International Journal of Applied Electromagnetics and Communication Systems
Volume 1, Issue 03, 2025

A COMPARATIVE OVERVIEW OF OPTICAL FIBER COMMUNICATION ANALOG AND DIGITAL MODULATION FORMATS WITHIN AND BEYOND 100 GB/S

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Research Article

Date of Submission: 17-06-2025 **Date of Acceptance: 21-07-2025** **Date of Publication: 28-08-2025**

ABSTRACT

In fiber optic communication channels, several analog and digital methods are utilized to convey data in order to improve performance and simplify installation. Various digital modulation methods increase tolerance to transmission defects and promote spectral efficiency. In this study, a comparative comparison of several digital modulation formats both inside and outside of 100 Gbps is reviewed. An overview of several transmission methods that can send massive amounts of data at bit rates of up to 1 Tb/s or more. In this particular article, we examine the benefits of digital modulation forms over traditional analog modulation formats using a comparative tabular approach.

Keywords: Analog modulation format, digital modulation format, optical fiber communication, < 100Gb/s, ≥ 100Gb/s.

1. INTRODUCTION

Large bandwidth was a general need in communication technology for both consumer and industrial applications. In order to achieve high bandwidth data transfer, sophisticated modulation methods are used in optical communication. Advanced modulation formats use more complex methods to encode the electrical data pattern onto an optical carrier by using not just amplitude but also other signal domains, such as phase and the state of polarization. In comparison to the analog modulation formats of fiber optic transmission, this results in improved functionality and increased spectrum efficiency.

The main benefit of utilizing fiber optic digital modulation formats is that, in contrast to analog signals, which require a large number of wave forms and a large bandwidth for the symbol to be transmitted, digital signals reduce hardware complexity, noise, and interference issues [4].

In recent years, a number of digital modulation formats have been developed, mostly including 2.5, 10, 25, 40, and 100 Gb/s wave length channels. However, data rates per channel are already exceeding 100 Gb/s for optical communication systems. The IEEE standard 802.3ba [6] announced the 100 Gb/s Ethernet (GbE) interfaces in 2010 for 10 Km and 40 Km reach, using 4 channels with 25 Gb/s. The 2009 ITU-T standard G.709 [7] defines the line side bit rate of about 112 Gb/s (OTU4 bit rate) and the OTN multiplex with client data and standard Reed Soloman FEC.

100 Gb/s bandwidth solutions have been gradually advancing in various optical communication networks for industrial applications

since 2010. Higher data transfer rates, such as 200Gb/s, 400Gb/s, 1000Gb/s, and even 1T bit/s Ethernet, are necessary for current communication optical systems. 100 Gb/s transmission with 10 No. of 10 Gb/s or 4 No. of 25 Gb/s is preferred for short-range client side applications [6]. Serial transmission of a large number of digital wave division multiplexing channels with small channel spacing is essentially intended for high transmission capacity. The technical solutions for digital modulation for serial transmission of up to 100 Gb/s are compared in this section.

In the introduction, we describe the bit rate in Mb/s in relation to the optical source wavelength, repeater spacing, and optical carrier. Next, we discuss 40Gb/s optical systems in the first section and provide a summary of the modulation forms, ranging from M-QAM to binary amplitude shift keying.An summary of the many features, system tolerances, and key properties of 100Gb/s systems is provided in the second part. The digital modulation formats for systems faster than 100 Gb/s are the subject of the third part.

2. CLASSIFICATION OF OPTICAL FIBER MODULATION TECHNIQUES

Sl. No.	Modulation formats	Type	Notation
01.	Analog modulation formats	Amplitude modulation/Intensity modulation sub-carrier	AM/IMSC
		Frequency modulation/Intensity modulation sub-carrier	FM/IMSC
		Phase modulation	PM
02.	Digital modulation formats	ON-OFF keying/binary amplitude shift keying.	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 multiplexing QPSK	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	SC
		Multi carrier modulation formats	MC

3. ANALOG OPTICAL FIBER MODULATION TECHNIQUES

Optic baseband transmission uses a light beam that has been modulated at the information's baseband frequencies to carry the signal. Intensity modulation is an analog modulation in which the optic power changes according to the input current.

3.1 AM/IM Subcarrier modulation

Conventional AM places message on a carrier whose frequency is much greater than the messages . AM of a single sinusoid can be written as

$$i = \text{Is}\ (1+\text{m}\ \cos\omega_m)\ \cos\omega_{sc}t \qquad (1)$$

where ω_{sc} is the subcarrier frequency.We can add a dc current I_0 to the above current and drive an optic source with the result producing IM of a light beam by an AM signal. This is AM/IM modulation that generates optic power.

$$P=P_0 + P_s(1+\text{m}\ \cos\omega_m)\ \cos\omega_{sc}t \qquad (2)$$

3.2 FM/IM Subcarrier modulation Adding a dc current to the FM equation , $i = \text{Is}\ \cos\ (\omega_{sc}t+\beta \sin\omega_m t)$ (3)

where β is the modulation index and intensity modulating an optic source with it produces FM/IM modulation. For the sine wave optic power varies as

$$P=P_0 + P_s\ \cos(\omega_{sc}t+\beta\ \sin\omega_m t) \qquad (4)$$

The detected current has the same waveform as the optic power. As the FM bandwidth is larger than the AM bandwidth , fewer FM messages can be fitted within the fiber's limited range of frequencies.

3.3 PM Subcarrier modulation

Phase modulation is a sophisticated modulation scheme for analog optical communication that produces a phase shift using the electro-optic effect concept [3]. The applied field has a linear relationship with that phase shift. In contrast to the amplitude demodulator, the phase demodulation method employs heterodyne detection, which imposes a sinusoidal nonlinearity on the demodulated signal [3].

4. OPTICAL FIBER DIGITAL MODULATION TECHNIQUES

In its broadest definition, modulation includes CODING to display transmission defects and is a technique for imprinting digital information onto an optical carrier. Information is transferred between locations using electromagnetic waves at frequency close to 200 THz in optical fibers. The complex plane, where information symbols are mapped, may be better used in optical fiber communication systems by modulating the carrier's amplitude and phase, which increases spectral efficiency.

4.1 OOK/BASK

In optical fiber communication systems, the original signals are modulated into high frequency optical carriers. Binary 0 is broadcast with 0 Watt and binary 1 with A Watt in ASK format, which multiplies the baseband signal by a carrier frequency. By using photodetectors to convert the optical signal to the electrical signal, the demodulation operation at the receiving end is carried out effectively. In order to increase the transmission capacity, 4-ary ASK digital modulation schemes are created, with M=2b, where b is

the amount of bits per symbol. The gain factor in relation to DBPSK is shown in Table 11. Table 12 illustrates the inadequate bandwidth efficiency and information capacity.

4.2 BFSK

BFSK is a data signal that is transformed into a certain frequency so that it may be sent to a destination via optical fiber medium. The available bandwidth determines the frequency variation to be used. A FSK signal's entire bandwidth is roughly equal to 2Δf+2B, where B is the bit rate. The bandwidth approaches 2Δf and is almost independent of the bit rate when Δ ² B. Table 12 shows that although the information capacity with OOK is somewhat greater, the bandwidth with OOK is not as effective..

4.3 BPSK

Binary data are modulated onto the optical carrier using the phase difference between binary 0 and binary 1 in the BPSK modulation method. The binary 0 is represented by -sinωt, whereas the binary 1 is represented by sinωt. Compared to other digital modulation schemes, its demodulation procedure is quite complicated.The benefits and drawbacks of the BPSK modulation scheme are presented in Table 9. Table 9 illustrates its low mistake rate.

4.4 DPSK

The DPSK is favored in optical transmission systems because to its strong resistance to nonlinear propagation [8] and, to a lesser degree, to polarization mode dispersion (PMD) [9]. It is a quick and reliable modulation type that works well in a variety of optical applications. Compared to binary PSK, it offers various benefits, such as a reduced phase error rate and no need to know the precise phase. According to Table 12, the information capacity is double the BFSK.

4.5 NRZ/RZ-DPSK

A single semiconductor optical amplifier (SOA) is used to convert multichannel parallel formats from non-return-to-zero DPSK (NRZ-DPSK) to return-to-zero DPSK (RZ-DPSK). The cross phase modulation (xpm) effect, which is produced by a synchronized optical clock signal with high input power, provides the foundation for the simultaneous conversions. Every input bit receives an identical phase shift from the XPM, which leaves the phase difference unaltered [5].Six channel NRZ-DPSK signals at 40Gb/s may be converted to the matching RZ-DPSK signals with about 0.8 to -1dB power penalty for all the channels by broadening the input spectra and then using a filter to remove the relevant section to generate a RZ pulse. According to Table 7, the OSNR sensitivity at BER=2 ×10-3 (dB) is 12.5, which is quite low.

4.6 QPSK

Two bits are extracted from the bit stream in QPSK, and the four possible permutations of the two bits are represented by four carrier frequency phases. The four potential combinations of two bits—00, 01, 10, and 11—are represented by various carrier phases. By encoding two bits in a single symbol and using 50Gbaud to get 100Gb/s, it doubles the line rate compared to OOK. The information is conveyed in the four phase states of the optical phase of the light that is produced, and the transmitter's output signal has essentially constant optical strength. The PMD tolerance without compensation is greater than most DPSK formats, as Table 7 illustrates. Table 9 shows that it performs better in terms of errors than BPSK and BFSK.

4.7 DQPSK

DQPSK is a four-level version of DPSK that transmits two bits for each symbol (the bit combinations being 00, 01, 11, and 10). Its advantage over DPSK is that it has a narrower optical spectrum, which permits closer channel spacing, stronger optical filtering, and more dispersion (both chromatic and polarization mode).

Consequently, DQPSK enables 40Gb/s data processing in a 50GHz channel spacing system. Table 11 shows that DQPSK may increase the efficiency and reach of WDM systems due to its bandwidth savings over both DD-OOK and DPSK.

4.8 RZ-DQPSK

A single phase modulator powered by an electrical 4-level modulation signal or two phase modulators cascaded for the modulation of the optical phase by 0 to $\pi/2$ and by 0 to $\pi/4$ using binary modulation signals are used to get the RZ-DQPSK signal. With FEC overhead at 107Gb/s [13–17], 111Gb/s [18], and 112Gb/s OTU-4 channel bit rate [19, 20], 100Gb/s transmission utilizing DQPSK modulation format has been extensively proven across lab or field fibers at 100Gb/s [10–12]. The OSNR values of RZ-DQPSK and NRZ-DQPSK are shown in Table 8. The modulated bandwidth, which doubles in comparison to the NRZ-DQPSK format, is also summarized in Table 8.

4.9 RZ-DPSK-3ASK

This is a very basic mixer of phase and ASK modulation. In order to handle the OTU4 line rate [7] of 112Gb/s, the RZ-DPSK-3ASK modulation format codes 2.5 bits into a single symbol, resulting in a symbol rate of 43Gbauds [21–24]. This modulation style has a limited OSNR tolerance, which limits the transmission reach [25, 26]. According to Table 13, the primary application area is in the metro, where its projected reach is fewer than 500.

4.10 PM-QPSK or DP-QPSK

The 100Gb/s PM-QPSK transmission technique [27], which operates at a symbol rate of 25–28Gbaud, is often used for offline signal processing of electrical signals captured by 4-channel high-speed real-time oscilloscopes that function as quick A/D converters [28, 29]. Its compatibility with 10Gb/s and 40Gb/s is good, according to Table 13. This modulation scheme is ideal for long-distance OIF applications.

4.11 PM-OFDM-QPSK or DP-OFDM-QPSK

Two narrowly spaced (20GHz) optical carriers, each modulated with PM-QPSK format based on 14Gbaud modulation, are used in another commercially available 100Gb/s transponder [30,27]. Two 50Gb/s PM-QPSK transmitters and receivers are needed for this modulation format, which is known as DP or PM-OFDM-QPSK. According to Table 13, the compatibility with 10Gb/s and 40Gb/s is unfavorable.

4.12 OP-FDM-RZ-DQPSK

Fast automated optical polarization demultiplexures may be avoided by using two polarizations to transport two light carriers [27]. Optical fibers may be used to multiplex and demultiplex the two carriers. This modulation scheme, known as orthogonal polarization frequency division multiplex RZ-DQPSK, is based on 28 Gbps. However, only 100GHz channel spacing is supported for the separation of two optical carriers in two polarizations. According to Table 13, the compatibility with 10Gb/s and 40Gb/s is positive (which is negative in the case of PM-OFDM-QPSK).

4.13 PM-DQPSK or DP-DQPSK

We can lower the symbol rate by using polarization division multiplexing (PM). Consequently, the symbol rate drops to half or the line rate doubles [27]. In order to handle the OTU 4 line rate, this results in 100Gb/s polarization multiplexed DQPSK signals or dual polarization (DP) with a symbol rate of 28Gbaud. The 100G DWDM transmission with 50 GHz channel spacing is supported by the 28Gbaud modulation types. A polarization beam combiner is used to combine the two DQPSK signals in an orthogonally polarized manner. Table 13 summarizes the symbol rate as 28, which is almost identical to the OP-FDM-RZ-DQPSK optical digital modulation standard.

4.14 M-QAM

A channel rate of 200Gb/s with 16QAM has recently been achieved using a QAM method with polarization multiplexing. M bits are sent in a single time slot in an M-QAM [27]. It has previously been shown at submarine transmission topologies [33] employing RZ at PM-QPSK that optimizing the SE of signals with M-QAM constellations by Nyquist filtering towards Nyquist-WDM [32] is now of great research interest. In order

to obtain 224 Gb/s channel rate (200G+FEC overhead) [45–47] and 448 Gb/s channel rate [48], polarization multiplexed 16 QAM signals have been generated via multilevel generation employing passive combining of binary signals. Transmission distances ranging from 670 to 1500 km have been shown using polarization multiplexing and QAM modulation style [45–47]. To get a 112Gb/s channel rate, RF-assisted optical dual-carrier 112Gb/s polarization-multiplexed 16QAM is used [49]. A 240Gb/s channel with 12 bits per symbol has been achieved using the DP-64QAM format [50]. Lower data rate channels of 100Gb/s using 32QAM [51], 100Gb/s using 35QAM [52], 112Gb/s and 120Gb/s using 64QAM [53,54], 56Gb/s with a spectral efficiency of 11.8bit/s/Hz using DP-256QAM [55], and 54Gb/s using DP-512QAM [56]. Table 15 shows the results of our comparison of several M-QAM modulation methods with varying data rates (Gb/s).

4.15 MSK

When compared to existing digital modulation formats, the novel optical minimum shift keying modulation approach has a high spectrum efficiency. Similar to the DQPSK transmitter, the optical MSK transmitter is based on two Marh-Zehnder modulators (MZM). The DPSK receiver and the MSK receiver with one delay and add filter (DAF) and photodiodes for direct detect detection are comparable. Table 9 shows that the signal coherence and derivation ratio are essentially unaffected based on error performance. Table 12 shows that the information capacity is twice that of the BFSK signal.

4.16 GMSK

Gaussian minimum shift keying is a straightforward optical binary modulation system that may be thought of as an optical MSK modulation technique derivative. In this format, a pre-modulation Gaussian pulse shaping filter is used to the modulating NRZ data waveform to further lower the side lobe levels of the spectrum. The connection between the bit period TB and the pre-modulation filter bandwidth B determines the bandwidth of an optical GMSK system. At 99.99%, the BTB decision based on 0.2GMSK, 0.25GMSK, and 0.5GMSK is 1.22, 1.37, and 2.08, respectively.

4.17 Single carrier (SC) modulation formats

more level modulation methods, such as QAM with PM, are employed to achieve a channel rate of 200Gb/s with 16QAM at bit rates more than 100Gb/s on a single carrier. Each symbol in this format transmits 2×m bits. The PM-QAM modulation type may be used with a variety of constellations [27.31]. It is now of great research interest to minimize the SE of signals with M-QAM constellation by Nyquist filtering towards Nyquist-WDM [32]. This has previously been shown at submarine transmission topologies [33] utilizing RZ at PM-QPSK. An overview of single channel M-QAM choices ranging from 200Gb/s to 1Tb/s is provided in Table 14 [27].

4.18 Multicarrier (MC) modulation formats:

[42] One MC modulation scheme that supports large bandwidth channels is optical OFDM transmission [34]. DSP is used in the transmitter to create the IFFT. High capacity transmission may be carried out by closely allocating many OFDM signals in the frequency domain without guard bands since O-OFDM transmissions are rectangular (almost) safe.

[43] Numerous transmission tests using PM-O-OFDM and polarization multiplexed O-OFDM have been documented [27, 35–41], transferring Tb/s super channels across undersea lengths [41]. Using 253 Gb/s OFDM super-channels with subcarriers carrying QPSK signals and 400 Gb/s super-channels 8QAM signals [42] over 768 Km and Tb/s super-channels over 454 Km [43] and 3560 Km [44], field transmission trials over installed standard SMF applying PM-OFDM format in co-propagation with 112G DQPSK channels. Table 13 shows an overview of this optical OFDM transmission using PM-QPSK modulation.

Generation	Wavelength of Optical source(μm)	Bit rate Mb/s	Repeater Spacing (Km)	Loss
I	0.8	4.5	10	1
II	1.3	1.7×10^2	50	<1
III	1.55	1.0×10^4	70	<0.2
Iv	1.55	1.0×10^5	100	<0.002
V	1.55	$>1.0\times10^9$	>100	<0.002

Table-1: Generations of optical fiber communication which shows analysis between wavelength and bit rate within Mb/s.

Level	Line rate	DS3 channel
OC-1	51.84Mbps	1
OC-3	155.52Mbps	3
OC-9	466.56Mbps	9
OC-12	622.08Mbps	12
OC-18	933.12Mbps	18
OC-24	1.244 Gbps	24
OC-36	1.866 Gbps	36
OC48	2.488 Gbps	48

Table-2: Optical interfaces related between Line rate with different DS3 channels.

Fiber		Optical loss (dB/km)			
Size(μ)	Type	780 nm	850 nm	1300 nm	1550 nm
9/125	SM	3.0	2.5	0.5-0.8	0.2-0.4
50/125	MM	3.5-7.0	2.5-6.0	0.7-4.0	0.6-3.5
62.5/125		4.0-8.0	3.0-7.0	1.0-4.0	1.0-5.0
100/140		4.5-8.0	3.5-7.0	1.5-5.0	1.5-5.0
110/125			15		
200/230			12		

Table-3: Performance analysis of optical fiber loss of analog modulation schemes.

PARAMETERS	CAUSES	CRITICAL POWER/CHANNEL	EFFECTS	COMPENSATION
Attenuation	Material absorption/system		.Reduced signal power levels .Increased bit errors	Shorter spans, purer fiber material.
Chromatic dispersion	Wavelength dependent group velocity		Increased bit errors	Use of compensation fiber or material.
Polarization mode dispersion	Polarization state dependent differential group delay		.Increased bit errors	New fiber with low PMD values; careful fiber layng;PMD compensators
Four wave mixing	Signal interference	10mW	.Power transfer from original Increased bit errors signal to other frequencies .Channel crosstalk	Use of the fiber with CD compensators; Unequal channel spacing
Self phase modulation and cross phase modulation	Intensity dependent refraction index	10Mw	.Spectral broadening .Initial pulse compression .Increased bit errors	Use of the fiber with CD compensators;
Stimulated Raman scattering	Interaction of signal with fiber modulator structure	1mW	.Decreased peak power .Decreased OSNR .Optical crosstalk	Careful power design
Stimulated Brillouin scattering	Interaction of signal with acoustic waves	5mW	.Signal instability .Decreased peak power .Decreased OSNR .Increased bit errors	Spectral broadening of the light source.

Table-4: Analysis of analog modulation of fiber optic transmission phenomena.

Fiber type	DESCRIPTION	ZERO DISPERSION WAVELENGTH	DISPERSION AT 1550 nm	Dispersion slope at 1550 nm
G 652	Non-dispersion shifted fiber	1300-1324 nm	-17 ps/nm/km	0.057 ps/nm^2/km
G 653	Dispersion shifted fiber	1500-1600 nm	0 ps/nm/km	0.07 ps/nm^2/km
G 655A-C	Non-zero dispersion shifted fiber	Not specified but 1450-1480 nm	4 ps/nm/km	0.045 to 0.1 to ps/nm^2/km
G 656	Negative Non-zero dispersion shifted fiber	Not specified	-5 ps/nm/km	0.05 to 0.12 ps/nm^2/km

Table-5: Performance analysis of different types of fibers with dispersion at 1550nm.

Bit rate per channel	Type of transmission	PMD delay limit(ps)	Max. CD at 1550 nm(ps)	Insertion loss	return loss.	physical plant verification	Attenuation profile
2.5 Gbps DWDM	OC-48/STM-16	40	18817	1550/1625 nm	1550 nm	1550/1625nm	1550-1625nm
10 Gbps DWDM	OC-192/STM-64	10	1176	1550/1625 nm	1550 nm	1550/1625nm	1550-1625nm
40 Gbps DWDM	OC-768/STM-256	2.5	73.5	1310/1550 nm	1550 nm	1310/1550nm	1550-1625nm
10 Gbps	Ethernet	5	738	1310/1550 nm	1550 nm	1310/1550nm	1550-1625nm

Table-6: Transmission rate performance for NRZ fiber modulation coding format within 40Gb/s.

Characteristics	ODB/PSPT	NRZ/DPSK	NRZ-ADSPK	RZ-ADPSK	RZ-DQPSK	PM-QPSK
OSNR Sensitivity at BER=2×10^3 dB	17.5	12.5	13	12.5	13.5	12.5
Nominal range using EDFA	700	1600	1600	2200	1400	1700
Filter tolerant (for 50 GHz channel spacing)	Yes	Affects range	Yes	Yes	Yes	Yes
PWM tolerance without compensation(PS)	2.5	3	3.5	3.5	6	10
Sensitivity to non-linear distortion	No	No	No	No	Yes	Yes
Complexity/cost	Low	Low	Low	Medium	High	High

Table-7: Comparative analysis of digital optical modulation formats for 40Gb/s.

Modulation techniques of PSK at 40Gb/s	Modulators used in transmitter	Modulators used in receiver	OSNR (dBm)	Chromatic dispersion	Modulated bandwidth	Clock recovery frequency
RZ DPSK	2 Nos.	1 delay intero - ferometer (DI) & 2 photo detectors(PD)	15.6	50	160	40
NRZ DPSK	1 Nos.	1DI +2PDs	18.5	74	80	40
RZ DQPSK	2 Nos.	2DIs + 4PDs	17.7	161	80	20
NRZ DQPSK	2 Nos.	2DIs+4PDs	20.5	168	40	20

Table-8: Performance analysis of different PSK digital modulation schemes for 40Gb/s.

Sl. No.	Modulation techniques	Demodulation performance	Error performance	Advantages	Disadvantages
1	BASK	Easy demodulation	Restricted in linear region	Hardware Implementations simple and low cost	Poor BW
2	BFSK	Matched filter detectors used	Performs well	Same as bask	Hardware design of receiver is complex
3	BPSK	Receiver circuit is complex due to phase shift detection	Small error rate	Used only for satellite communication.	Inefficient
4	DPSK	Receiver requires memory	Required 3 dB less than BFSK	Introduces the complexities of receiver design	Efficient less than coherent PSK
5	QPSK	Phase shift detection is used	Better over BPSK and BFSK	Bandwidth efficient than BPSK	Hardware design of receiver is complex
6	MSK	Direct inject to NRZ data to frequency modulator.	The signal coherence and derivation ratio are largely unaffected by variations in input data	Constant Envelope	The spectrum is not compact enough to realize data rates
7	QAM	Coherent detection	Small error rate	Better transmission than MSK	BW is same as ASK and PSK
8	16 QAM	Coherent detection	Same as QAM	Producing a very spectrally efficient transmission.	BW is same as ASK and PSK
9	64 QAM	Coherent detection	Same as QAM	Very efficient spectral efficiency	BW is same as ASK and PSK
10	GMSK	Bandwidth time product performance is measured by SNR Vs BER	The carrier is lag or lead by 90^0 over bit period w.r.t BT resulting BER	Constant envelope, spectrally efficient	It promotes ISI at higher bit rate transmission

Table-9: Modulation parameters of Digital modulation techniques in 40Gb/s modulation formats.

Modulation	Δv/Rb	Δv for Rb = 10 Gb/s
2 DPSK	3.0×10^{-3}	30 MHz
4 DPSK	5.0×10^{-4}	5 MHz
2 PSK	8.0×10^{-4}	8 MHz
4 PSK	2.5×10^{-5}	250 KHz
8 PSK	1.5×10^{-6}	15 KHz
16PSK	2.4×10^{-7}	24 KHz
8 QAM	9.0×10^{-6}	90 KHz
16 QAM	6.9×10^{-3}	69 KHz

Tale 10: Comparative analysis of the Laser linewidths required to implement various modulation techniques by assuming a 0.5 dB penalty.

Modulation	Code rate	Symbol rate (GHz)	Energy DD-00K	Gain (dB) Vs DBPSK
DD-00K	15/16	42.7	---	-2.46
D-BPSK	15/16	42.7	2.46	---
D-QPSK	15/32	42.7	4.43	1.97
	1/2	40.0	4.37	1.91
	2/3	30.0	3.83	1.37
	3/4	26.7	3.40	0.94
	7/8	22.9	2.41	-0.05
	15/16	21.3	1.52	-0.94

Table-11: Performance analysis of bandwidth of DQPSK over DD-OOK and DPSK suggest that DQPSK can improve the reach and efficiency.

Sl.No.	Modulation formats	Points	Symbols	Information capacity	Derived form	BW efficiency
01	BASK	01	01	Poor	ASK	Poor
02	BFSK	01	01	Better than BASK	FSK	Not efficient
03	BPSK	02	02	2 BFSK	PSK	Only for high speed data transfer
04	DPSK	01	02	2BFSK	PSK	Only for medium speed communication
05	QPSK	04	04	2BFSK	PSK	High
06	MSK	04	04	2BFSK	OQPSK	Lower than QPSK
07	QAM	02	04	Better than BASK	ASK & PSK	Less than other techniques
08	16 QAM	04	04	Better than QAM	ASK & PSK	Less than other techniques
09	64 QAM	06	04	Better than QAM	ASK & PSK	Less than other techniques
10	GMSK	04	04	Same as QAM	FSK	Excellent

Table 12: Parametric comparison of optical fiber digital modulation formats for 40Gb/s

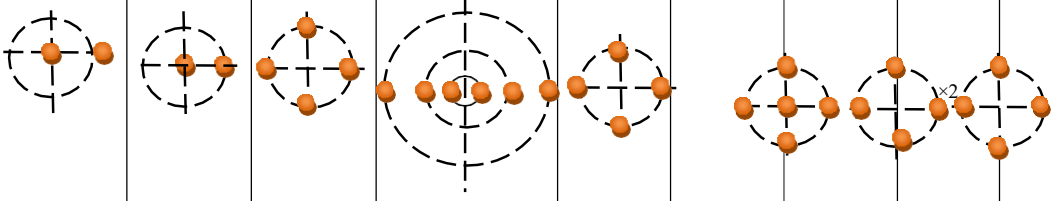
Modulation formats	OOK	OOK-VSB	DQPSK	RZ-DPSK-3ASK	PM-DQPSK	OP-FDM-RZ-DQPSK	PM-QPSK	PM_OFDM_QPSK
Bits/symbol	1	1	2	2.5	2×2	2×2	2×2	2×2×2
Spectral efficiency	0.5	1	1	2	2	1	2	2
Estimated reach(Km)	< 500	< 500	1000	< 500	600	1500	1500	2000
Compatibility with 10G & 40G	Positive	positive	positive	positive	positive	positive	positive	negative
Application area	Short reach	Short reach	metro	metro	metro	Long haul	Long haul OIF	Long haul
Constellation								
Symbol rate	112	112	56	44	28	28	28	14
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
Green field	------	------	------	-------	------	-------	Yes	Yes
OSNR tolerance(dB) @BER4×10^{-3}	17.5	18.5	15.5	>20	15.5	15.5	<15	<15
CD tolerance(ps/nm)@ 2dB penalty	±5	±5	±20	±30	±90	±90	>>	>>
Max. DGD tolerance(ps) @ 2 dB penalty	4	4	9	10	18	18	>>	>>
Power consumption	Positive	Positive	positive	Negative	positive	Negative	positive	Negative
Practical issues	E&E/O Components CD and adapt. PMD copmensation	E&E/O Components CD & adapt PMD compensation	CD & adaptive PMD-comp at old fibers	CD & adaptive PMD-comp at old fibers	Opt. polarization demux,CD & adaptive PMD comp at old fibers	2×50G	None superior solution	2×50G interfaces
Effectiveness of cost	-----	------	For metro	-------	--------	--------	For long haul	--------

Table13: Vital features of 100 Gb/s digital modulation formats.

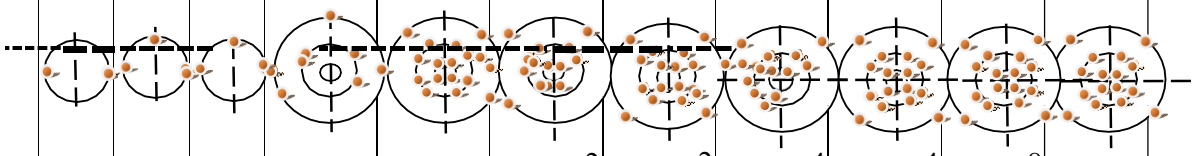
Modulation format	PM-BPSK	PM-QPSK	PM-QPSK	PM-8QAM	PM-16QAM	PM-16QAM	PM-32QAM	PM-32QAM	PM-64QAM	PM-64QAM	PM-256QAM
Bit rate(Gb/s)	100	100	400	400	200	400	400	1000	400	1000	400
Bits/Symbol	2×1	2×2	2×2	2×3	2×4	2×4	2×5	2×5	2×6	2×6	2×8
Constellation							×2	×2	×4	×4	×8
Symbol rate(Gbd)	28-32	28-32	112-128	75-85	28-32	56-64	45-51	112-128	37-43	93-107	28-32
OSNR(dB)@minimum Baud rate	10.8	12.2	18.2	20.2	19.2	22.2	24.2	28.2	26.7	30.7	>30
OSNR(dB)@maximum Baud rate	8.2	9.8	15.8	17.8	16.8	19.8	21.8	25.8	24.3	28.3	>30
Channel Spacing	50	50	200	133	50	100	80	200	67	166	50
No. of C-band channels	44	88	22	33	44	44	55	22	66	26	88
Penalty Vs. 100G(dB)	00	00	06	08	07	10	12	16	14.5	18.5	>20
Total capacity (Tb/s)	8.8	8.8	8.8	13.3	17.6	17.6	22	22	26.4	26	35

Table14: Comparative overview of different modulation formats for 100Gb/s, 200Gb/s, 400Gb/s and 1000Gb/s by taking reference to theoretical 40Gb/s values.

5. COMPARISON

Table 1-14 examines several optical analog and digital modulation schemes with various parameters. Table 1 presents an initial comparison of various optical source wavelengths in the um range from the first generation to the most recent generation, where the bit rate is much higher than that of earlier generations. Table 3 summarizes the optical losses per kilometer range of several optical fiber types in the analog modulation format. In Table 4, we examine several optical fiber properties such as attenuation, CD, self phase and cross modulation, and stimulated Raman scattering. Table 5 summarizes the dispersion at 1550 nm of several fiber types, including G.652, G.653, G.655A-C, and G.656. Table 6 shows the bit rates per channel (2.5Gb/s, 10Gb/s, 40Gb/s, etc.) and compares the return loss with the PMD delay limit in ps. It demonstrates that the return loss is particularly the same for < 40Gb/s. 256 (optical carrier) optical interfaces are specified under SONET, and Table 2 shows a comparison of their line rates.

A comparative summary of filter tolerance for 50 GHz channel spacing with PMD tolerance without compensation is shown in Table 7. The nominal range EDFA of the RZ-ADPSK and NRZ-ADPSK is 2200 and 1600, respectively. Table 8 summarizes the number of delay interoferometers and photodetectors utilized for various optical modulation forms, such as RZ-DPSK, NRZ-DPSK, RZ-DQPSK, and NRZ-DQPSK (i.e., phase shift keying modulation formats). Table 8 examines the modulated bandwidth of several BPSK algorithms. Table 8,9 shows the OSNR and error performance of several PSK formats at 40Gb/s. Table 9 compares the demodulation performances of the QAM, 16QAM, and 64QAM modulation schemes. Table 10 shows the laser line lengths needed to apply several optical digital modulation algorithms with a 0.5 dB penalty and 10Gb/s. Differential quadrature PSK's bandwidth savings over DD-OOK and DPSK in Table 11 indicate that DQPSK may increase the effectiveness of the various optical digital modulation schemes. When compared to other optical digital modulation methods with superior bandwidth efficiency, the GMSK error performance encourages ISI at larger data rate transmission Table 9,12. For PM-QAM modulation formats, a variety of constellations may be used, such as circular QAM symbol constellations or quadratic constellations with various diameters, as shown in Tables 13 and 14 [27]. Table 13 compares the various symbol rates of various modulation schemes with their predicted reach, spectral efficiency, and area of application. A comparative overview of single channel M-QAM alternatives, such as PM-16QAM of 200Gb/s, PM-8QAM of 400Gb/s, PM-32QAM of 1000Gb/s, PM-64QAM of 1000Gb/s, and PM-256QAM of 1000Gb/s, is shown in Table 14, which takes polarization multiplexing for all possibilities.

6. CONCLUSION

This article's comparative examination of the analog and digital optical modulation formats concludes that the digital modulation format is extremely appropriate for good applications. The system designer must think about better modulation techniques like MSK, GMSK, and PM-QPSK, where PM-QPSK has demonstrated its superiority over the other two in the field of fiber optic communication, since BASK, BFSK, BPSK, DPSK, and DQPSK do not fall under the region of consideration at 40Gb/s. A multisource agreement and an OIF framework have specified the 100Gb/s modulation format.

The symbol rate up to 32Gbaud is a highly reused current electrical approach in the next s ophisticated technology of 400Gb/s. Optical

ROADM technologies are compatible with a symbol rate of 32 Gbps. Therefore, whether or not future 400Gb/s and 1Tb/s bit rates support the ITU-T grid is up for debate. However, the solution to this problem has higher symbol rates than those now in use. The aforementioned issue may be resolved with a spectral efficiency of 4 if two carriers with 200Gb/s PM-16QAM modulated with 32Gbaud are used. However, a superior solution to the aforementioned issue is single carrier PM-MQAM.

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