively: a-b) Proposed and c-d) Conventional

Table 2: The comparision of the results for proposed and conventional DWDM OWC system at different distances

	Proposed DWDM OWC system			Conventional DWDM OWC system		
Distance (km)	Q-factor	BER	SNR (dB)	Q-factor	BER	SNR (dB)
250	33.28	3.1×10^{-243}	33.75	15.26	6.09×10^{-53}	33.22
500	31.49	5.4×10^{-218}	32.55	15.19	1.7×10^{-52}	30.91
750	26.72	1.2×10^{-157}	30.18	14.29	1.2×10^{-46}	27.40
1000	19.90	1.7×10^{-88}	26.56	11.53	4.5×10^{-31}	23.21
1250	12.86	3.6×10^{-38}	22.11	8.160	1.6×10^{-16}	18.85

more Q-factor and less BER. However, due to more impairments of crosstalk and mixing of polarizations of adjacent WDM channels in conventional multichannel system results into low eye opening and more BER. It is observed that BER varies directly with the distance. As distance increases in both proposed and conventional DWDM OWC system, BER also increases which consequently shows degradation in Signal to Noise Ratio (SNR) and Q-factor. Fig. 9c and d represent eye diagram of conventional DWDM OWC system.

Greater eye opening is observed at shorter distance and in case of polarized interleaved system. It is noteworthy that to design a dense and high capacity DWDM optical wireless system, polarization diversity is best to exhibit enhanced performance in terms of Q factor, BER and SNR at 40 GB/sec.

CONCLUSION

In this research study, an ultra high capacity and ultra dense inter-satellite optical wireless communication system is demonstrated. The high speed system is accomplished to cater the bandwidth hungry demands of information services in inter-satellites with 64 channel dense WDM system at channel spacing of 50 GHz. To quell the polarization crosstalk and nonlinearity among adjacent channels of WDM, a polarization diversity technique is incorporated in the system.

RECOMMENDATIONS

Furthermore, comparative analysis is established for the polarization interleaved and conventional DWDM optical wireless system. It is observed that system carrying different states of polarization among adjacent channels shows enhanced performance in terms of Q-factor, BER and SNR as compared to conventional system at 40 GB/sec.

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