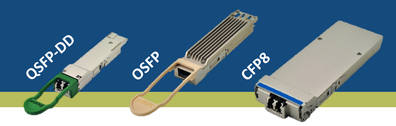
400G PAM4 High-Speed Client-Side Interface

OSFP & QSFP-DD Optical Transceiver Technologies

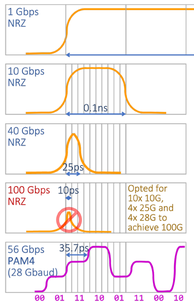
VeEX The Verification Experts



PAM4 Modulation vs. Legacy NRZ-OOK

The Need for Modulation

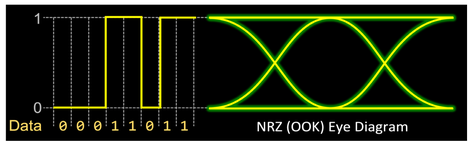
PAM4 modulation is used in the electrical and optical interfaces to improve total bus bandwidth.

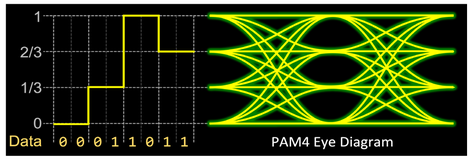


As bit rates grow faster, the physical bits get smaller, carry less energy and face the switching and detection limits of electronics and optics, creating reach and error challenges for simple OOK techniques, such as NRZ.

Although there is a 40 Gbps version of NRZ, 28 Gbps is now considered a safe limit for reliable electrical and optical transmission. Multiple electrical and optical lanes are used to increase transceivers' data rates to 100 Gbps (either multi-fiber or single-fiber WDM).

To break the 200 and 400 Gbps barrier an amplitude modulation scheme was introduced, PAM4, reducing the 56 Gbps lane rate to 28 Gbaud.





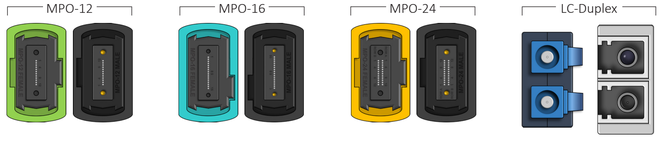
GRAY CODING

Also known as Reflected Binary Code (RBC), the Gray coding reorders the symbols so that any two successive values differ by only one bit, to reduce bit errors and facilitate error correction.

Data Symbol	Gray Code
00	00
01	01
10	11
11	10

Optical Connectors & Cables

Common Fiber Optics Connectors (as of 2020)



Newly Approved Duplex and Quadruplex Fiber Optics Connectors (2019)

Standard Fiber Optics Cable Color Code (Based on TIA-492/598C)*

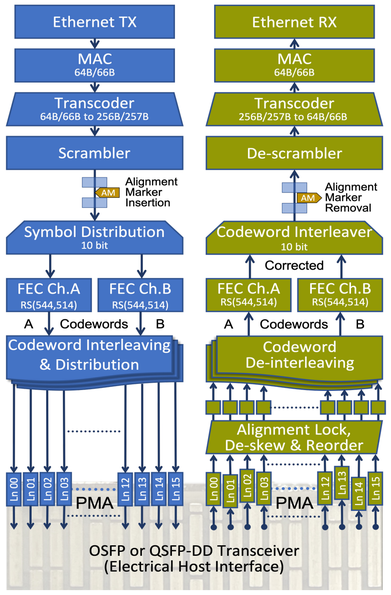
Type	Mode	Core/Cladding	Jacket	Connector	Comment
OM1	MMF	62.5/125 µm	Orange	Beige	LED multi-modal applications
OM2	MMF	50/125 µm	Orange	Black	LED multi-modal applications
OM3	MMF	50/125 µm	Aqua	Aqua	850 nm VCSEL optimized
OM4	MMF	50/125 µm	Aqua	Aqua	850 nm VCSEL optimized
OM4+	MMF	50/125 µm	Violet	Violet	850 nm VCSEL optimized
OM5	MMF	50/125 µm	Lime Green	Lime Green	953 nm VCSEL optimized
OS1, OS2	SMF	9/125 µm	Yellow	Blue	Green connector for APC

Actual commercial colors may vary

400G KP4 Forward Error Correction (FEC)

Pre & Post FEC Errors

High speed Ethernet interfaces are inherently prone to errors, as they push the limits of electronics, optics and physical mediums. They all require error correction to be able to deliver error-free payloads end-to-end. KP4-FEC can correct up to 15 symbol errors within a codeword (correctable errors). If there are >15 errors within a codeword, then the user data (payload) is affected (uncorrectable or pos-FEC errors). Since pre-FEC errors will occur, link quality and performance testing focuses on lower symbol error distribution (symbol errors per codeword statistics) and on any post-FEC errors that affect the payload.



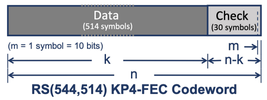
This PCS/FEC flow diagram shows how the 400GBASE-R host data is encoded and decoded through the FEC/PCS sub-layers.

KP4 FEC is defined in IEEE 802.3bs. It can fully correct up to 15 errored symbols in the data within the codeword, which would not affect the payload. If the error count is >15, the data becomes uncorrectable and will affect the (Ethernet) payload.

Reed-Solomon FEC Notation

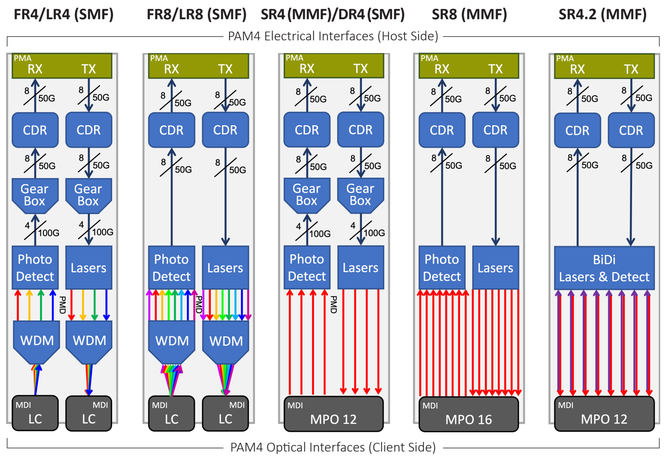
FEC notation is **RS(n,k,t,m)**, which for KP4 is RS(544,514,15,10), but it is often written as RS(544,514) or simply RS(544).

- **n** FEC Codeword (544 symbols)
- **k** Data (514 symbols)
- **r** Added checksum (n-k = 30 symbols)
- **t** Correctable errors per codeword
- **m** Number of bits per symbol (10)



That is, a KP4 FEC codeword contains 5440 bits (5140 data + 300 checksum).

The (Simplified) Anatomy of 400G Transceivers



400G Interfaces

IEEE® 802.3bs 400GBASE-R

The 400G Ethernet interfaces (PHY or PMD) naming Structure follow an industry standard notation, but new MSA variants continue to be defined. Recommended pull-tab colors may vary.

PMD	Optic. Interface	Mode/mn	TX+RX	Connector	Reach Typ.	Tab OSFP/QSFP
SR16	16x 25G NRZ	MMF/850	32 (1λ)	MPO-32	100 m	/
SR8	8x 50G PAM4	MMF/850	16 (1λ)	MPO-16	100 m	/
FR8	8x 50G PAM4	SMF/1310	2 (8λ)	LC duplex	2 km	/
LR8	8x 50G PAM4	SMF/1310	2 (8λ)	LC duplex	10 km	/
SR4	4x 100G PAM4	SMF/850	8 (1λ)	MPO-12	100 m	/
DR4	4x 100G PAM4	SMF/1310	8 (1λ)	MPO-12	500 m	/
FR4	4x 100G PAM4	SMF/1310	2 (4λ)	LC duplex	2 km	/
LR4	4x 100G PAM4	SMF/1310	2 (4λ)	LC duplex	10 km	/

IEEE® 802.3cm/cn/ct

PMD	Optic. Interface	Mode/nm	TX+RX	Connector	Reach	Tab OSFP/QSFP
SR4.2	8x 50G PAM4	MMF/850/910	8 BiDi (2λ)	MPO-12	100 m	/
ER8	4x 100G PAM4	SMF/1310	2 (8λ)	LC duplex	40 km	/
ZR8*	4x 100G PAM4	SMF/1550	2 (1λ)	LC duplex	80 km	/

**Currently IEEE 400GBASE-ZR is not necessarily the same as OIF's 400ZR or 400ZR+*

Other Interfaces (MSAs)

Uses compatible PAM4 electrical bus. Created to lower cost, complexity and power requirements.

PMD	Optic. Interface	Mode/nm	TX+RX	Connector	Reach	Tab OSFP/QSFP
CWDM8	8x 50G NRZ	SMF	2 (8λ)	LC duplex	2-10 km	/

Passive & Active Direct Attach Cables

Used in local intra-connect (at switch and rack levels).

PMD	Optic. Interface	Mode/mn	TX+RX	Connector	Reach Typ.	Tab OSFP/QSFP
CR8	Copper (DAC)	N/A	16 Twin-ax	N/A	3 m	/
CR4	Copper (DAC)	N/A	8 Twin-ax	N/A	3 m	/
AOC	Fiber	MMF/850	16 (1λ)	N/A	20 m	/

N TYPE-X Y Z (e.g. 400GBASE-LR4)

N		Data Rate (e.g. 400G)
TYPE		Modulation (e.g. BASEband)
X	C	= **C**opper (e.g. Coaxial)
	S	= **S**hort reach (e.g. 100 m)
	D	= **D**atacenter (e.g. 500 m)
	F	= **F**iber (e.g. 2 km)
	L	= **L**ong reach (e.g. 10 km)
	E	= **E**xtra long reach (e.g. 40 km)
Y		R = esc**R**ambled
Z		No. of optical lanes or copper pairs

Power Class	1	2	3	4	5	6	7	8
Max (mW)	1.5	3.5	7.0	8.0	10.0	12.0	14.0	>14.0

OTHER RESOURCES

400G IEEE®802.3bs	www.ieee802.org
CWDM4 MSA	www.cwdm4-msa.org
Ethernet Alliance	www.ethernetalliance.org
ITU-T	https://www.itu.int/rec/T-REC
OIF	www.oiforum.com
OSFP MSA	www.osfpmsa.org
QSFP-DD MSA	www.qsfp-dd.com
SFP / SFF	www.snia.org/sff/specifications
SFP-DD MSA	www.sfp-dd.com
SWDM Alliance & MSA	www.swdm.org

VeEX® 400G Test Solutions

MPA Rackmount Test System

RXT-6400 400G Handheld Test Set

- MPM-400AR: Dual QSFP-DD, QSFP56, SFP56
- MPM-400G: CFP8
- 400G Ethernet per IEEE 802.3bs
- Advanced KP4 FEC stress testing and analysis
- Physical, PCS/FEC, and Ethernet layer verification
- IC, transceiver, and board level testing
- Interoperability and product validation
- System level integration
- Multi-port traffic simulation and analysis
- Aggregation and load testing
- First portable 400G test solution supporting OSFP & QSFP-DD
- Native PAM4 OSFP and QSFP-DD interfaces for Best-in-Class signal integrity (no adapters required)
- All-in-one 1G-to-400G Ethernet test solution
- Advanced transceiver check
- Ideal for NEMs' SVT to FAEs assisting field demonstrations, evaluations, deployment, and troubleshooting
- Mobility and efficiency in large COs, nodes and datacenter
- RXT modular test platform offers complete solutions from 10M to 400G, Fiber Optics, C/DWDM

GLOSSARY

256B/257B	PCS Transcoding block (before scrambling and FEC)
400GE	400 Gbps Ethernet interface (IEEE®802.bs)
64B/66B	PCS Transcoding Block
AOC	Active Optical Cable
AM	Alignment Marker
BiDi	Bi-directional (single-fiber) transmission
CDR	Clock and Data Recovery circuitry
cFEC	Correctable FEC errors
CFP8	400G Form-factor Pluggable transceiver
CRC	Cyclic Redundancy Code
CW	FEC Codeword. Includes Data and Error Check symbols
CWDM	Coarse Wavelength Division Multiplexing
DAC	Direct Attach Cable
DCI	Data Center Interconnect links
DR4/DR8	Short (Datacenter) Reach (500 m) optical interface with 4 or 8 independent lasers into multiple fiber (typ. MPO SMF connector)
EA	Ethernet Alliance
FCS	Frame Check Sum
FEC	Forward Error Correction
FR4/FR8	Intermediate Reach (2 km) optical interface with 4 or 8 WDM lasers into single fiber (typ. LC SMF connector)
Gearbox	M:N data lane conversion (e.g. 8x50G to 4x100G)
Gray Code	Reflected Binary Code (RBC) reorders the symbols so that any two successive values differ by only one bit, to reduce bit errors and facilitate error correction
HSE	High-Speed Ethernet
I2C	IIC, Inter-Integrated Circuit interface (see also MDIO)
IEEE	Institute of Electrical and Electronics Engineers
KP4-FEC	FEC (802.3.bj) a.k.a. RS-544 FEC or RS (544,514)
KR4-FEC	FEC (802.3bm) a.k.a. RS-528 FEC or RS (544,528)
Line Side	High-power ultra-long reach (ULR) optical interface (e.g. used in transoceanic cables)
LLC	Logical Link Control
LOA	Loss Of Alignment
LOAMPS	Loss of Alignment Marker Payload Sequence
LOS	Loss of Signal
LR4/LR8	Long Reach (10 km) optical interface with 4 or 8 WDM lasers into single fiber (typ. LC SMF connector)
MAC	Media Access Control
Markers	As 400G high-speed data is split into 16 slower lanes, alignment markers are inserted to allow proper reconstruction of the original data stream
MDI	Media Dependent Interface
MDIO	Management Data Input/Output (see also I2C)
MII	Media Independent Interface
MMF	Multi-Mode Fiber
MPO	Multi-fiber Push ON connector (IEC 61754-7, TIA 604-5)
MSA	Multi-Source/Supplier industry Agreement
NRZ	Non-Return to Zero, electrical or optical line coding (see OOK)
OIF	Optical Internetworking Forum
OM3/4/5	Optical Mode. MMF cable grades with different min. Modal Bandwidth (MBW) requirement (ISO 11801)
OM5	OMMF cable with optical and mechanical attributes suitable for VCSEL and effective modal bandwidth and attenuation at 953 nm
OOK	On/Off Keying, electrical or optical line coding (see NRZ)
OSFP	Octal small Form Factor Pluggable transceiver with 8x50 Gbps PAM4 interface
OTN	Optical Transport Network (ITU-T G.709)
PAD	Padding bits
PAM4	Pulse Amplitude Modulation, 4 levels
PCS	Payload Coding Sublayer
PHY	Physical Coding Sublayer
PMA	Physical Media Attachment Sublayer
PMD	Physical Medium Dependent Sublayer
Post-FEC	Errors detected after error correction (uFEC)
Power Class	Transceiver's maximum allowed power consumption
PRBS	Pseudo-Random Bit Sequence test pattern
Pre-FEC	Errors detected before error correction (uFEC + cFEC)
QSFP	Quad Small Form Factor Pluggable transceiver with 4x10 Gbps NRZ interface
QSFP28	QSFP with 4x25 Gbps NRZ interface
QSFP56	QSFP with 4x50 Gbps PAM4 interface
QSFP-DD	QSFP Double Density with 2x4x50 Gbps PAM4 interface
RS-FEC	Reed-Solomon FEC encoder-Error correction technique)
Scrambler	Reversible mathematical manipulation of data stream used to increase the density of 1s, 0s and physical pulses to help with data integrity and clock recovery
SER	Symbol Error Rate
SFP	Small Form-factor Pluggable transceiver with 1 Gbps NRZ interface
SFP+	SFP with 10 Gbps NRZ interface
SFP28	SFP with 25 Gbps NRZ interface
SFP56	SFP with 50 Gbps PAM4 interface
SFP-DD	SFP with 25 Gbps NRZ double-density interface
SMF	Single-Mode Fiber
SR4/SR8	Short Reach (100~200 m) optical interface with 4 or 8 individual lasers into multiple fibers (typ. MPO MMF connector)
SWDM	Multi-mode WDM with four λ (850 to 940 nm)
Transcoder	Converts data blocks from one format to another (e.g. a 64B/66B-to-256/257 transcoder removes the 2-bit header from four 66-bit blocks, consolidates them into a 256-bit block and ads a 1-bit header)
uFEC	Uncorrectable FEC error
VCSEL	Vertical-Cavity Surface-Emitting Laser
WDM	Wavelength Division multiplexing
ZR/ZR+	Extended-reach coherent optical interface for DCI

For more information, visit **www.veexinc.com**