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PERFORMANCE ANALYSIS AND MONITORING OF VARIOUS ADVANCED DIGITAL MODULATION AND MULTIPLEXING TECHNIQUES OF F.O.C WITHIN AND BEYOND 400 GB/S.

Sumant Ku. Mohapatra, Ramya Ranjan Choudhury, Rabindra Bhojray and
Pravanjan Das

Department of Electronics & Telecommunication Engineering,
Trident Academy of Technology, B.P.U.T, Bhubaneswar, Odisha, India

ABSTRACT

To achieve better calculative performance in optical fiber communication and for simplicity of implementation different digital modulation, detection and multiplexing techniques are used. These techniques maximize the spectral efficiency. This paper reviews a tabular comparative analysis with 3D graphical representation for different optical digital modulation formats and multiplexing techniques within and beyond 400 Gb/s. In this particular article we survey about different parameters related to digital fiber optic communication.

KEYWORDS

OFDM, Digital Modulation formats, Multiplexing techniques, QAM & WDM.

1. INTRODUCTION

Now a days by digital communication one can improve the performance of OSNR sensitivity, Bit error rate, nominal range, sensitivity to non-linear distortion, transmission, attenuation profile, modulated bandwidth efficiency, information capacity, Spectral efficiency etc, The goal behind each type of optical modulation and multiplexing techniques is to increase the data rate, transmission fidelity and transmission distance between stations. Over the last years several types of modulation techniques are designed which consists of 2.5, 10, 20, 25, 40 and 100 Gb/s wavelength channels. But now a day the data rate with respect to the channel increases to 400 Gb/s and above. Media Access control parameters, physical layers, and management parameter [17] using 4-channels with 25Gb/s. 107 Gb/s NRZ-DQPSK transmission at 1.0 b/s/Hz over 12-100Km have been introduced [18] by P.J.Winzer including 6 optical routing nodes (published in Proc.OFC2007, post deadline paper PDP24). Now a days in modern digital optical fiber communication to improve transmission data rate200Gb/s , 400Gb/s , 800Gb/s , 1000Gb/s , 1Tbit/s and above have been used. This paper also provides a tabular manner survey of modulation methods, with emphasis on probability of error, photons per pulse and spectral efficiency and other DFOC parameters. Multiplexing is a promising technique in optical fiber communication. Different types of fiber optic multiplexing techniques such as OTDM, OFDM, COFDM, WDM, CWDM and DWDM are analyzed in a tabular manner compared with different digital modulation formats. The comparative analysis taking suitability of various modulation formats over bit error rates of 0.004 is studied in this approach. The robustness of DPSK direct detection transmission format in standard fiber WDM systems have been published in2000 [33].

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In this paper we mainly emphasize on WDM, CWDM and DWDM. W. Idler publishes WDM field over 764 Km SSMF with 16-112Gb/s NRZ DQPSK[34]. These performances are comparatively analyzed in a tabular manner and also by different 3D graphical formats.

2. CLASSIFICATION OF DIGITAL OPTICAL FIBER MODULATION AND MULTIPLEXING TECHNIQUES.

Sl. No.	DFOC Format	Type	Notation
01.	Digital modulation formats	On-OFF keying /Binary Amplitude	OOK/BASK
		Binary frequency shift keying	BFSK
		Binary Phase Shift Keying	BPSK
		Differential Phase Shift Keying	DPSK
		Return to zero DPSK	RZ-DPSK
		Quadrature Phase Shift Keying	QPSK
		Differential QPSK	DQPSK
		Return to zero DQPSK	RZ-DQPSK
		Return to zero DPSK-3ASK	RZ-DPSK-3ASK
		Polarization division multiplexing QPSK	PM-QPSK/DP-QPSK
		PM-Orthogonal frequency division	PM-OFDM-QPSK/DP-OFDM-QPSK
		Optical Polarization FDM-RZ-DQPSK	OP-FDM-RZ-DQPSK
		Polarization division multiplexing DQPSK	PM-DQPSK or DP-DQPSK
		M-ary Quadrature amplitude modulation	M-QAM
		Minimum Shift Keying	MSK
		Gaussian MSK	GMSK
		Single Carrier Modulation formats	SCM
		Multicarrier Modulation formats	MCM
02.	Digital Multiplexing Formats	Optical Time Division Multiplexing	OTDM
		Subcarrier Multiplexing	SCM
		Orthogonal Frequency Division Multiplexing	OFDM(UNCODED)
		Coded Frequency Division Multiplexing	COFDM(coded)
		Duty Cycle Division Multiplexing	DCDM
		Optical Polarization Division Multiplexing	OPDM
		Wavelength Division Multiplexing	WDM
		Coarse WDM	CWDM
		Dense WDM	DWDM

3. OPTICAL FIBER DIGITAL MODULATION FORMATS.

Modulation is a technique by which the digital information is printed onto an optical carrier [16] and in its most general sense also including coding to present transmission errors. In digital optical fibers the electromagnetic waves with frequencies of nearly 200 THz are used to transfer information from one point to another.

3.1. On-Off Keying/Binary Amplitude Shift Keying

In BFSK, for better demodulation performance matched filter detectors are used. The information capacity is better than BASK indicated in **Table-5**. It is not efficient due to its hardware design of receiver, is complex as directed in **Table-2.**

3.2. Binary Phase Shift Keying

In BFSK, for better demodulation performance matched filter detectors are used. The information capacity is better than BASK indicated in **Table-5**. It is not efficient due to its hardware design of receiver, is complex as directed in **Table-2.**

3.3. Binary Phase Shift Keying

In BPSK error performance is very less as compared to BASK and BFSK. It is widely used for satellite communication. The binary 1 is signed as $\sin\omega t$ and 0 signed as $-\sin\omega t$. 2,4,8,16 BPSK formats using coherent detection techniques to improve their BER performance as shown in **Table-4**.The information capacity of BPSK is twice times the BFSK indicated in **Table-5.**

3.4. Differential Phase Shift Keying

The non-linear propagation [33] in Optical Transmission systems is only valid for DPSK FOC digital modulation techniques. For 400 Gb/s performance, it requires DPSK receiver Optical channel monitoring in optical line system. The maximum bandwidth is 80 ps/nm for RZ-DPSK shown in **Table-10.**

3.5. Non Return to Zero /Return to Zero Differential Phase Shift Keying

In NRZ/RZ-DPSK, the receiver design consists of one interferometric detector and two photo detectors which increases the hardware complexity in comparison to transmitter design which uses only one modulator at 400 Gb/s aggregation bit rate shown in **Table-10.**

3.6. Quadrature Phase Shift Keying

In QPSK, the bandwidth efficiency is very high in comparison to other primary optical digital modulation techniques as illustrated in Table-5. Also the information capacity is twice the Binary Frequency Shift Keying which gives major effect on different primary modulation techniques.

3.7. Differential Quadrature Phase Shift Keying

At 400 Gb/s DQPSK requires two modulators which improves the performance in comparison to QPSK. Also the BER graph of DQPSK gives better results when probability of error is taken into account. This four level version of DPSK has the advantage of tolerating better dispersion which is narrated in **Table-7.**

3.8. Return to Zero - Differential Quadrature Phase Shift Keying

To get RZ-DQPSK signal, two phase modulators are cascaded for the modulation of the optical phase by 0 to $\pi/2$ and 0 to $\pi/4$ applying binary modulation. The Optical signal-to-noise-ratio tolerance is higher than DQPSK that results in better performance in the context of signal quality at 111 Gb/s [35] and at112Gb/s OUT-4 channel bit-rate [34] ,[36].The maximum bandwidth (ps/nm) of this format is half that of NRZ-DQPSK as compared in **Table-10.**

3.9. Return to Zero - Differential Phase Shift Keying - 3 Amplitude Shift Keying

This is a very fundamental mixer of ASK modulation and phase modulation. In RZ-DPSK-3ASK modulation formats 2.5bits are coded in one symbol which leads to symbol rate of 43Gbauds [37-38], [65- 66] for support of the OUT-4 line-rate [67] of 112Gb/s. This modulation technique when applied to field fiber has OSNR limitation, but this could be improved by reducing channel bit-rate.

3.10. Polarization Mode -QPSK/Differential Phase –QPSK

The 100Gb/s PM-QPSK transmission process [16] running at a symbol rate of 25-28Gbaud is widely applied with offline signal processing of electrical signal which is measured by 4- channel high speed real time Oscilloscopes acting as fast A/D converters[28-29], [40], [69]. **Table-4** shows that the PM-QPSK format has higher modulation efficiency compared to QPSK format.

3.11. Polarization Mode OFDM-QPSK/ Differential Phase -OFDM-QPSK

Another commercially available 100Gb/s transponder applies two narrow spaced (20GHz) optical carries each modulated with PM-QPSK formats based on 14 Gbaud modulation [41],[16]. The hardware implementation features of transmitter and receiver of this modulation technique is given in **Table-10.** It has highest estimated reach of about 2000 Km rather than QPSK, DQPSK and PM-DQPSK as suggested in **Table-7.**

3.12. Optical Polarization -FDM-RZ-DQPSK

To carry two optical carrier there are polarizations can be used to eliminate the fast automatic optical polarization de-multiplexers[16]. In this modulation format two carriers are alternatively multiplexed and de-multiplexed with optical fiber at 28 Gbaud. The compatibility with 100Gb/s & 400Gb/s is being positive w.r.t PM-OFDM-QPSK as shown in **Table-7.**

3.13. Polarization Mode -DQPSK / Differential Phase –DQPSK

By applying polarization division multiplexing (PM), we can reduce the symbol rate. As a result the line-rate doubles or the symbol rate becomes half [16]. The 28Gbaud modulation formats supports the 400G DWDM transmission with 50 GHz channel spacing. **Table-7** indicates that the OSNR tolerance (dB) @ BER 4X10-3 is higher than OP-FDM-RZ-DQPSK but less than RZ-DPSK-3ASK format.

3.14. M-QAM

‘M’ number of binary bits are transmitted in a particular slot in this modulation scheme [16]. This technique currently is of high research interest and is illustrated at submarine transmission configurations[70] using RZ at PM-QPSK. Polarization multiplexed 16- QAM signals have been realized by multi-level generation using passive combination of binary signals to achieve 224 Gb/s channel rate (200G + FEC overhead)[71-73] and for higher than 400 Gb/s channel rate [74]. Using Polarization multiplexing and QAM modulation format transmission lengths between 670km to 1500km have been demonstrated [71-73]. RF-assisted optical Dual carrier 112 Gb/s polarization multiplexed 16-QAM is applied to achieve 112 Gb/s channel rate[75]. According to **Table-8**, we conclude a comparative analysis between different M-QAM modulation techniques having different bit rates (Gb/s). A channel rate of 400 Gb/s has been achieved using 16-QAM recently with polarization multiplexing.

3.15. Minimum Shift Keying

The new optical minimum shift keying modulation schemes have the high spectral efficiency as compared to other digital modulation formats. The transmitters for optical MSK based on two MZM similar to the transmitter for DQPSK. As compared to other modulation formats the spectrum is not compact enough to realize data rates as shown in **Table-2.**

3.16. Gaussian Minimum Shift Keying

GMSK is a digital optical binary modulation schemes and is treated as a extension of optical Minimum Shift Keying technique. In this format the side lobe levels of the spectrum are again minimized by passing the modulating NRZ data waveform through a pre-modulation Gaussian pulse-shaping filter. It promotes ISI at higher bit rate transmission than MSK as compared in **Table-2.**

3.17. Sub-Carrier Modulation

In this format 2xm bits are transmitted per symbol. Various constellations [16],[42] can be applied for PM-QAM modulation format. To optimize the signal error with M-QAM constellation by Nyquist filtering towards Nyquist wavelength division multiplexing which is currently of high research interest which has been demonstrated at submarine transmission configurations[70] using RZ at PM-QPSK. **Table-8** gives an overview in single channel M-QAM options from 200Gb/s to 1Tb/s .

3.18. Multi-Carrier Modulation

Multi-carrier modulation format approach supports high bandwidth channels [76]. Forming inverse fourier transform, Signal Processing is applied in the transmitter. As OFDM has rectangular shape, high capacity transmission can be performed by close allocation of multiple OFDM signals in the frequency domain without guard bands. The orthogonal multiplexing behavior of PM-QPSK modulation has been depicted in **Table-7.** A number of transmission experiments using polarization multiplexed O-OFDM and PM-O-OFDM have been reported [16], [77], [44-45] transporting Tb/s super channels over submarine distances [78].

4. OPTICAL FIBER DIGITAL MULTIPLEXING FORMATS

Multiple users can transmit data simultaneously through a single optical fiber link by digital multiplexing techniques described in this section. This is widely employed in optical communication systems due to its capability to increase the channel utilization and decrease system costs.

4.1. Optical Time Division Multiplexing

In OTDM the bit-rate of digital optical fiber systems is increased beyond the bandwidth capabilities of the opto-electronics. [59-60].

4.2. Sub-Carrier Multiplexing

The subcarrier enables multiple broadband signals to be transmitted over single mode fiber and appear particularly attractive for video distribution systems. Also with SCM, the orthodox microwave solid-state devices could be used to further divide the intensity modulation available, thereby increasing the bandwidth.

4.3. Orthogonal Frequency Division Multiplexing

Reduction in the channel spacing is a major adaptability, which is employed in the orthogonal set of signals and is known as Orthogonal Frequency Division Multiplexing [76-78].**Table-7** shows an comparative analysis of OFDM with different modulation formats.

4.4. Coded Frequency Division Multiplexing

The Coded Frequency Division Multiplexing is also called as OFDM [77], is a system where individual data bits of a word are coded onto individual carriers. Mutually orthogonal frequency carriers are used over one symbol period in this method. It has higher spectral efficiency OP-FDM-RZ-DQPSK as shown in **Table-7.**

4.5. Duty Cycle Division Multiplexing

In this Duty Cycle Division Multiplexing (DCDM) technique [75], different users sign with different RZ duty cycles and the combine together synchronously to form a multi-level step shape signal.

4.6. Optical Polarization Division Multiplexing

Optical Polarization Division Multiplexing is a technique in which the capacity of the system and spectral efficiency is enhanced by using two independently modulated channels keeping the wavelength constant [75]. A brief comparison between 4-QAM(4 bits/symbol), 8-QAM (6 bits/symbol) and 16-QAM(8 bits/symbol) on the basis of polarization multiplexed transmission is illustrated in **Table-12.**

4.7. Wavelength Division Multiplexing

WDM is an optical modulation technique in optical fiber communication employing more than one wavelength. In this communication format , multiple optical carrier signals on a single fiber optic cable is multiplexed by using different wavelengths of laser light to carry various signals . In multimode the 850nm, 1310nm wavelengths are used [34-36]. In single mode 1310 and 1550 nm are used[43].The OSNR (dBm) , maximum bandwidth (ps/nm), CRF (GHz) like parameters are clearly compared in **Table-10.**

4.8. Coarse WDM

Coarse WDM gives the ability to combine upto 18 wavelengths onto one fiber. The spacing of these eighteen wavelengths which are employed evenly from 1270-1610 nm in 20nm increments have been discussed.. The aggregate fiber capacity of CWDM is only 20-40 Gb/s(70Km) as indicated in **Table-14.**

4.9. Dense WDM

Dense WDM takes bandwidth and throughput to higher level. DWDM permits up to 80 wavelengths [46] to share are fiber[32]. The aggregate fiber capacity of DWDM is higher than CWDM that is up to 1Tb/s (900 Km) as indicated in figure 15 of **Table-18.**

Table 1. Comparative analysis of different PSK Schemes

Digital PSK Modulation Techniques	**Probability of Error**	**Degradation**	**Power Spectral Density (PSD)**	B_{Null}
BPSK	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$	0dB(ref.)	$A^2T_b\left(\frac{Sin\ \pi f T_b}{\pi f T_b}\right)^2$	$\frac{2}{T_b}$
DEBPSK	$\approx 2Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$	<0.5 dB	$A^2T_b\left(\frac{Sin\ \pi f T_b}{\pi f T_b}\right)^2$	$\frac{2}{T_b}$
DBPSK (Optimum)	$\frac{1}{2}e^{-E_b/N_0}$	0.5-1 dB	$A^2T_b\left(\frac{Sin\ \pi f T_b}{\pi f T_b}\right)^2$	$\frac{2}{T_b}$
QPSK	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$	0dB(ref.)	$2A^2T_b\left(\frac{Sin\ 2\pi f T_b}{2\pi f T_b}\right)^2$	$\frac{1}{T_b}$
DEQPSK	$\approx 2Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$	<0.5 dB	$2A^2T_b\left(\frac{Sin\ 2\pi f T_b}{2\pi f T_b}\right)^2$	$\frac{1}{T_b}$
DQPSK (Optimum)	$\approx Q\left(\sqrt{\frac{4E_b}{N_0}}\right) sin\frac{\pi}{4\sqrt{2}}$	2-3dB	$2A^2T_b\left(\frac{Sin\ 2\pi f T_b}{2\pi f T_b}\right)^2$	$\frac{1}{T_b}$
DMPSK (Optimum)	$\approx\frac{2}{n} Q\left(\sqrt{\frac{2nE_b}{N_0}} sin\frac{\pi}{\sqrt{2M}}\right)$	3 dB	$nA^2T_b\left(\frac{Sin\ n\pi f T_b}{n\pi f T_b}\right)^2$	$\frac{2}{nT_b}$

Table 2. Modulation parameters of different Digital modulation techniques in 40Gb/s modulation formats.

Digital Modulation	**Demodulation performance**	**Error performance**	**Advantages**	**Disadvantages**
BASK	Easy demodulation	Restricted in linear region	Hardware Implementations simple and low	Poor BW
BFSK	Matched filter detectors used	Performs well	Same as Bask	Complex Hardware design
BPSK	Receiver circuit is complex.	Small error rate	Used only for satellite	Inefficient
DPSK	Receiver requires memory	Required 3 dB less than BFSK	Introduces the complexities of receiver	Efficient less than coherent PSK
QPSK	Phase shift detection is used	Better over BPSK and BFSK	Bandwidth efficient than BPSK	Hardware design of receiver is
64 QAM	Coherent detection	Same as QAM	Very efficient spectral efficiency	BW is same as ASK and PSK
GMSK	Bandwidth time product is measured by SNR Vs BER	The carrier lags or leads by 90^0 over bit period w.r.t BT.	Constant envelope, spectrally efficient	It promotes ISI at higher bit rate transmission

Table 3. Comparison of performance and implementation for 400Gb/s.

Digital Modulation Techniques	**400 Gb/s performance and implementation Advantages**	**400 Gb/s performance and implementation Disadvantages**
NRZ	• "baseline" (no OSNR penalty)	• "baseline" : Single modulator stage. • 90% spectral width = 33 GHz
RZ	• No OSNR penalty. • Versatility to non-linear optical fiber propagation is achieved.	• 66 GHz channel spacing is achieved with ninety percentage spectral width . (unfiltered), channel spacing limited to 100GHz. • Auxilary modulator stages are required
SCM + M-QAM	• Sectral narrowing = f(M) • Symbol duration = f(M) • Lower carrier frequency and/or longer symbol duration improves tolerance to uncompensated CD and PMD	• OSNR penalty = f(# carriers,M) spectral efficiency gains more than offset by large OSNR penalty • Requires complex analog RF electronics • Stringent linearity requirements in modulator and driver.
DPSK	• 3 dB OSNR improvement (with balanced receiver) • Constant envelope modulation	• Interferometric detection required. • Requires DPSK receiver optical channel monitoring in optical line system.

	decreases SPM,XPM	
DQPSK	• No OSNR penalty • Decrease in cross polarization modulation by employing constant envelope modulation. • 33 GHz channel spacing is achieved with ninety percentage spectral width .	• Interferometric detection required • Requires complicated drive signal or 2 modulators • Requires DQPSK receiver receiver optical channel monitoring in optical line system.

Table 4. . Comparison of FOC Digital Modulation Spectral Efficiency and Modulation Efficiency

Digital Modulation Techniques ≤ 100Gb/s	**Data Rate**	**Number of Channels**	**Channel Spacing**	**Spectral Efficiency (bits/s)/Hz**	**Modulation Efficiency (Bits/Baud)**	**Effective Baud Rate (Symbol Rate)**
NRZ-00K	10	40	100	0.1	1	100 G
DPSK	40	40	100	0.4	1	100G
QPSK	10	80	50	0.2	2	50G
DPSK-3ASK	100	40	100	1	2.5	40G
PM-QPSK	100	80	50	2	4	25G

Table 5. Parametric comparison of fiber optics digital modulation formats for 400Gb/s.

Digital Modulation	**Points**	**Symbols**	**Information capacity**	**Derived form**	**BW efficiency**
BASK	01	01	Poor	ASK	Poor
BFSK	01	01	Better than BASK	FSK	Not efficient
BPSK	02	02	2 BFSK	PSK	Only for high speed data
QPSK	04	04	2BFSK	PSK	High
MSK	04	04	2BFSK	OQPSK	Lower than QPSK
QAM	02	04	Better than BASK	ASK & PSK	Less than other techniques
16 QAM	04	04	Better than QAM	ASK & PSK	Less than other techniques
64 QAM	06	04	Better than QAM	ASK & PSK	Less than other techniques
GMSK	04	04	Same as	FSK	Excellent

Table 6. The standardized voice-band data modems with duplex methods for different DFOC

Digital Modulation Techniques	**Speed (b/s)**	**Symbol rate (Hz)**	**Duplex method**	**CCITT standard**
2-FSK	≤ 300	≤ 300	Full FDM	V.21
2-FSK	1200	1200	Half	V.23
4-PSK	1200	600	Full FDM	V.22
4-PSK	2400	1200	Half	V.26
16-QAM	2400	600	Full FDM	V.22bis
4-PSK	2400	1200	Full-EC	V.26ter
8-PSK	4800	1600	Half	V.27
4-QPSK	4800	2400	Full-EC	V.32
16-AM/PM	9600	2400	Half	V.29
32- QAM + TC	9600	2400	Full-EC	V.32
1024- QAM + TC	≤ 28,800	≤ 3429	Full-EC	V.fast (V.34)

Table 7. Major parameters of modulation methods at 400 Gb/s.

Digital Modulation Formats	**OOK**	**OOK-VSB**	**DQPSK**	**RZ-DPSK-3ASK**	**PM-DQPSK**	**OP-FDM-RZ-DQPSK**	**PM-QPSK**	**PM-OFDM-QPSK**
Symbol rate	112	112	56	44	28	28	28	14
Bits/ Symbol	01	01	02	2.5	2x2	2x2	2x2	2x2x2
Estimated Reach (km)	< 500	< 500	1000	<500	600	1500	1500	2000
Spectral Efficiency	0.5	01	01	02	02	01	02	02
CD tolerance (ps/nm)@2dB penalty	± 5	± 5	± 20	± 30	± 90	± 90	>>	>>
OSNR tolerance(dB)@ BER $4x10^{-3}$	17.5	18.5	15.5	>20	15.5	15.5	<15	<15
Coherent/ Non-coherent	Non-coherent	Non-coherent	Non-coherent	Non-coherent	Non-coherent	Non-coherent	Coherent	Coherent
Product Available	No	No	No	No	No	Yes	Yes	Yes

Table 8. Analysis of various digital modulation methods up to 1000Gb/s with theoretical value of 40Gb/s taken as reference.

Digital Modulation Formats	**PM-BPSK**	**PM-QPSK**	**PM-8 QAM**	**PM-16 QAM**	**PM-32 QAM**	**PM-32 QAM**	**PM-64 QAM**	**PM-256-QAM**
Channel Spacing	50	200	133	100	80	200	67	50
Bit-Rate (Gb/s)	100	400	400	400	400	1000	400	400
Bits/Symbol	2x1	2x2	2x3	2x4	2x5	2x5	2x6	2x8
Symbol Rate	28-32	112-128	75-85	56-64	45-51	112-128	37-43	28-32
Penalty vs 100G (dB)	00	06	08	10	12	16	14.5	> 20
No. of C-Band Channels	44	22	33	44	55	22	66	88
Total Capacity (Tb/s)	8.8	8.8	13.3	17.6	22	22	26.4	35
OSNR (dB) @ Min. Baud Rate	10.8	18.2	20.2	22.2	24.2	28.2	26.7	>30
OSNR (dB) @ Max. Baud Rate	8.2	15.8	17.8	19.8	21.8	25.8	24.3	>32

Table 9. Transmission rate performance comparison for NRZ fiber modulation coding format within 400Gb/s.

Channel Bit Rate	**Multiplexing Method**	**PMD delay (pico-second**	**Maximum Dispersion at 1550**	**Insertion Loss**	**Return Loss**	**Physical plant verification**	**Attenuation Profile**
2.5 Gbps DWDM	OC-48/STM-16	40	18817	1550/1625 nm	1550 nm	1550/1625 nm	1550-1625nm
10 Gbps DWDM	OC-192/STM-64	10	1176	1550/1625 nm	1550 nm	1550/1625 nm	1550-1625nm
40 Gbps DWDM	OC-768/STM-256	2.5	73.5	1310/1550 nm	1550 nm	1310/1550 nm	1550-1625nm
10 Gbps	Ethernet	5	738	1310/1550	1550 nm	1310/1550 nm	1550-1625nm

Table 10. Performances and complexity Comparison between different multiplexing techniques and modulation formats at 400 Gb/s aggregation bit-rate.

Digital Modulation & Multiplexing techniques	**Transmitter T_X**	**Receiver R_X**	**OSNR (dBm)**	**CD (PS/nm)**	**MBW (Ps/nm)**	**CRF (GHz)**
NRZ-WDM	1M	1PD	Sim : 16.5 (E-3) 19.8(E-9) Exp: ≈23.3 (E-9)	54	80	40

50% RZ-WDM	2Ms	?	Sim : 14.4 (E-3) 18.3(E-9) Exp: ≈21 (E-9)	48	160	40
DB	?	?	Sim : 22.4 (E-9)	?	40	?
NRZ-DPSK	1M	1DI + 2PDs	Sim : 11.7 (E-3), 13.5 (E-3) Exp: ≈20 (E-9)	74	80	40
NRZ-16-QAM	3PCs,1M	2PDs,3PCs,POI, TFL	Sim : 20.9 (E-9)	?	20	10
E-DCDM (2X20Gb/s)	1M	1PD	Sim : 17.8 (E-3) 21.74(E-9)	62	120	20
E-DCDM (4X10Gb/s)	1M	1PD	Sim : 21.6 (E-3) 26.4(E-9)	58	100	10
E-DCDM (7X5.71Gb/s)	1M	1PD	Sim : 27 (E-3) 31.4(E-9)	52	91.4	5.71

Table 11. The proposed ITU-standard for DWDM channel codes.

DWDM Channel Code	**λ (nm)**	**DWDM Channel Code**	**λ (nm)**	**DWDM Channel Code**	**λ (nm)**	**DWDM Channel Code**	**λ (nm)**
18	1563.05	30	1553.33	42	1543.73	54	1534.25
19	1562.23	31	1552.53	43	1542.94	55	1533.47
20	1561.42	32	1551.72	44	1542.14	56	1532.68
21	1560.61	33	1550.92	45	1541.35	57	1531.90
22	1559.80	34	1550.12	46	1540.56	58	1531.12
23	1558.98	35	1549.32	47	1539.77	59	1530.33
24	1558.17	36	1548.52	48	1538.98	60	1529.55
25	1557.36	37	1547.72	49	1538.19	61	1528.77
26	1556.56	38	1546.92	50	1537.40	62	1527.99
27	1555.75	39	1546.12	51	1536.61		
28	1554.94	40	1545.32	53	1535.82		
29	1554.13	41	1544.53	53	1535.04		

Table 12. Optical OFDM Parameters for 100Gb/s using Polarization-multiplexed QAM.

Transmission Distance (Km)	**Polarization-Multiplexed Transmission**								
	4-QAM (4 bits/symbol)			**8-QAM (6 bits/symbol)**			**16-QAM (8 bits/symbol)**		
	Npre	**Nc**	**Nu**	**Npre**	**Nc**	**Nu**	**Npre**	**Nc**	**Nu**
1000	5	32	26	4	32	26	2	16	13
2000	8	64	52	5	32	26	4	32	26
3000	10	64	52	6	32	26	5	32	26
5000	14	128	104	8	64	52	6	32	26

Table 13. Polarization multiplexed complexity of single-carrier transmission compared to Optical Orthogonal Frequency Division Multiplexing at 400Gb/s.

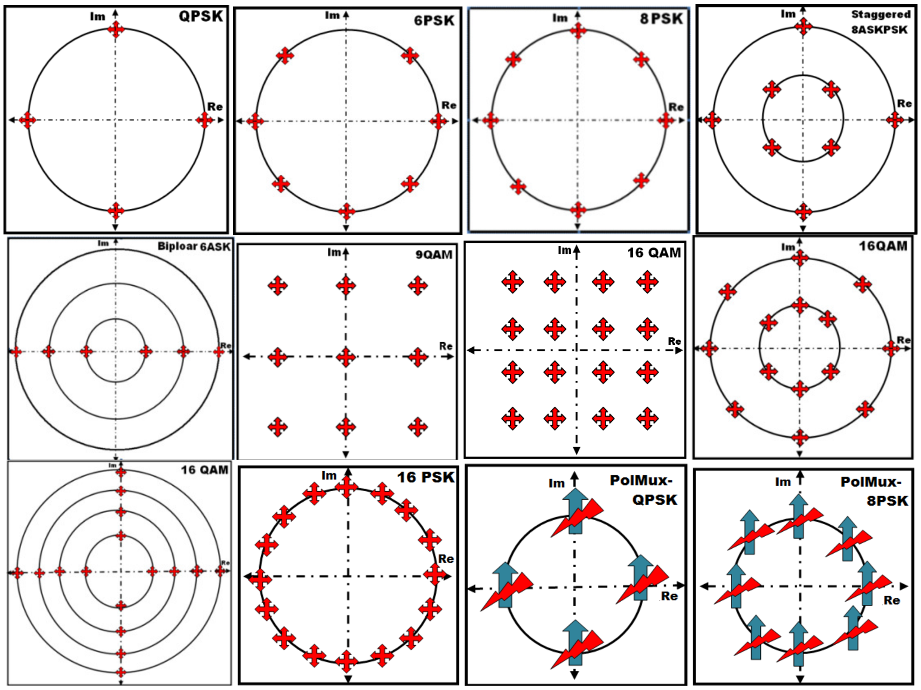
Transmission Distance (Km)	**Single-Carrier**			**OFDM**		
	Direct	**FFT**				
		Block size (B)	**Complexity**	**Transmitter**	**Receiver**	**Total**
1000	12.0	6	13.3	6.2	10.2	16.4
2000	24.0	27	16.6	7.4	11.4	18.8
3000	32.0	25	17.9	7.4	11.4	18.8
5000	52.0	52	19.7	8.6	12.6	21.2

Table 14. Performance Comparison of CWDM and DWDM technology at 400Gb/s of WDM.

Features of WDM in DFOC	**Coarse WDM**	**Dense WDM**
Laser Transmitter types	Uncooled DFB	Cooled DFB, external modulation
Spacing of wavelentghs	2500GHz (20nm)	100 GHz (0.8 nm)
Wavelenghts/ fiber (λ)	8-16 (O,E,S,C,L bands)	40-80 (C,L bands)
Capacity of each wavelength	Up to 2.5 Gbps	Up to 10 Gbps
Total Capacity	20-40 Gbps	100-1000 Gbps
Fiber Technology	Thin film	Thin film, AWG, Bragg grating
Transmission distances	Up to 70 KM	Up to 900 KM
Overall Cost	Very low	Medium

Application	Enterprise, metro-access	Access, metro-core, regional
Transmitter Board Area	20 cm^2 (3.1in^2)	100 cm^2 (16in^2)
Power Consumption per Tx Card (SDI)	1.6 W(100 GHz)	5 W typically(100 GHz)
Laser Wavelength variation (0-40°C)	±6.5 nm	±0.16 nm
Channel Spacing	20 nm	0.8 nm
Channels per frame	4 + 1 upgrade port	4 + 1 upgrade port
Wavelength Selection	Standard ITU wavelength	Reduced
Raman Crosstalk	Significant without mitigation techniques	Minimal with selective wavelength spacing
Four-wave mixing	Not Applicable	Not Applicable
Dependence on the Dispersion of delayed fiber	Low dependence	High Dependence
No. of Wavelengths	2-5	2-8

Table 15. Constellation diagrams of different FOC digital modulation formats.



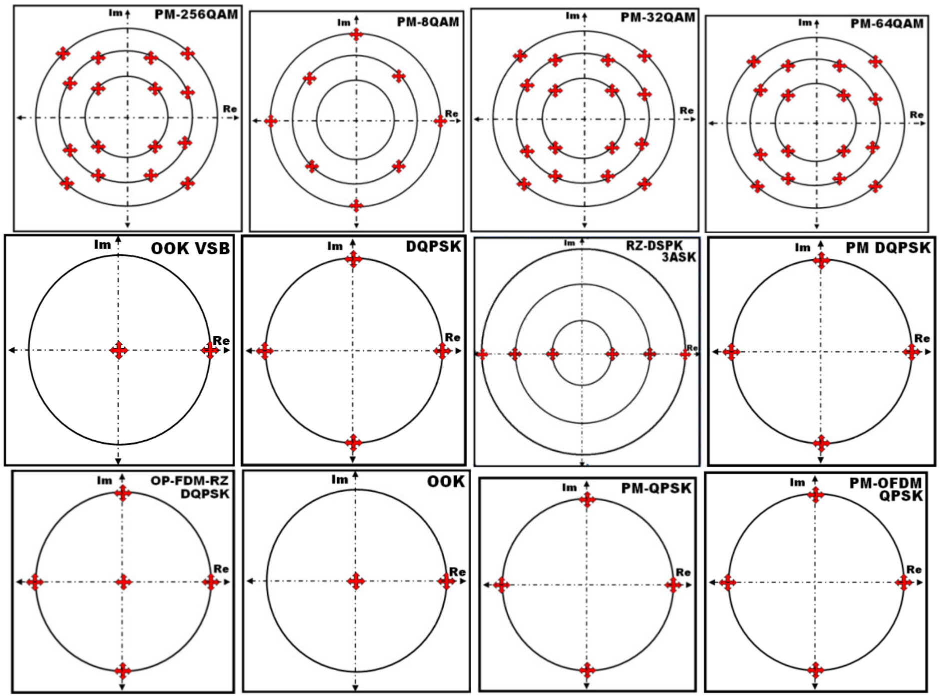


Table 16. 3D graphical comparison between different DFOC parameters within 100 Gb/s

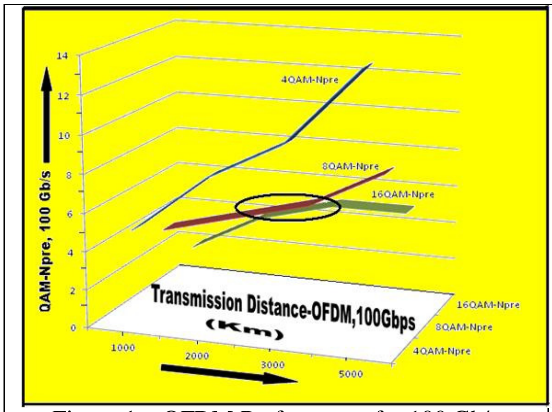
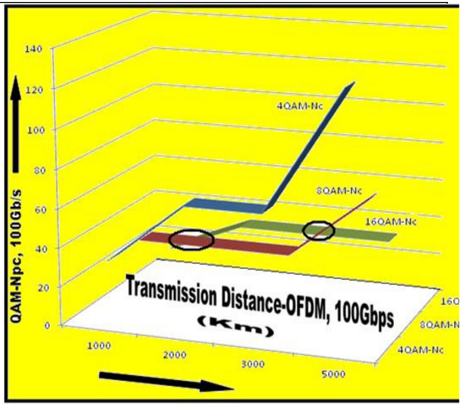
	

Figure 1. OFDM Performance for 100 Gb/s Transmission using Polarization Multiplexed QAM	Figure 2. OFDM Performance for 100 Gb/s Transmission using Polarization Multiplexed QAM

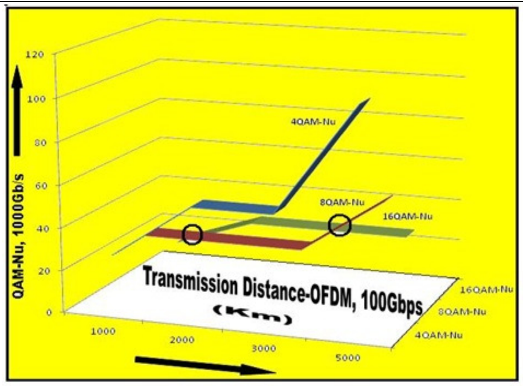


Figure 3. OFDM Performance for 100 Gb/s Transmission using Polarization Multiplexed QAM

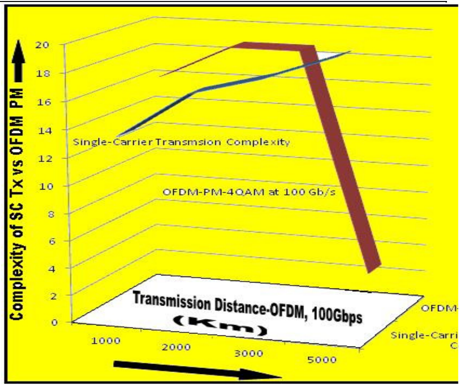


Figure 4. Computational complexity of Single-carrier transmission vs OFDM-PM-4QAM at 100Gb/s

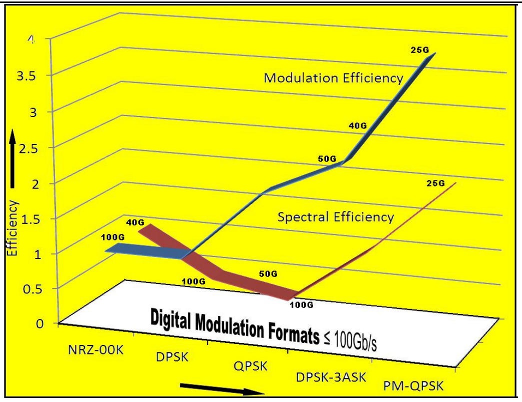


Figure 5. Spectral efficiency features w.r.t modulation efficiency for ≤ 100 Gb/s Digital Modulation Formats.

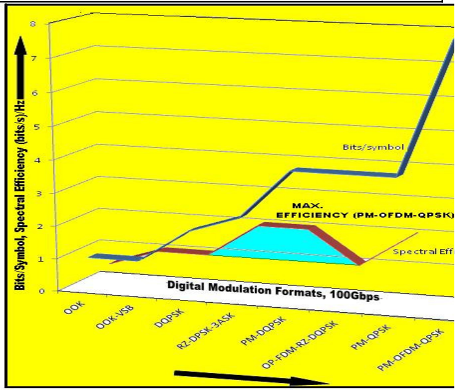


Figure 6. Spectral Efficiency features w.r.t bits/symbol for 100 Gb/s Digital Modulation Formats.

Table 17. 3D graphical comparison between different DFOC parameters within 1Tb/s .

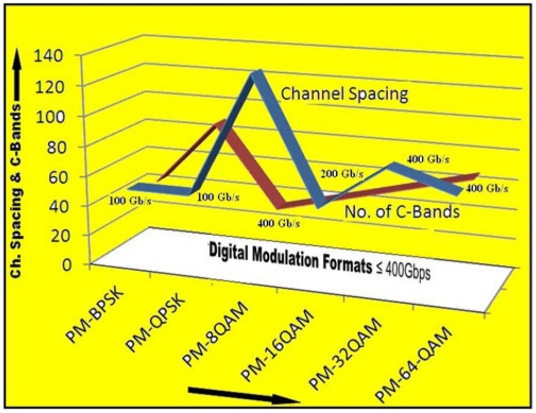


Figure 7. Channel Spacing features w.r.t no. Of C-Band ≤ 400 Gb/s Digital Modulation Formats.

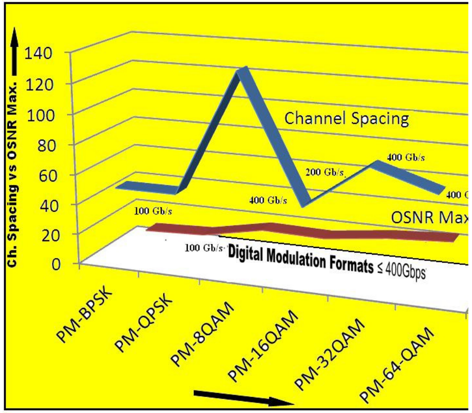


Figure 8. Channel Spacing features w.r.t OSNR (max.) for ≤ 400 Gb/s Digital Modulation Formats.

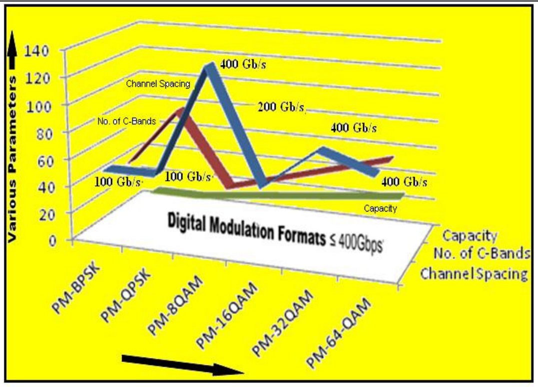


Figure 9. Channel Spacing vs No. of C-bands vs Capacity at ≤ 400 Gb/s rate.

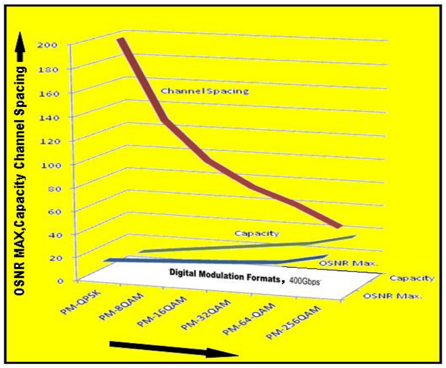


Figure 10. Channel Spacing vs OSNR (max.) vs Capacity at ≤ 400 Gb/s

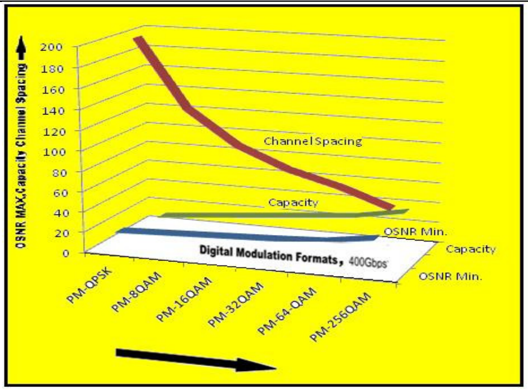


Figure 11. Channel Spacing vs OSNR (min.) vs Capacity for ≤ 400 Gb/s Digital Modulation Formats.

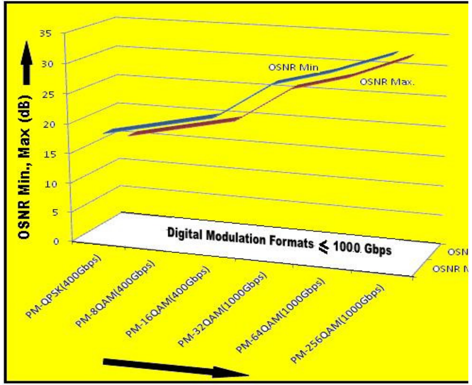


Figure 12. OSNR (max.) vs OSNR (min.) for ≤ 1Tb/s Digital Modulation Formats.

Table 18. 3D graphical comparison between different digital Modulation and Multiplexing parameters within 1Tb/s .

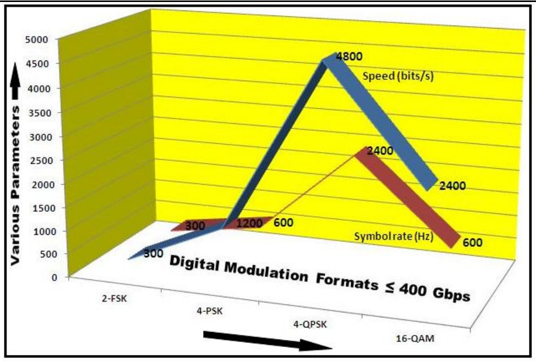


Figure 13. Speed vs symbol rate for ≤ 400 Gb/s Digital Modulation Formats. (Full-Duplex).

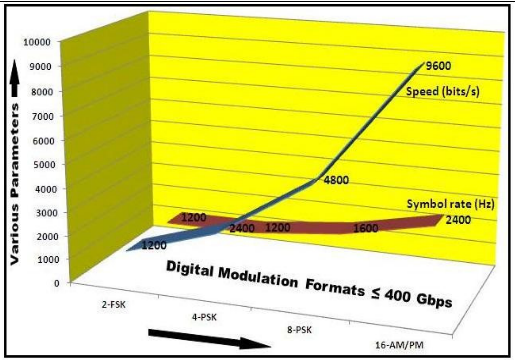


Figure 14. Speed vs symbol rate for ≤ 400 Gb/s Digital Modulation Formats. (Half-Duplex).

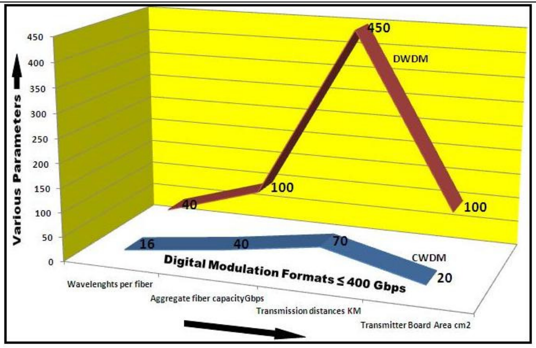


Figure 15. Performance Comparison of CWDM and DWDM technology at 400 Gbp/s

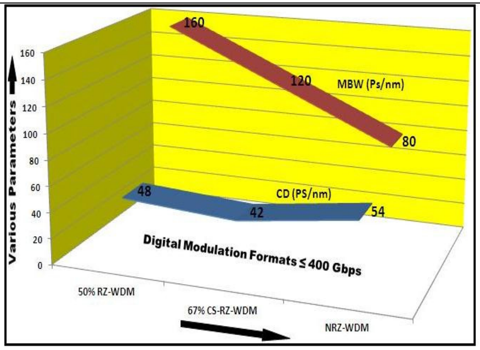


Figure 16. Complexity Comparison of Chromatic Dispersion (Ps/nm) & MBW(Ps/nm).

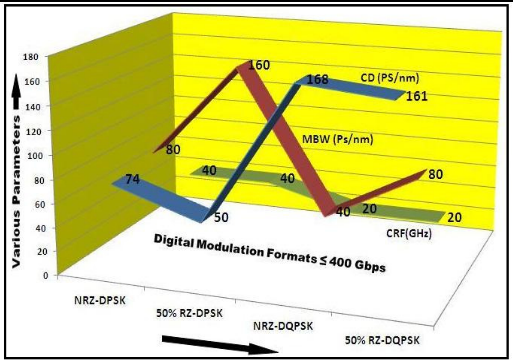


Figure 17. Performances Comparison of CRF (GHz), Chromatic Dispersion (Ps/nm) & W (Ps/nm)

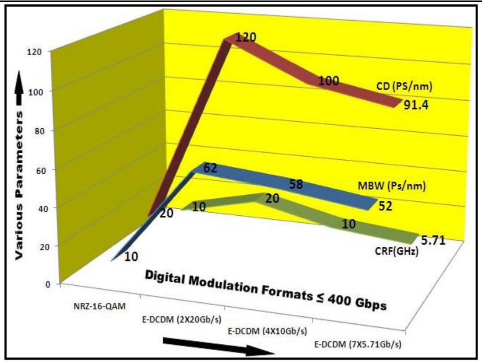


Figure 18. Performances Comparison of CRF (GHz), Chromatic Dispersion (Ps/nm) and MBW (Ps/nm).

5. COMPARATIVE ANALYSIS

The parameters of different types of digital fiber optic communication modulation formats with their multiplexing techniques are compared in a tabular manner from **Table 1-10**. Also by 3D graph representation from **Table 16, 17 & 18**, we compare the characteristics of different formats having bit-rate of 400 Gb/s – 1Tb/s. The bandwidth efficiency is excellent in case of GMSK compared to BASK, BPSK, BFSK, QPSK and M-QAM modulation techniques summarized in **Table-5**. The modulation formats having speed (b/s) of 2-FSK (≤ 300 b/s and 1200 b/s), 4-PSK (1200b/s) up to 1024-QAM + TC (≤ 28,800 b/s) compared on the basis of their duplex methods used in **Table-6**. An comparative survey reflects in **Table 7 & 8** on single channel M-QAM options like PM-16QAM of 200 Gb/s, PM-8QAM of 400Gb/s, PM-32-QAM of 1000Gb/s, PM-64-QAM of 1000Gb/s, PM-256-QAM of 1000Gb/s by taking 40Gb/s value as reference, which considering Polarization multiplexing for all options. The 67% CS-RZ-WDM and 50% RZ-WDM utilizes two modulators as well as in 50% RZ-DPSK shown in **Table-10**. The complexity between different FOC digital modulation techniques and multiplexing techniques are indicated in **Table-10**. The proposed 1550 nm window i.e DWDM by ITU is shown in **Table-11**. A survey of single carrier transmission vs OFDM for polarization multiplexed 4-QAM at 400 Gb/s is summarized in **Table-13**. The transmission distance is up to 70km (CWDM) and upto 900km (DWDM) is indicated in **Table-14**. The 4-QAM,8-QAM &16-QAM modulation formats having their polarization multiplexed transmission performances compares in **Table-12**. The **Table-15** comparatively exhibits the constellation diagrams of different FOC digital modulation formats.

Figure 1, 2 & 3 of **Table-16** reflects a 3D-comparative survey on OFDM performance for 100Gb/s. A comparison between channel spacing and C-Bands of PM-BPSK, PM-QPSK, PM-M-QAM having 100 Gb/s to 400 Gb/s is shown in figure 7 of **Table-17**. The OSNR at maximum range compares with channel spacing by taking different modulation techniques summarizes in a 3-D pattern in figure 8 & 9 of **Table-17**. The symbol rate of 400-1000 Gb/s applied for comparison of OSNR-maximum & OSNR-minimum. of different digital fiber optic communication modulation formats in figure 12 of **Table-17**. The comparative analysis of complexity between different WDM multiplexing techniques (50% RZ-WDM, 67% CS-RZ-WDM & NRZ-WDM) are shown in figure 16 of **Table-18.** Here MBW (ps/nm) compared with chromatic dispersion at 400 Gb/s. The symbol rate varies with the bit/sec for 2FSK, 4PSK, 4QPSK and 16-QAM at 2400 Hz (4800 bits/sec). Various parameters like wavelength per fiber, aggregate fiber capacity at 400 Gb/s, transmission distances and transmitter board area of CWDM and DWDM are analyzed in figure 15 of **Table-18.** The symbol rate vs speed for different FOC digital modulation formats are compared for half and full duplex standardized voice-band data modems.

6. CONCLUSIONS

In this article we describe the influence of bit rate (Gb/s) on different fiber optic communication digital modulation, detection and multiplexing techniques. We analyzed the performance of PM-QPSK (100Gb/s, 400Gb/s), PM-8QAM (400Gb/s), PM-16QAM (200Gb/s), PM-16QAM (200Gb/s, 400Gb/s), PM-32QAM (400Gb/s), PM-32QAM (1000Gb/s), PM-256QAM (400Gb/s) and PM-64QAM (1000Gb/s). This paper not only affords simple digital modulation techniques but also provides a comparative analysis about different detection and multiplexing techniques in the optical transmission system. In this article, applications are build up using 3D practical exposure in the digital fiber optic communication.

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Authors

Sumant Ku Mohapatra was born in Bhubaneswar, Orissa, India . He received the B.Tech degree from ITER, Bhubaneswar, India in 2002 & M.Tech(Electronics & Instrumentation Engg) from GIET, BPUT, Odisha in 2011.. His research interest are in signal and image processing , optical fiber communication and wireless communication. Currently he is working in Trident Academy of Technology, B.P.U.T, Bhubaneswar, Odisha, India as an Assistant Professor in the Department of ETC.

Ramya Ranjan Choudhury was born in the Balasore district, Orissa, India . He received the B.Tech degree from Silicon Institute of Technology, Bhubaneswar, India in 2008 & M.Tech (Electronics & Communication Engg) from C.E.B, BPUT, Odisha in 2012. His research interests include digital signal processing, digital image processing, optical fiber communication and wireless communication. He is currently working in Trident Academy of Technology, Bhubaneswar, Odisha, India as an Assistant Professor.

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Rabindra Bhojray was born in the Cuttack district, Odisha, India . He received the graduate Engineering from I.E.T.E New Delhi , India in 1998 and received the master engineering in field of communication system engineering from U.C.E, Burla, Orissa (At present V.S.S.U.T, Burla), in 2001 and Ph.D. (continuing). His research interest are in signal and image processing ,optical fiber communication and wireless communication. Currently he is an associate professor in Trident Academy of Technology, B.P.U.T, Bhubaneswar, Odisha.

Pravanjan Das was born in the Cuttack district, Odisha, India . He received the B.Tech degree from TAT, Bhubaneswar, India in 2010 & M.Tech(Communication Systems) from SVNIT,Surat,Gujrat in 2013. Currently he is working in Trident Academy of Technology, B.P.U.T, Bhubaneswar, Odisha, as an Assistant Professor. His research interest are in signal processing , and wireless communication.