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Invited Papers

Modulation formats for 100G and beyond

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This paper reviews technological options for the modulation formats for serial optical transmission of 100 Gb/s and beyond.

In the first part an overview on various modulation formats for 100 Gbit/s is presented, covering classical binary electronic time division multiplexed 100 Gbit/s NRZ systems, operating a highest speed, and mature product solutions of system vendors running at lower symbol rates which are using quaternary phase shift keying and polarization division multiplexing, coherent technologies and digital signal processing in the receiver.

The second part is focusing on the next generation of transmission systems carrying data at channel bitrates higher than 100 Gbit/s, e.g. 400 Gbit/s up to 1 Tbit/s or even beyond, which may apply higher constellation M-QAM modulation of a single carrier or multiple electrical subcarriers and optical superchannels which also form one WDM channel.

At both parts, for 100 Gbit/s and higher bitrates, the paper provides a performance comparison together with the main characteristics of the modulation formats and indicates appropriate application areas of transport technologies for future networks.

1. Introduction

The perpetual demand for increasing the bandwidth of optical carrier networks leads to the advent of new transmission hierarchies beyond the current installed basis which are mainly consist of 2.5, 10 and 40 Gb/s wavelength channels. In research and development there is a big pressure to investigate new transport technologies and to develop and design the next generation of optical systems carrying data on one channel of 100 Gb/s for the today's need and 400 Gb/s or even more for future networks.

The 100 Gb/s is the first optical transport bitrate hierarchy where IEEE Ethernet and the ITU-T optical transport network (OTN) standardisation bodies agreed to meet with standards for client and line side interfaces, respectively. The client side 100 Gb/s Ethernet (GbE) interfaces have been published by the IEEE standard 802.3ba [1] in 2010 for 10 km and 40 km reach, using four channels with 25 Gb/s. The line side bitrate of about 112 Gb/s (OTU4 bitrate) and the OTN multiplex with the client data and standard Reed Solomon FEC has been defined by ITU-T standard G.709 [2], published in 2009. In addition, a new direction was given in order to focus work on a reduction of the energy consumption of our network to reduce significantly the carbon footprint of ICT, which exhibits a dramatic annual increase mainly due to tremendous growth of Internet traffic.

Commercial deployments of 100 Gb/s systems in the optical networks of several service providers are in progress since 2010. Optical systems with bitrates beyond 100 Gb/s are currently investigated in research and the kick-off for the standardisation activities for 400 Gb/s Ethernet and even 1 Tbit/s Ethernet are expected soon.

Parallel 100 Gb/s transmission with 10×10 Gb/s or with 4×25 Gb/s [1] is currently the widely predominant technique for short reach client side applications and optical interconnects where usually no high spectral efficiency is needed and cost efficiency is the main target. For metro networks as well as for the core network where a high transmission capacity is required serial transmission of a large number of DWDM channels at narrow channel spacing is a key requirement.

This article reviews the technological options for the modulation formats for serial transmission of 100 Gb/s and beyond.

In the first part we put the focus on 100 Gb/s systems and give an overview on the modulation formats starting from time-division multiplexed (ETDM) binary 100-Gb/s systems operating a highest speed of electronics and opto-electronics components and end up with advanced systems running at lower symbol rate which use quaternary phase shift keying and polarization multiplexing in the transmitter, coherent technologies and digital signal processing in the receiver.

The second section is focussing on the next generation of transmission systems beyond 100 Gb/s which will apply higher constellation M-QAM modulation formats on a single carrier or

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multiple electrical subcarriers and optical superchannels which also form one DWDM channel.

The final section summarizes and makes suggestions for appropriate transport technologies in future networks.

2. Modulation formats for 100 Gb/s systems

Table 1 depicts various options of 100 Gb/s modulation formats, been of research interest and/or have been already deployed, by their main properties in terms of reception (coherent or non-coherent), bits per symbol, symbol rate, constellations (with or without polarization multiplexing) and signal channel arrangements within the DWDM grid and finally the related spectral efficiency. Obviously with the reduction of the symbol rate, the modulation format realization becomes more and more complex. The main advantages of choosing low symbol rates are (a) using lower speed mature components with lower power consumption and lower cost and (b) fitting into the 50 GHz channel grid.

Note, that polarization division multiplexing (PDM) with two orthogonal polarizations have been widely differently denoted, by either PDM, or polarization multiplexing (PM), or dual polarization (DP) or othogonal polarization (OP). In the following, we depict the realization and transmission experiments of the modulation formats summarized in Table 1.

2.1. The 100 Gbaud binary amplitude modulation

The classical approach for the transmission of data over fiber-optic link has been the use on–off-keying (OOK) by binary intensity modulation of the output of transmitters with zeros and ones. For channel rates higher than 10 Gb/s the continuous light of a DFB-laser is modulated utilizing external Mach–Zehnder modulators (MZM) or electro-absorption modulators (EAM). In the receiver the data signal is detected by a high-speed photodiode and processed utilizing high-speed digital electronics. A scheme of the set-up of a modulator based OOK system is shown in Fig. 1.

For the realization of 100 Gb/s OOK systems the performance of high-speed electronic and opto-electronic components and as well as integration and packaging technologies have to be pushed to current technology limits. To obtain binary 100 Gb signal data, signal electronic 2:1 multiplexer are realized with InP technology [3,4] or SiGe technology [5].

Various technologies are available to realize of Mach–Zehnder modulators at 1.55 μm wavelength. The prevalent modulator technology is based on Mach–Zehnder structures on Lithium-Niobate which are large in size to keep the modulation voltages low but

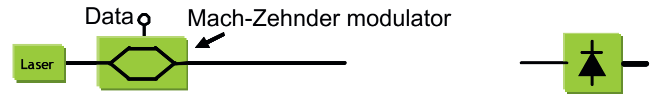


Fig. 1. Schematic setup of the opto-electronic components of a typical OOK transmitter (left) and receiver (right side).

benefit from the travelling wave principle to achieve a high modulation bandwidth of up to 45–50 GHz. EA-modulators on the other hand are more compact in size and enable the monolithic integration with the DFB-laser [6,7] using standard semiconductor process technology.

On the receiver side a high speed photodiode is applied for direct detection of the 100 Gb/s optical data. Photodiodes for 100 Gb/s OOK-receiver based on InP technologies are commercially available with the required bandwidth of >60 GHz. At the output of the photo-diode electronic processing is performed. Fast decision-flip-flops realized with SiGe [5] for electronic demultiplexing or InP-based demultiplexer [8] are utilized for 1:2 demultiplexing together and with hybrid clock extraction circuits [5,9]. First integration steps of a 100 Gb/s photodiode and an electronic 1:2 demultiplexer have been achieved [10]. Recently integrated 100 Gb/s-ETDM receivers including clock recovery and electronic demultiplexing have been reported [11–13]. A complete ETDM system based on monolithically integrated transmitter and receiver modules have been reported in [14].

The 100 bit/s systems based on OOK [5,15–18] as well as Duo-Binary Format [19,20] have been widely investigated by different research teams. Due to limitations of the modulation bandwidth of driver amplifier and MZ-modulator at 100 Gb/s OOK the optical eye diagram is only partly open and optical equalizers are applied to improve the signal quality at the transmitter output [21,22] or at the receiver input.

Among the 100 Gb/s transmission formats binary OOK signals exhibit the shortest bit period and use the largest optical bandwidth. The used optical bandwidth of OOK systems is about twice the symbol rate and thus the bitrate. For Nx100 Gb/s DWDM application a channel spacing on the ITU-T channel grid of 200 GHz is possible [18]. Minimum channel spacing of 144 GHz has also been demonstrated for a 10×107 Gb/s DWDM transmission experiment [21]. A narrower channel allocation can be achieved by optical filtering of the 100 Gb/s output signal by steep optical filters to achieve an optical vestigial side band signal (VSB). VSB filtering can either be realized by using tunable planar equalizer on the channel basis [23], or periodic structures like optical interleaver which exhibit steep filtering characteristics and filter all DWDM channels

Table 1
Main features of 100 Gb/s modulation formats.

Modulation format	OOK	OOK-VSB	DQPSK	RZ-DPSK-3ASK	PM-DQPSK	OP-FDM-RZ-DQPSK	PM-QPSK	PM-OFDM-QPSK
coh. / noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	coh.	coh.
Bits/symbol	1	1	2	2.5	2x2	2x2	2x2	2x2x2
Symbol Rate (Gbd)	112	112	56	44	28	28	28	14
Constellation								x2
DWDM Grid (GHz)	200	100	100	50	50	100	50	50
Spectral Efficiency (bits/s/Hz)	0.5	1	1	2	2	1	2	2

simultaneously [24]. VSB-filtering of 100 Gb/s OOK signals enables a 100 GHz channel spacing and improves signal quality by acting as optical equalizer for all DWDM channels simultaneously, due to its high-pass characteristics counteracting bandwidth limitations of the transmitter.

At a given bitrate OOK systems are in general most sensitive towards signal distortions at fiber transmission like chromatic dispersion (CD) and polarization mode dispersion (PMD). Compared to 10 Gb/s OOK systems the tolerance of 100 Gb/s for chromatic dispersion mismatch is 100 times lower and for PMD 10 times lower. (see Ref. [25]), Thus, without compensation, the CD and PMD tolerances for 100 Gb/s OOK are below 10 ps/nm and only about 1 ps, respectively.

However, various single channel and DWDM transmission experiments using 100 Gb/s OOK or 100 Gb/s PSBT format have been reported in the literature. OOK transmission has been performed over lab fibers with a typical transmission reach between 400 km up to 1000 km [26–28].

The 107 Gb/s OOK-VSB transmission has been performed over lab fibers [29–31] as well as over field fiber infrastructure [23,32,33] including CD and PMD compensation.

2.2. The 100 Gb/s system technology using multi-level modulation formats

In order to relax the high speed bandwidth requirements of the electronic circuits and opto-electronic components multi-level coding (e.g. DQPSK) is utilized. Multi-level formats coding of several bits in one symbol enable a reduction of the symbol rate of the system on the expense of an increased transmitter and receiver complexity. On the other hand multi-level coding reduces the optical bandwidth consumption of the channel and enables WDM transmission with a narrower DWDM channel spacing. In this chapter we are focussing on multi-leveling modulation formats which have been applied for field trials together with system suppliers and have been already developed and deployed.

2.3. (RZ-) DQPSK format and direct detection

Quaternary phase shift keying (QPSK) doubles the line rate compared to OOK by coding two bits in one symbol, applying 50 Gbaud to obtain 100 Gb/s. The output signal of the transmitter has mainly constant optical power and the information is carried in the four phase states of the optical phase of the emitted light. QPSK modulation can be obtained by using a single embedded MZ-I/Q-modulator which is driven by two binary electrical modulation signals at the in-phase and quadrature-phase modulators (see Fig. 2).

Alternatively DQPSK signals can be achieved by using a cascade of two phase modulators for the modulation of the optical phase by 0..pi/2 and by 0..pi/4 applying binary modulation signals or a single phase modulator driven by an electrical 4-level modulation signal. These approaches are not efficient regarding size, cost and power consumption and the latter needed a high quality electrical 4-level modulation signal.

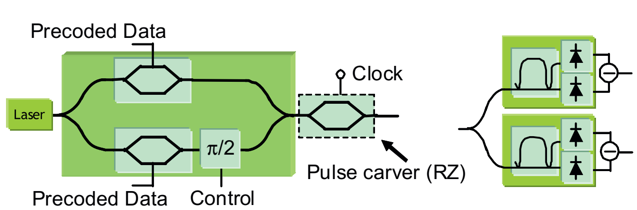


Fig. 2. Schematic setup of the opto-electronic components of a typical transmitter (at left side) for DQPSK format and the receiver with direct detection (at right side).

On the receiver side two optical delay-line interferometers (DLI) with 1 bit delay are applied to demodulate the in-phase and quadrature phase components, having a phase difference of $\pm\pi/2$. The differential optical output signals of the two demodulators are fed to differential photodiodes or differential photoreceivers which are applied for the detection of the phase changes of the QPSK signal. Classical electronic clock recovery, hard decision and electronic demultiplexing is performed by high speed circuits.

In order to retrieve the two initial data streams at the receiver there is a need for electronic pre-coding in the transmitter to generate appropriate I and Q modulation signals. Various concepts for DQPSK precoder can found in the literature.

The spectral width of 56 Gbaud DQPSK signal enables a channel spacing of 100 GHz for WDM application. Due to the reduced symbol rate of DQPSK compared to OOK larger system tolerances regarding chromatic dispersion and PMD are observed [33]. In Table 2 we are summarizing the comparison of system tolerances of 100 Gb/s modulation formats.

The 100 Gb/s transmission using DQPSK modulation format has widely been demonstrated over either lab or field fibers at 100 Gb/s [34–36], with FEC overhead at 107 Gb/s [37–41] and at 111 Gb/s [42] and at 112 Gb/s OTU4 channel bitrate [43,44]. For real-time transmission demonstration at 53.7 Gbaud DQPSK a precoder has been implemented in FPGA [45–47] and applied in a field trial transmitting HDTV live video over installed fiber link carrying live traffic of 10 Gb/s channels [48,49].

2.4. RZ-DPSK-3ASK modulation format and direct detection

This approach is a combination of mixed ASK-modulation and phase modulation. The idea of this approach is to benefit from the commercial availability of mature components for 40 Gb/s systems. The 2.5 bits are coded in one symbol which leads to a symbol rate of 43 Gbauds [50–53] for support of the OTU4 line rate [2] of 112 Gb/s. The transmitter as depicted in the left part of Fig. 3 consists mainly of three optical modulators. The first MZM generates a three level amplitude modulated signal, the second MZM applies additionally phase modulation, yielding a DPSK-3ASK modulation format. Finally RZ-carving is applied to counteract for intersymbol interferences. The constellation of this modulation format has been shown in Table 1.

In the receiver the optical signal is splitted and distributed to a DPSK receiver with DLI-based demodulator and an ASK receiver.

Due to limited extinction ratios of the ASK modulated levels, the OSNR tolerance of the RZ-DPSK-3ASK modulation formats is also limited, finally strongly limiting the transmission reach [54,55].

2.5. PM-DQPSK (DP-DQPSK) with polarization demux and direct detection

A further reduction of the symbol rate can be achieved by applying polarization division multiplexing (PM) which doubles the line rate or halves the symbol rate. This leads to 100 Gb/s polarization multiplexed DQPSK signals or dual polarization (DP) with a symbol rate of 28 Gbaud to support the OTU4 line rate. The key advantage of 28 Gbaud modulation formats is the support of 100G DWDM transmission with 50 GHz channel spacing.

At a PM-DQPSK transmitter a more complex modulator is needed consisting of two embedded MZ-I/Q-modulator which modulate each half of the laser light. The two DQPSK signals are combined orthogonally polarized using a polarization beam combiner. Compared to single polarization DQPSK two pre-coders are needed each operated at 28 Gbaud. For fiber transmission chromatic dispersion compensation is needed, even when dispersion tolerance is 4× larger compared to single polarization DQPSK format.

Table 2
System tolerances of 100 Gb/s modulation formats.

Modulation format	OOK	OOK-VSB	DQPSK	RZ-DPSK-3ASK	PM-DQPSK	OP-FDM-RZ-DQPSK	PM-QPSK	PM-OFDM-QPSK
coh. / noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	coh.	coh.
DWDM Grid (GHz)	200	100	100	50	50	100	50	50
Estimated Reach (km)	< 500	< 500	1000	<500	600	1500	1500	2000
Tolerances	−	−	+	−	+	+	++	++
OSNR tolerance (dB) @ BER $4x10^{-3}$	17.5	18.5	15.5	>20	15.5	15.5	< 15	< 15
CD tolerance (ps/nm) @ 2dB penalty	± 5	± 5	± 22	± 30	± 90	± 90	>>	>>
Max. DGD tolerance (ps) @ 2dB penalty	4	4	9	10	18	18	>>	>>
Compatibility with 10G and 40G	+	+	+	+	+	+	+	−
Filtering with ROADMs	−	−	+	+	+	+	+	−

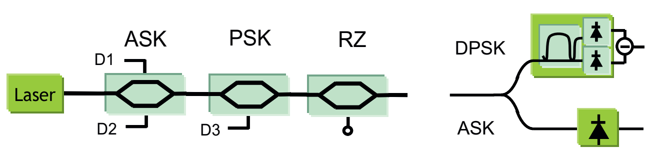


Fig. 3. Schematic setup of the opto-electronic components of a transmitter (at left side) and receiver (at right side) for DPSK-3ASK transmission format.

On the receiver side a polarization demultiplexer is applied to split the both orthogonal DQPSK data signals and feed them to integrated DLI-Photodiodes or integrated DLI-Photoreceiver with DLIs having a bit delay corresponding to 25–28 Gbaud (see Fig. 4).

For a stable operation and to avoid a large penalty, a fast automatic polarization demultiplexing has to be implemented for the adaption [56,57], by control of the polarization demultipexer dithering of the data of one or both polarization components. On the other hand low frequency beat noise, which is generated on a photodiode or a monitor diode by coherent crosstalk if polarization demultiplexing is not perfect can be applied as feedback signal for the control electronics [58,59]. Using DP-DQPSK format 100G transmission has been demonstrated over lab fiber [60,61] and over field fiber infrastructure recently [62].

2.6. OP-FDM-RZ-DQPSK and direct detection

To eliminate the fast automatic optical polarization demultiplexer, alternatively, the two polarizations can be used to carry two optical carriers. The two carriers can be multiplexed and demultiplexed with optical filters, as depicted in Fig. 5. The two frequency locked optical carriers (FDM), obtained by carrier suppressed RZ-carving, are splitted by an optical filter, modulated by DQPSK modulators and combined with orthogonal polarization (OP). At the receiver, the two carriers set on two orthogonal polarizations are demultiplexed by an optical filter. The carriers versus polarizations schematic is shown in Table 2. This modulation format is also based on 28 Gbaud and has been entitled as Orthogonal Polarization Frequency Division Multiplex RZ-DQPSK. But due to the separation of two optical carrier in two polarizations only 100 GHz channel spacing is supported.

2.7. PM-QPSK (DP-QPSK) and coherent detection

For the 100 Gb/s PM-QPSK transmission and coherent detection together with digital signal processing is widely been applied [63–65]. The electromechanical dimensioning of a line interface with the PM-QPSK transmitter together with the coherent receiver has been specified [66]. The principle of the PM-QPSK transmitter and receiver is shown in Fig. 6. In contrast to direct detection schemes no pre-coding in the transmitter is required because the optical phase is directly recovered by coherent mixing the received optical signal with a narrow linewidth local oscillator laser. In the receiver a dual polarization optical 90°-hybrid which splits the incoming 100G signal in orthogonal components and combines them with the light of the optical local oscillator on four different photodiodes or balanced photoreceivers. The four electrical output signal are converted by four high speed digital-to-analog converters into the electrical domain and processed by the DSP. Due to the reception of signal amplitude and phase by the coherent receiver, the polarization can be demultiplexed electronically and linear fiber distortions like the chromatic dispersion as well as the PMD can be compensated by digital signal processing [67–69].

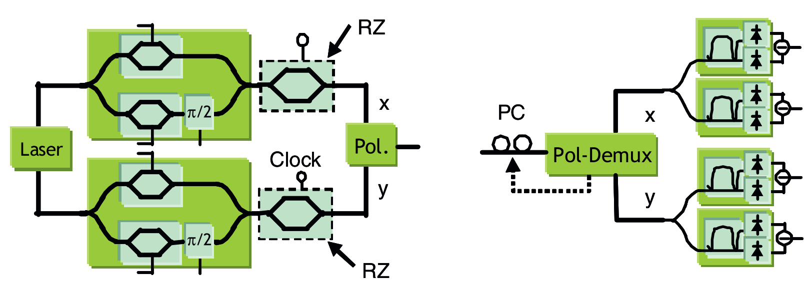


Fig. 4. Schematic setup of the opto-electronic components of a typical transmitter for PM-DQPSK format and the receiver with polarization demultiplex and direct detection.

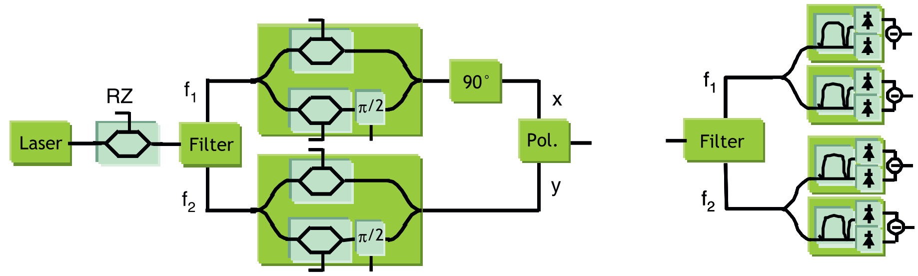


Fig. 5. Schematic setup of the opto-electronic components of a transmitter and a receiver for OP-FDM-DQPSK format.

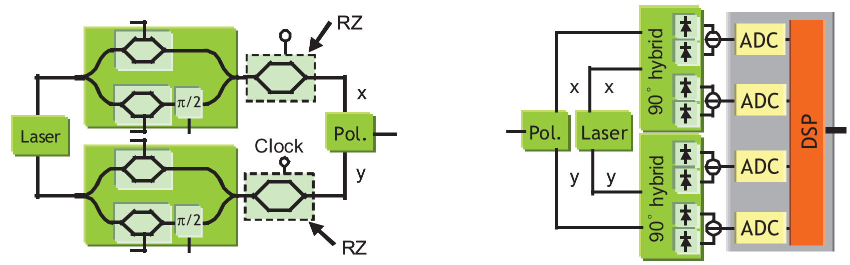


Fig. 6. Schematic setup of the opto-electronic components of a typical transmitter for PM-QPSK format and the intradyne receiver with coherent detection and DSP.

The 100G PM-QPSK transmission experiments running at a symbol rate of 25–28 Gbaud have mostly been demonstrated with off-line signal processing of the electrical signals which are measured by 4-channel high speed realtime oscilloscopes acting as fast A/D converters [70,71].

Various high capacity DWDM transmission experiments are reported at 50 GHz channel spacing [72–78] and with reduced channel spacing corresponding to the symbol rate [79] to further increase the spectral efficiency. PM-QPSK format with 56 GBaud has been reported for DWDM transmission at 224 Gb/s channel rate [80,81].

Realtime implementations using multiplex FPGA have been realized for field transmission trials [82,83] in 2010. However, since 2010, also first single channel 100 Gb/s transponder with PM-QPSK format according to the OIF implementation agreement [84] became commercially available utilizing an ASIC based coherent receiver.

2.8. PM-OFDM-QPSK (DP-OFDM-QPSK) and coherent detection

Another already commercially available 100 Gb/s transponder applies two narrow spaced (20 GHz) optical carriers each modulated with PM-QPSK format based on 14 Gbaud modulation [85]. This modulation format has been denoted as DP- or PM-OFDM-QPSK and requires the hardware of two 50 Gb/s PM-QPSK transmitters and receivers.

2.9. System tolerances of 100 Gb/s modulation formats

In Table 2 we are summarizing the system tolerances of the described 100 Gb/s modulation formats in terms of OSNR, CD, PMD (DGD), compatibility with 10 Gb and 40 Gb/s line rates and filtering with cascaded ROADMs. Without restrictions, the PM-QPSK modulation format appears as the best performing 100 Gb/s

Table 3
Overview on the main characteristic of the 100 Gb/s modulation formats.

Modulation format	OOK	OOK-VSB	DQPSK	RZ-DPSK-3ASK	PM-DQPSK	OP-FDM-RZ-DQPSK	PM-QPSK	PM-OFDM-QPSK
Coh. / Noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	noncoh.	coh.	coh.
DWDM Grid (GHz)	200	100	100	50	50	100	50	50
Application Area	Short Reach	Short Reach	Metro	Metro	Metro	Long haul	Long Haul OIF	Long haul
Product available	no	no	no	no	no	yes	yes	yes
Power consumption and footprint	+	+	+	−	+	−	+	−
Critical issues	E & E/O components CD & adapt. PMD compensation	E & E/O components CD & adapt. PMD compensation	CD & adaptive PMD-comp at old fibres	CD & adaptive PMD-comp at old fibres	Opt Pol-Demux, CD & adaptive PMD-comp at old fibres	2x 50G interfaces	none -------- superior solution	2 x 50G interfaces
Cost effective	-	-	for Metro	-	-	-	most cost-effective for long haul	-
Green field	-	-	-	-	-	-	yes	yes

modulation format solution. That is why OIF has chosen the 100 Gb/s PM-QPSK format and to develop a multi-source agreement for 100 Gb/s line-side interfaces supporting up to about 1500 km fiber transport.

2.10. Main characteristics of 100 Gb/s modulation formats

Table 3 summarizes the main characteristic of the presented 100 Gb/s modulation formats with respect to their application area, the product availability, the power consumption and footprint, related critical issues, their cost effectiveness and finally their suitability for green field application without dispersion compensation fibers. Table 3 also indicates the strong advantages of PM-QPSK (DP-QPSK) versus alternative solutions with and without coherent receivers, confirming that PM-QPSK can be considered as a premium solution.

3. Modulation formats for systems beyond 100 Gb/s

Transmission of optical signals beyond 100 Gb/s by increase of spectral efficiency are currently of high interest at research. The major focus is on multi-level modulation format based on M-QAM (quadrature-amplitude modulation) and coherent reception applied at single carrier as well as at multi-subcarrier modulations formats. The major target is to maximize their spectral efficiency. With respect to potential future 400 Gb/s and 1 Tb/s options, the need of a flexible grid has been raised [86] but without discussing the feasibility of these single carrier options. Thus, in this respect the need of a flexible grid appears not verified.

3.1. Single carrier modulation formats

To achieve bitrates beyond 100 Gb/s on a single carrier higher level modulation schemes have to be applied. Recently QAM scheme together with polarization multiplexing is utilized to achieve a channel rate of 200 Gb/s with 16 QAM. In an M-QAM or 2^m QAM signal, m bits are transmitted in a single time slot or symbol, where m is an integer value. Adding polarization multiplexing to make PM-2^m-QAM format, $2\times m$ bits are transmitted per symbol. A PM-M-QAM signals can be realized in principle by parallel arrangements of PM-QPSK modulators, where the modulators are driven with binary data signals, respectively. For example, two parallel PM-QPSK modulators are required to form a PM-16QAM modulator. A more compact and generic approach is based on the reuse of a PM-QPSK modulator, shown in Fig. 5, for the generation of all PM-M-QAM modulation formats, where the modulators are driven with electrical multilevel signals, as depicted below in Fig. 6.

Various constellations [87] can be applied for PM-QAM modulation format, e.g. circular QAM symbol constellations or quadratic constellation with different sizes as depicted in Table 4. With increasing the number of symbols the Euclidian distances between the symbols reduces significantly. Thus, unfortunately, the sensitivity to noise or the OSNR tolerance reduces correspondingly with increasing the number of symbols of a QAM constellation. Table 4 includes the theoretical OSNR penalty [88] values assuming the same bitrate at all formats. According to Shannon' theory increasing of the spectral efficiency (SE) must be paid by a higher SNR. Shannon's theory has been extended [89] to describe the capacity limits of optical fiber transport and networks including the classical fiber impairments of amplified spontaneous emission, chromatic dispersion and fiber nonlinearity based on the Kerr effect.

Optimizing the SE of signals with M-QAM constellations by Nyquist filtering towards Nyquist-WDM (N-WDM) [90] is currently of high research interest and has already been demonstrated at submarine transmission configurations [91] using RZ at PM-QPSK. At N-WDM, the channel spacing is equal with channel spacing ($f_N = 1$). At terrestrial (Metro) transmission configurations, RZ modulation has been omitted due to cost issues and N-WDM appears questionable in cost-effective terrestrial transmission configurations where transmission over multiple installed ROADMs is a key requirement.

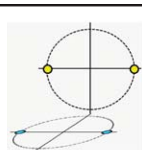
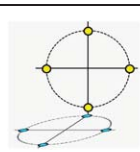
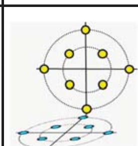
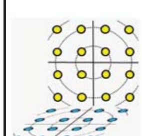
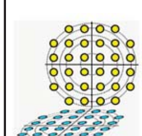
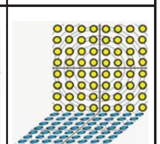
Thus, in this paper we are not considering N-WDM with a "Nyquist-Factor" of $f_N = 1$ but a more pessimistic value of $f_N = 1.56$ as reference for the SE data of single carrier formats beyond 100 Gb/s. By considering $f_N = 1.56$ (=50 GHz/32 Gbaud) we are treating all formats with the same spectral tolerances we are obtaining for 100 Gb/s PM-QPSK at 50 GHz channel spacing and with a maximal symbol rate of 32 Gbaud; addressing higher overhead (~20%) currently considered for soft decision based enhanced FEC [92]. With 32 Gbaud symbol rate the actual "100 Gb/s transmission bitrate" will be ~128 Gb/s instead of 112 Gb/s under symbol rate of 28 Gbaud.

3.2. M-QAM realizations and demonstrations

For example, for realization of 16QAM a 4-level electrical modulation signal is needed at each electrode. This can either be realized by passive combination of two electrical data signal with different amplitude or by using digital signal processing and D/A conversion (DAC), as shown in Fig. 7.

Polarization multiplexed 16QAM signals have been realized by multilevel generation using passive combination of binary signals to achieve 224 Gb/s channel rate (200G + FEC overhead) [93–95] and for 448 Gb/s channel rate [96]. Multilevel modulation to obtain PM-MQAM according to Fig. 7 with a DAC has been demonstrated with 4-level drive signal using a 6-bit DAC to generate 224 Gb/s PM-16QAM [97] and with 8-level drive signal using a DAC with only 3 bit resolution to generate a 257 Gb/s PM-64QAM signals [98].

Table 4
Comparison of modulation formats 100G and beyond; OSNR penalties related to same bitrates (PM-BPSK serves as reference).

Modulation format	PM-BPSK	PM-QPSK	PM-8QAM	PM-16QAM	PM-32QAM	PM-64QAM
bits/Symbol	2x1	2x2	2x3	2x4	2x5	2x6
Constellation						
OSNR penalty (dB)	0	0	2	4	6	8.5

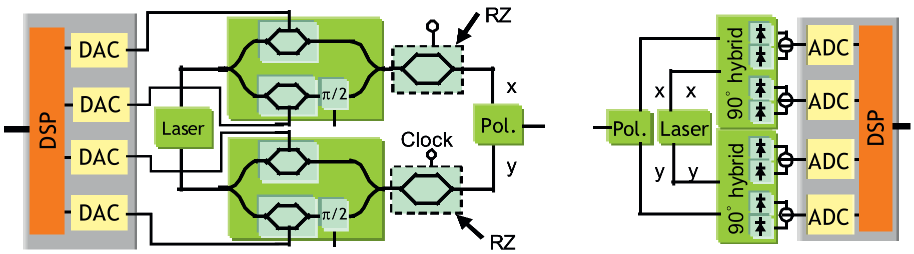


Fig. 7. Schematic setup of the opto-electronic components of a flexible transmitter for polarization multiplexed higher level modulation formats like N-PSK or M-QAM and the receiver with coherent detection.

Digital signal processing and D/A conversion in the transmitter is currently feasible up to symbol rates of 28–32 Gbaud. A realtime implementation using DSP and DAC increases the complexity of the transmitter but gives on the other hand a higher flexibility to compensate for nonlinear characteristics of the driver amplifier and modulator and change of modulation format [99]. Compared to DP-QPSK transmitter a laser with narrower linewidth and linear driver amplifiers are required for DP-n-QAM transmitters.

The setup of the coherent polarization multiplexed QAM receiver is similar to the 100G receiver but a higher resolution of the ADC is required for the detection the multiple level signals. Additionally the local oscillator laser requires a narrower linewidth.

Using polarization multiplexing and QAM modulation format various high capacity DWDM transmission experiments with high spectral efficiency have been performed. Channel rate of 240 Gb/s is achieved by 8PSK [100] and transmission over 320 km line is demonstrated.

Using DP-16QAM transmission lengths between 670 up to 1500 km have been demonstrated [93–95]. RF-assisted optical Dual-Carrier 112 Gb/s Polarization-Multiplexed 16-QAM is applied to achieve 112 Gb/s channel rate [101].

DP-64QAM format has been applied to achieve a 240 Gb/s channel with 12 bits/symbol [102]. QAM modulation is reported for lower bitrate channels of 100 Gb/s using 32QAM [103], 100 Gb/s using 35QAM [104], 112 Gb/s and 120 Gb/s using 64QAM [105,106], 56 Gb/s with a spectral efficiency of 11.8 bit/s/Hz using DP-256QAM [107], 54 Gb/s using DP-512QAM [108].

3.3. Overview on single carrier M-QAM options

Table 5 gives an overview on single channel M-QAM options for 200 Gb/s and 400 Gb/s including 1 Tb/s, using 100 Gb/s as reference and considering polarization multiplexing for all options. The applied minimum symbol rates, e.g. 28 Gbaud, are addressing line transport with 7% overhead by 2nd generation FEC (proprietary enhanced FEC solutions [109]). The maximum considered symbol rates are addressing higher overhead (∼20%) currently considered for soft decision based enhanced FEC [92].

As already explained above, the indicated channel spacing data in Table 5 might appear pessimistic compared versus other published data [91,86]. Under the circumstances of $f_N = 1.56$ (=50 GHz/32 Gbaud), the SE data of 400 Gb/s PM-256QAM would be limited to 8 bits/s/Hz and the total capacity over C-band would be about 35 Tb/s. However, if considering Nyquist filtering approaches [90] and high performance MLSI [91] our figure of M-QAM versus SE could change that 8 bit/s/Hz are possibly obtained with lower M-QAM options: PM-128QAM, PM-64QAM or even PM-32QAM.

Table 5
Overview on M-QAM options for 400 Gb/s and 1000 Gb/s using 100 Gb/s (PM-QPSK) and 200 Gb/s (PM-16QAM) as reference.

Modulation format	PM-QPSK	PM-16QAM	PM-QPSK	PM-8QAM	PM-16QAM	PM-32QAM	PM-64QAM	PM-256QAM	PM-32QAM	PM-64QAM
Bitrate (Gb/s)	100	200	400						1000	
Symbol Rate (Gbd)	28-32	28-32	112-128	75-85	56-64	45-51	37-43	28-32	112-128	93-107
Bits/Symbol	4	8	4	6	8	10	12	16	10	12
Channel Spacing[1] (GHz)	50	50	200	133	100	80	67	50	200	166
SE [1] (bits/s/Hz)	2	4	2	3	4	5	6	8	5	6
no. of C-band channels	88	44	22	33	44	55	66	88	22	26
Total Capacity (Tb/s)	8.8	17.6	8.8	13.3	17.6	22	26.4	35	22	26
ONSR[2] (dB) @ min Baudrate	12.2	19.2	18.2	20.2	22.2	24.2	26.7	> 30	28.2	30.7
ONSR[2] (dB) @ max Baudrate	9.8	16.8	15.8	17.8	19.8	21.8	24.3	> 30	25.8	28.3
Penalty vs. 100G (dB)	0	7	6	8	10	12	14.5	> 20	16	18.5
1) same margin to fitering as 100G (f_N=1.56)										
2) ref to theoretical 40 Gb/s values										

The two 1 Tb/s PM-M-QAM options are added only to indicate the need of very challenging high symbol rates, considering at Table 5 the same (pessimistic) spectral efficiencies values as above (f_N = 1.56) for the 400 Gb/s PM-MQAM options. Therefore, today only multi carrier solutions are suggested for 1 Tb/s transport.

The shown OSNR sensitivity values in Table 5 are given with respect to the minimum and maximum symbol rates, all referred to a theoretical OSNR value of 8.2 dB calculated for 40 Gb/s PM-QPSK [110]. The OSNR values at min. symbol rate are related with a minimum *Q* factor = 8.5 dB (max BER of 3.8e−3, obtained with the best proprietary enhanced FEC solution [109]). The OSNR values at max. symbol rate are related with a minimum Q factor = 6.4 dB (max BER of 1.8e−2 [92]), supported with soft decision FEC. Considering the higher bandwidth and achievement of about 3 dB of extra FEC gain [92], the net OSNR gain for the higher baudrate would be about 2.4 dB.

The OSNR penalty values are referred to 100 Gb/s. The OSNR penalty, e.g. for PM-64QAM at 400 Gb/s reaches already 14.5 dB, which means the high constellation 400 Gb/s M-QAM carriers need to be regenerated sooner than 100 Gb/s QPSK carriers.

The main limiting factors for high symbol rates are the DAC and ADCs. If we are looking at realistic symbol rates of likely 43 Gbaud in near future, 400 Gb/s single carrier with PM 64QAM might be a feasible option. However, simple upgrade and even co-propagation of this 400 Gb/s option with 100 Gb/s or 40 Gb/s appears challenging due to the different OSNR requirements. As state above, the indicated 67 GHz channel spacing might appear pessimistic and 50 GHz channel spacing could be feasible but on the cost of significantly lower filtering tolerances, than obtained with 28–32 Gbaud approaches.

3.4. Multi carrier modulation formats – optical OFDM transmission

In contrast to single carrier transmission formats various options had been proposed splitting the transmitted data onto multiple electrical and also optical subcarriers. Only in cases where the frequency spacing of these subcarriers is equal with the symbol rate and the subcarriers are aligned orthogonally, the format can be denoted as optical OFDM. O-OFDM as multi-carrier formats is an attractive approach to support high bandwidth channels [111]. The transmitter and the receiver of O-OFDM systems have a similar setup as QAM-based systems. DSP is applied in the transmitter to form the Inverse Fast Fourier transformation (IFFT) as well as in the coherent receiver to form the FFT. By an appropriate modulation signal a multi-carrier O-OFDM signal is achieved by a single embedded MZ-I/Q-modulator or PM-QPSK modulator as polarization multiplexing becomes state of the art also together with O-OFDM.

O-OFDM may use a high number of low symbol rate modulated electrical subcarriers (a few Mbaud) each modulated by a higher constellation M-QAM modulation format in combination with the modulation of a certain number of frequency locked optical channels, also denoted as "superchannels". The no. of bits/symbol of the OFDM channel finally is determined by the number of electrical subcarriers plus the number of optical superchannels. Due to the almost rectangular shape of O-OFDM signals high-capacity transmission can be performed by close allocation of multiple OFDM signals in the frequency domain without guard bands.

Various transmission experiments using polarization multiplexed O-OFDM and PM-O-OFDM have been reported [112–118], transporting Tb/s superchannels channels over submarine distances [118]. Recently field transmission trials over installed standard SMF applying PM-OFDM format in co-propagation with 112G DQPSK channels are reported using 253 Gb/s OFDM superchannels with subcarriers carrying QPSK signals and 400 Gb/s superchannel carrying 8QAM signals [119] over 768 km and Terabit/s superchannels over 454 km [120] and 3560 km [121].

4. Conclusions

At 100 Gb/s line transport the dominant advantages of the PM-QPSK (DP-QPSK) modulation format together with the coherent receiver have been widely recognized as the best and most cost-effective solution for Metro and long haul transport. Thus, this 100 Gb/s modulation format and the transponder realization has been defined by an OIF framework and multi-source agreement.

For the next hierarchy of 400 Gb/s line transport there is a high desire to reuse current electronic technologies supporting symbol rates up to 32 Gbaud, but also to be compatible with optical ROADM technologies supporting a fixed grid of 50 GHz. The need of flexible grid requirements have been argued as future 400 Gb/s and 1 Tb/s bitrates will not fit into the fixed ITU-T grid, but this argument has been based on format solutions with challenging symbol rates being twice or four times higher than currently feasible.

The currently most promising solution for 400 Gb/s line transport is based on two carriers with 200 Gb/s PM-16QAM modulated with symbol rate of 32 GBaud, supporting a spectral efficiency of 4. With this solution, the OSNR gap versus 100 Gb/s PM-QPSK can be limited to about 4 dB. If a single carrier PM-MQAM solution will become feasible, this will depend on progress on DAC and ADC speed, Nyquist filtering techniques and implementation of high performance MLSI.

Towards 1 Tb/s line transport, an O-OFDM based solution with multiple optical super-channels with or without additional electrical subcarriers appears promising as single carrier options requires unrealistic high symbol rates that might technologically not feasible within the next 10 years, and/or high M-QAM constellation sizes, that OEO regeneration might be required after few fiber spans due to OSNR constraints.

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