BELDEN | PRECISION OPTICAL TECHNOLOGIES

400G ZRx:
AN OPERATOR'S GUIDE

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1.0 Introduction

400G ZRx refers to a family of pluggable coherent DWDM transceivers where "ZRx" represents variations in design such as different transmit power levels, Forward Error Correction (FEC) methods, data rates, and specific applications. Available in QSFP-DD, OSFP, or CFP2 form factors, these transceivers can be deployed directly in IP routers or switches, enabling long-haul connectivity over a DWDM network (IPoDWDM) without requiring specialized transport equipment. Recent advancements in integrating full coherent technology into QSFP-DD or OSFP form factors have reduced power consumption per optic and increased the number of transceivers that can be deployed per rack unit, ultimately lowering the total cost per 100G.

2.0 400G ZRx Standards Variations: The Road to Interoperability

There have been several efforts over the last 10-15 years to integrate the capabilities of 400G transport equipment into a pluggable form factor. Back in 2016, the Open ROADM initiative was created by a consortium of telecom industry leaders to promote open, interoperable, and programmable optical networks. Its development was driven by Internet Service Providers (ISPs) and the need to overcome vendor lock-in, reduce costs, and enhance network efficiency through standardization and collaboration. The main goal of Open ROADM was in support of transport backbone networks and metro applications, with multi-rate 100G-400G (both Ethernet and OTN protocols) + oFEC (Open FEC) and reach in the 100s of kilometers with amplification. The earlier implementations of Open ROADM transceivers were mainly in a CFP2 form factor but it now has also been implemented in QSFP-DD/OSFP form factors.

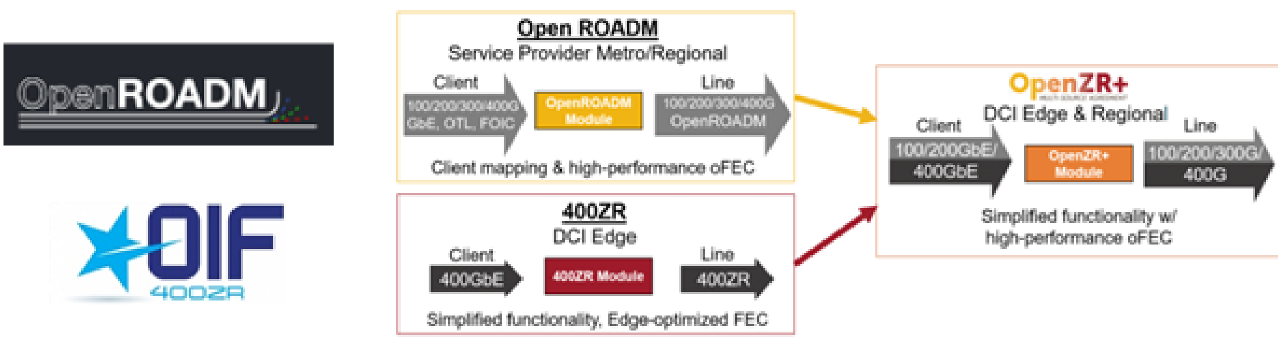

Figure 1. Development of 400G ZRx Standards

Concurrently, the OIF (Optical Internetworking Forum) 400ZR led an initiative driven by the need of Hyperscalers to achieve 400GbE DCIs (Data Center Interconnects) on DWDM amplified links up to 120km using smaller form factors such as QSFP-DD and OSFP. Characterized by a simplified network design and a new error correcting code C-FEC (Concatenated FEC), 400ZR achieved much success in terms of establishing a widely adopted, interoperable standard for 400 Gbps coherent optical transport and meeting the growing demands of modern data centers. These two efforts paved the way for OpenZR+, the latest standard for 400G coherent pluggables. OpenZR+, an MSA (Multi-Source Agreement), merges some of the multi-rate capabilities from Open ROADM with higher performance oFEC and new form factors such as QSFP-DD and OSFP to build on the success and learnings of the widely adopted 400ZR standard. For additional information about 400ZR and OpenZR+, see some of our blogs and additional whitepapers.

3.0 400G ZRx Transceiver Solutions: A Full Range of Possibilities

Precision OT offers several 400G coherent product options that adhere to both the OIF 400ZR and OpenZR+ standards. Table 1 below is a summary of our 400G ZRx product offerings:

Precision PN	Standard	Max Distance	Line Rate	Applications	λ	TX output power
PRE-QSFP56DD-ZR	OIF 400ZR	40km (unamplified) 120km (amplified)	400G	1x400G DP-16QAM C-FEC 4x100G DP-16QAM C-FEC	Tunable DWDM	~ -10 dBm
PRE-QSFP56DD-ZRHT	OIF 400ZR	80km (unamplified) 120km (amplified)	400G	1x400G DP-16QAM C-FEC 4x100G DP-16QAM C-FEC	Tunable DWDM	~ 0 dBm
PRE-QSFP56DD-ZRXT	OIF 400ZR	120km (unamplified)	400G	1x400G DP-16QAM C-FEC	fixed DWDM ITU ch. 37 1547.72 nm	~ +4 dBm
PRE-QSFP56DD-ZRP	OpenZR+	480km+ (amplified)	400G 300G 200G 100G	1x400G DP-16QAM O-FEC Nx100G DP-16QAM/8QAM/QPSK O-FEC 1x400G DP-16QAM C-FEC 4x100G DP-16QAM C-FEC	Tunable DWDM	~ -10 dBm
PRE-QSFP56DD-ZRPHT	OpenZR+	1000km (amplified)	400G 300G 200G 100G	1x400G DP-16QAM O-FEC Nx100G DP-16QAM/8QAM/QPSK O-FEC 1x400G DP-16QAM C-FEC 4x100G DP-16QAM C-FEC	Tunable DWDM	~ 0 dBm

Table 1. Summary of Precision OT's 400G ZRx Products

All these transceivers come in the QSFP-DD form factor. Below are some of the key differences and practical considerations for these coherent pluggable transceivers:

PRE-QSFP56DD-ZR => is the baseline standard OIF 400ZR product. It's a tunable DWDM optic which we refer to as the *low Tx power* option.

PRE-QSFP56DD-ZRHT => similar to the ZR product and using the OIF 400ZR standard as a baseline but with higher TX output power to fit the needs of legacy/brownfield applications that require TX output power around ~0dBm. Also useful for longer reach unamplified links compared to the standard ZR.

PRE-QSFP56DD-ZRXT => This product is a unique 400G transceiver for long reach point-to-point solutions. Not DWDM tunable but fixed at DWDM ITU ch. 37, also provides a fixed TX output power (+4dBm) higher than our other solutions. This optic offers a link budget accommodating long distances up to 120km on unamplified links. Considered the closest of the modules to being "plug-and-play" it does not require anything special regarding tunability or optical design or host compatibility. The -ZRXT is basically a big pipe of 400G up to 120km, perfect for grey links/dark fiber applications. As a fixed DWDM optic there's always the option of using this transceiver in a MUX/DEMUX design if you happen to have the ITU channel 37 free.

PRE-QSFP56DD-ZRP => The baseline Open ZR+ product which can do 400G as well as all the breakout applications at N x 100G speeds and different modulation types as advertised by the MSA. It's a full C-band DWDM tunable with *Low* Tx output powers and different reach depending on each application and network design.

PRE-QSFP56DD-ZRPHT => This product is very similar to the 400G ZRP, but has a *High Tx output power* (up to +1 dBm), to fit the needs of implementation in legacy/brownfield Transport line systems. Also a good fit for longer reach multi-rate 100G-400G applications with unamplified links compared to the standard ZRP.

4.0 400G ZRx Applications

The applications enabled by 400G ZRx products represent a significant advancement in optical networking technology, enabling faster, more efficient, and scalable solutions to meet the demands of modern data-intensive applications and services. For discussion purposes, we've divided these applications into 3 categories: grey + unamplified links, DWDM unamplified links, and amplified links.

4.1 Grey + Unamplified Links

A grey link is just a straight fiber link, point-to-point, with no DWDM MUX/DEMUX (Dense Wavelength Division Multiplexing/Demultiplexing) and no amplification. With 400G ZRx optics such as the ones we presented above in Table 1, a grey link can be formed and a simple power link budget calculated as follows by subtracting the receiver (RX) sensitivity from the transmitter (TX) output power:

Optical Power Link Budget = (TX Power) – (RX Sensitivity)

- PRE-QSFP56DD-ZR → -10 dBm – (-18 dBm) = 8 dB
- PRE-QSFP56DD-ZRHT → 0 dBm – (-20 dBm) = 20 dB
- PRE-QSFP56DD-ZRXT → +4 dBm – (-20 dBm) = 24 dB

To estimate the distance attainable for a particular grey link, one must also consider factors such as fiber loss as shown below in Table 2. Here we have estimated, for example, a loss level of 0.25 dB/km for older fiber out in the field. For newer fiber, such as one we have in our lab (no splices, no issues, new untouched fiber) we can represent the loss as ~0.2 dB/km. And then estimating the typical or average value for fiber loss at DWDM C-band, we'll use 0.22 dB/km.

		Fiber Loss (dB/km)			
		0.25	0.22	0.2	
Optical Power Link Budget (dB)	8 dB	32	36	40	PRE-QSFP56DD-ZR
	20 dB	80	90	100	PRE-QSFP56DD-ZRHT
	24 dB	96	109	120	PRE-QSFP56DD-ZRXT

Table 2. Theoretical Max Distance (km) for Optical Power Link Budget vs Fiber Loss

We then calculated the theoretical Max Distance attainable in km for each combination of link budget and fiber loss for each 400G ZRx module shown in Table 2.

4.2 DWDM Unamplified Links

A slightly different application to consider is an unamplified grey link with MUX/DEMUX added to the system. For the sake of simplicity we are using the TX and RX specs when using the 400G OFEC DP-16QAM application from a PRE-QSFP56DD-ZRPHT. Lower data rate applications can have better power link budget margins.

A basic power link budget calculation can be made as in this example:

PRE-QSFP56DD-ZRPHT → +1 dBm – (-22 dBm) = ~23 dB

And then we need to consider the MUX/DEMUX insertion losses (IL) from both sides of the link and factor those into our calculation. Table 3 shows the Theoretical Max Distance in km obtainable for different combinations of Link budget vs Fiber Loss using different MUX+DEMUX configurations with PRE-QSFP56DD-ZRPHT (@400G OFEC DP-16QAM) transceivers on each side:

MUX + DEMUX Configuration	Optical Power Link Budget (dB) Subtracting IL of MUX + DEMUX	Fiber Loss (dB/km)		
		0.25	0.22	0.2
No MUX + DEMUX	**23**	92	105	115
With 4 Ch.	**18**	72	82	90
With 8 Ch.	**17**	68	77	85
With 12-16 Ch.	**16**	64	73	80
With 20 Ch.	**15.4**	62	70	77
With 40-48 Ch. (AWG)	**11**	44	50	55
With 40-48 Ch. (TFF)	**14**	56	64	70

Table 3. Theoretical Max Distance(km) for Link Budget vs Fiber Loss for various MUX+DEMUX Configurations

An example as seen from the table: using PRE-QSFP56DD-ZRPHT transceivers and an 8 channel MUX+DEMUX, you would be able to reach between ~70 to 80 km unamplified, point to point.

Note: for any deployment using Coherent transceivers in a MUX/DEMUX DWDM network design it is important to remember that when using Coherent transceivers with a single laser (which is the case for all of the products in Table 1) these will only be able to be deployed in dual fiber DWDM designs, and not single fiber DWDM networks. IM-DD transceivers have a wider range of wavelengths they can receive and detect so they can be used in both single and dual fiber DWDM Networks. However, Coherent transceivers with a single laser must use the same frequency/wavelength/channel for transmitting and receiving. The reason is that the local oscillator used for the laser that is transmitting the signal is also used as a reference signal to compare against the RX signal detected. Coherent transceivers with dual laser configurations are the only possible solution for DWDM single fiber deployments.

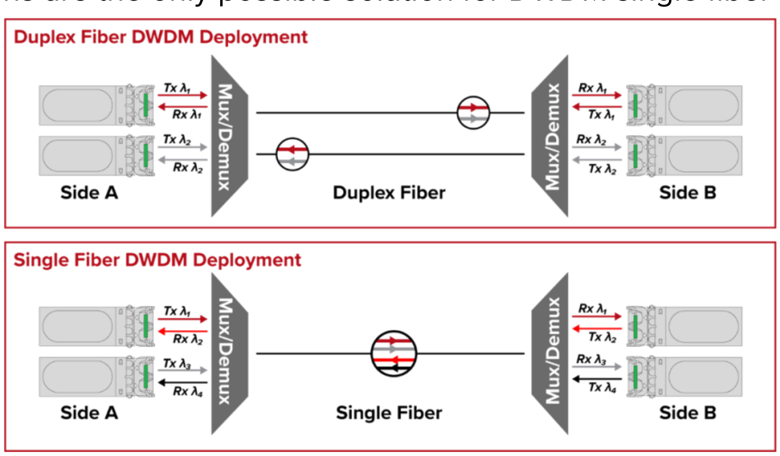

Figure 2. Single Fiber vs Dual Fiber DWDM Deployment

4.3 Amplified Links

Next, we'll look at amplified links in which we typically will have DWDM MUX/DEMUX (either passive or via ROADMs) plus some sort of amplification, typically EDFA (Erbium Doped Fiber Amplifier) or Raman amplifiers.

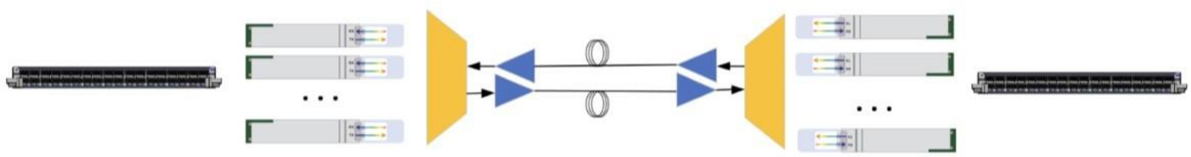

Figure 3. Ex. 400G ZRx Application with DWDM MUX/DEMUX and Amplification

In this case we're going from a power link budget calculation to an OSNR(Optical Signal to Noise Ratio) link budget calculation. The OSNR will be degraded by the noise figure (NF) of each amplifier included in the optical network design.

Key parameters for this type of optical network design include:

a.) TX output power
b.) Transmitter OSNR
c.) OSNR tolerance at the Receiver
d.) Chromatic Dispersion tolerance at the Receiver

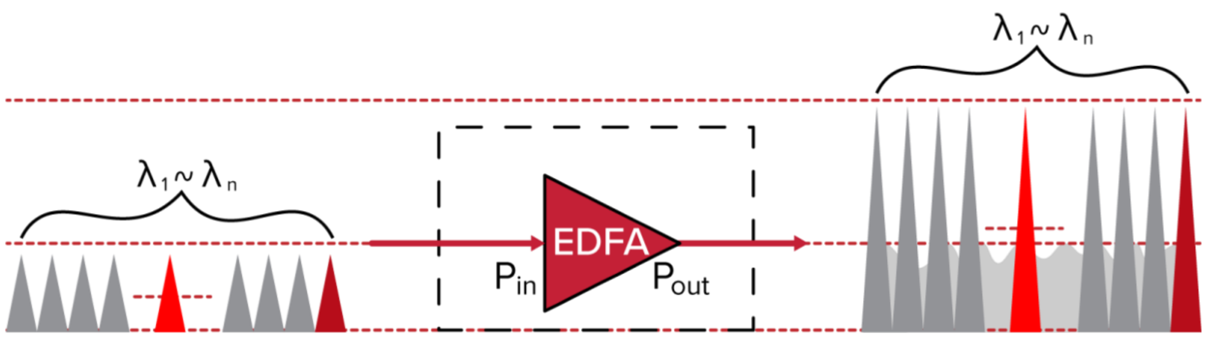

Figure 4. Visual Representation of Amplification using an EDFA

In this scenario shown in Figure 4, you have several multiplexed signals as input into the amplifier. Those signals will go through an amplifier — in this case, an EDFA – and then all the signals are amplified, including the noise (as depicted by the background grey area on the right side graph). For every amplifier in the network, the signal will be amplified along with the noise. Plus, the noise figure of each amplifier will decrease the OSNR after each amplification stage. So, the OSNR budget keeps decreasing at each amplification span and that is ultimately THE main limitation on this type of network application.

5.0 Decision Maps

You may be wondering for a particular application: which type of 400G ZRx transceiver do I use, when do I use it, and why? As most everyone involved with optical networks is likely aware, coherent technology brings many benefits in terms of capability and performance. Coherent is also more complicated than Intensity Modulated Direct Detect (IM-DD) transceivers and although there are standards, certain intricacies and details around the implementation of 400G ZRx transceivers into routers and switches require special knowledge and expertise. To aid customers in the process of determining which 400G ZRx transceiver is right for a particular application, Precision OT has developed some simplified decision maps; one for grey link applications and one for DWDM amplified links. While these decision maps are by no means a substitute for the robust network design process needed to develop end-to-end solutions, they can assist network designers and teams by introducing them to the use of coherent pluggables.

5.1 400G ZRx Transceiver Decision Map for Grey Links

Determining which transceiver to use for any application starts with first understanding a customer's needs. The first question is "Are your needs unique to 400G or are there other data rates needed for your application?" The decision tree shown in Figure 5 was created to help navigate through this type of discussion. Behind this simplified tree diagram is a significant amount of technical knowledge and experience vital to helping make an educated decision about which transceiver to use, when and why.

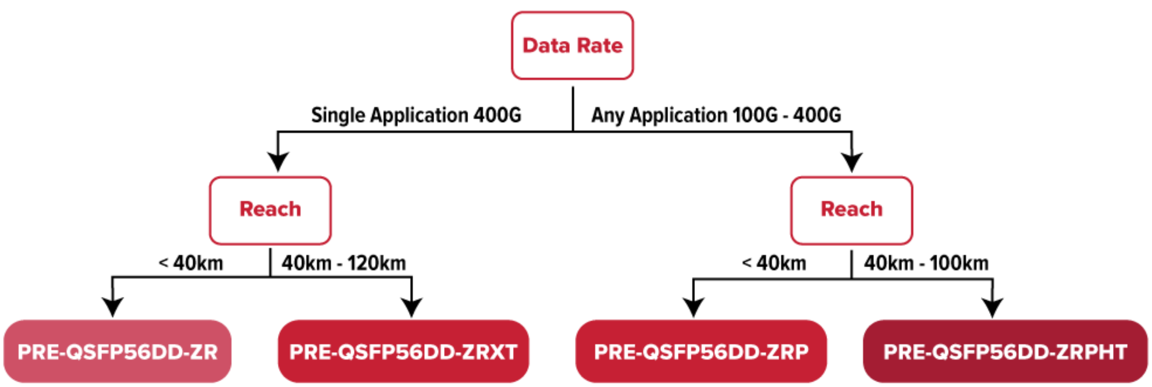

Figure 5. 400G ZRx Transceiver Decision Map – Grey Link

For example, if you are interested in grey link lengths greater than 40 km, we know that by performing some simple optical power budget calculations and considering key factors such as fiber loss, we can estimate a range of theoretical max link distances particular transceivers can achieve (see Table 2 above). Transceiver product datasheets typically provide the TX power and RX sensitivity we use in our power link budget calculation:

Power Link Budget = (TX Power) – (RX Sensitivity)

Usually, the minimum TX power is used for IM-DD transceivers, although in the case of variable TX power transceivers, we can use the highest value that can provide the greatest power link budget. The PRE-QSFP56DD-ZRPHT, for example, can have a max TX power of +1 dBm. Or the PRE-QSFP56DD-ZR can be varied up to -8 dBm. These are the kinds of intricacies one needs to know (or should get help to determine) when deciding which transceiver to use for a particular network application. New host platforms with new SW will allow the user to configure and set the TX power via CLI (command line interface) or their Network Management System (NMS). Some older legacy platforms and SW versions, however, won't allow the user to do that. In such cases, Precision OT can customize the transceiver to initialize at a certain TX power that fits the need of the customer's application.

5.2 400G ZRx Transceiver Decision Map for DWDM/Amplified Links

Similarly, with DWDM/Amplified links, we start by determining whether it's a single application (400G) or multi-rate application (100G – 400G). Then we consider the TX power. In Optical Line Systems (OLS), companies have designed their TX optical input power to be a certain value. Depending on their optical network design, it may require Low TX power input (typically between –10 dBm and –8 dBm) or High TX power input (typically between 0 dBm and +2 dBm). Especially in brownfield applications, there's a need to get all the optical signals going through the OLS at the same level so that the OLS can perform amplification and equalization with all signals coming in at the same signal strength.

In DWDM Amplified networks the max reach will also depend on the transceiver chosen and optical network design. The PRE-QSFP56DD-ZR and PRE-QSFP56DD-ZRHT follow the OIF 400ZR which uses C-FEC and will only be able to reach max 120km regardless of your optical network design. The PRE-QSFP56DD-ZRP and PRE-QSFP56DD-ZRPHT support all the OpenZR+ applications, using O-FEC, and can reach up to 100s of km depending on the optical network design: number of link spans being amplified, link span distances, type of amplifiers (EDFA vs Raman), fiber quality, etc.

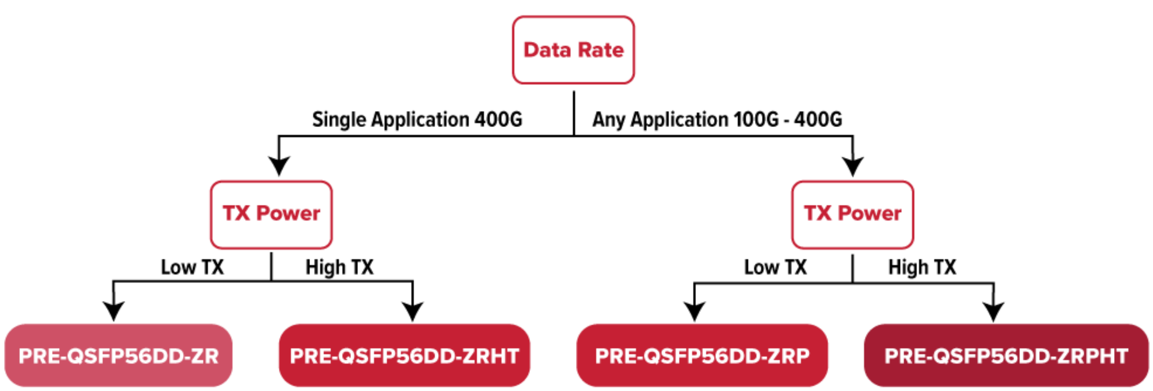

Figure 6. 400G ZRx Transceiver Decision Map – DWDM/Amplified Link

6.0 What Precision OT Brings to 400G ZRx

Precision OT is a systems engineering, and integration company focused on end-to-end optical networking solutions. We excel in network design, development and implementations customized to the needs of our customers. Our team of experts have a deep technical understanding of all network layers and take time to fully understand our customers' platform right down to knowing the latest SW versions needed. We provide comprehensive network partnership including the following:

- **INTEROPERABILITY** – Ensure fully interoperable and compatible modules and avoid vendor-locked/proprietary DSP based modules
- **COMPLIANCE** – Follow industry standards in terms of 400ZR, OpenZR+, SFF and CMIS approved documents and agreements
- **MULTI-PLATFORM COMPATIBILITY** – Perform multi-platform host system integration
- **FUNCTIONALITY –** Test minimum host SW version releases for each NEM HW/SW
- **SUPPLY CHAIN –** Provide supply chain diversity of 400G ZRx modules
- **DEVELOPMENTS –** Participation in Industry wide standardization groups, plugfests and demos to keep up to date

Precision OT knows the importance of delivering reliable, interoperable high-quality products designed to help you bring together all the systems within your network. Contact us about 400G ZRx applications and all your optical network needs!