Mobile Optical Pluggables Alliance (MOPA)

Technical Paper – New Technologies

Version 26a

March 16, 2026

Work item drivers (in alphabetical order

Antonio Tartaglia[1]
Fabio Cavaliere[1]
François Fredricx[4]
Kenneth Jackson[3]
Kevin Cheng[8]
Kumi Omori[7]
Ulf Parkholm[1]

Contributors (in alphabetical order)

Alberto Artuso[3]
Antonio Napoli[4]
Amjad Haddad[2]
Bo Pedersen[10]
David Sinicrope[1]
Faraz Shouka[9]
Hock Gin Lim[2]
James Kannan[3]
Jesper Bevensee Jensen[10]
Ken Cockerham[5]
Nicke Svee[1]
Raza Khan[6]
Ryan Latchman[8]
Sezer Erkilinc[4]
Stefan Dahlfort[1]
Steven Buchinger[6]
Takuya Kanai[12]
Ted Kuo[11]
Tero Kemilä[4]
Uwe Schmiade[4]

(1) Ericsson, (2) Lumentum, (3) Sumitomo Electric, (4) Nokia, (5) Coherent, (6) Semtech, (7) NEC, (8) MACOM, (9) Point 2 Technologies, (10) Bifrost, (11) APAC, (12) NTT Innovative Devices

Operator Advisory Board (in alphabetical order)

Dirk Breuer[10]
Philippe Chanclou[1] (Chair)
Henry Cheng[6]
Edwards James Echeverry Zuleta[5]
Jun-ichi Kani[3]
Francisco Javier Lopez Santolla[5]
Stefan Melin[4]
Albert Rafel[9]
Hongseok Shin[8]
Uladzimir Norka[4]
Mark T. Watts[2]

(1) Orange, (2) Verizon, (3) NTT, (4) Telia, (5) Telefonica, (6) T-Mobile, (8) SK Telecom, (9) BT, (10) DT

1. Executive summary

MOPA aims to develop a shared and common view of the optical solutions needed for mobile transport [OptConn].

MOPA's shared and common view of the optical solutions needed for mobile transport are contained in three Technical Papers:

- **Requirements & Blueprints [MOPA-RBP]:** The mobile optical blueprints for C-RAN, D-RAN and VRAN, based on available technologies. Also covers general functional requirements.
- **New Technologies [MOPA-NT]:** Relevant emerging and future technologies that could be included in the blueprints.
- **Market outlook [MOPA-MO]:** The market outlook for optical solutions in the context of mobile networks.

The present document explores new technologies (emerging and longer-term) aiming to identify future solutions for addressing one or several of the blueprint cases described [MOPA-RBP]. Note that the novelty can be either in the hardware or logic of the device itself, or in the re-use of existing devices and methods in the context of mobile transport, or in the engineering practices.

It should be mentioned that much of the content generated by the MOPA group is made as contributions to standardization bodies such as ITU-T, SNIA/SFF, OIF and IEEE.

Contents

2. Introduction, purpose and scope

MOPA aims to develop a shared and common view of the optical solutions needed for mobile transport [OptConn].

MOPA's shared and common view of the optical solutions needed for mobile transport are contained in three Technical Papers:

- **Requirements & Blueprints [MOPA-RBP]:** The mobile optical blueprints for C-RAN, D-RAN and VRAN, based on available technologies. Also covers general functional requirements.
- **New Technologies [MOPA-NT]:** Relevant emerging and future technologies that could be included in the blueprints.
- **Market outlook [MOPA-MO]:** The market outlook for optical solutions in the context of mobile networks.

The new optical technologies of interest are those that have the potential to facilitate Mobile Blueprint deployments in terms of performance, availability, cost, and operations.
Whereas [MOPA-RBP] reviews existing technologies, this [MOPA-NT] document focuses on novel solutions. They are categorized as either emerging (short term) or future (longer term). There are also technologies dedicated to facilitate operations. They can cover both active and passive optical components. Note that the novelty can be either in the hardware or logic of the device itself, or in the re-use of existing devices and methods in the context of mobile transport, or in the engineering practices.

The purpose is to assess the emerging and future technologies and identify in which Blueprints they could be relevant once they reach mainstream status. It also mentions when the potential is not yet concluded or clear. Some technologies may already be widely adopted in some application areas, but would be new in the context of mobile transport.

The considered future technologies are
- Modified temperature operating point, higher temperatures
- Cost-effective high-capacity Transceivers
- Pluggable optical amplifiers and dispersion compensators
- Cost-effective tunable filters and wavelength switches
- Self-tuning DWDM transmitters
- Support of Tight Synchronization
- 50Gbit/s DWDM transceivers for 15km

The considered emerging technologies are
- LLS over TDM PON
- Higher speed PON
- WS-WDM PON
- Remote optical module management
- LLS data rate auto-negotiations

- 30-40 km LLS WDM solutions
- 100 Gb/s IM/DD LLS WDM solutions
- 100G retimed and linear technology outlook
- Hollow-core fiber for mobile networks
- Power consumption reduction technologies and methods
- Quasi-Coherent Receiver Technology
- Single-laser (wavelength) DSCM-based coherent communication for Adaptive and Flexible Bi-directional (Bi-Di) transmission over single fiber

The considered technologies for operational purposes are

- Transmission of pluggable identifier during interruption of connectivity
- Generation of Visual Fault Locator including pluggable identifier

3. Acronyms

5G	5th Generation mobile networks, generic term for 5G system (or just the RAN part)
5GC	5G core, packet core part of 5G system
6G	6th Generation mobile networks
ACC	Active Copper Cable
AI	Artificial Intelligence
AAV	Alternative Access Vendor
AN	Auto Negociation
AOC	Active Optical Cable
APC	Angled Polished Connector
AWG	Arrayed Waveguide Grating (optical DWDM multiplexer)
B5G	Beyond 5G
BiDi	BiDirectional (using a single fiber strand for both transmission directions from an optical pluggable pair, where the two directions use different wavelengths)
BER	Bit Error Rate
C-band	The conventional fiber transmission band, around 1550 nm (aka “3rd window”)
CapEx	Capital expenditure
CD	Chromatic Dispersion
CDC	Chromatic Dispersion Compensation
CDR	Clock and Data Recovery
CO	Central Office
CRAN	Centralized RAN
CPRI	Common Public Radio Interface
CU	Central Unit
CWDM	Coarse WDM (20 nm wavelength spacing)
DAC	Direct Attach Copper (cable)
DCO	Digital Coherent Optics
DDM	Digital Diagnostics Monitoring
DFB	Distributed Feedback (laser)
DME	Differential Manchester Encoding
DNANF	Double Nested Anti-resonant Fibre
DR	IEEE 802.3 nomenclature referring to physical layer specifications having up to 500m reaches.
DRAN	Distributed RAN
DSC	Digital Sub Carrier
DSCM	Digital Sub Carrier Multiplexing
DWDM	Dense WDM (<= 0.8 nm wavelength spacing in C-band)
DU	Distributed Unit
eCDC	electronic Chromatic Dispersion Compensation
ER	IEEE 802.3 nomenclature referring to physical layer specifications having up to 40 km reaches.
eCPRI	Ethernet-based CPRI
FP	Fabry-Pérot (laser)

FR	IEEE 802.3 nomenclature referring to physical layer specifications having up to 2 km reaches.
FWM	Four-Wave Mixing
HCF	Hollow Core Fibre
HLS	High-Layer Split
HTMC	Head-to-Tail Message Channel
IL	Insertion Loss
IM-DD	Intensity Modulated – Direct Detection
LC	Optical Connector
LLS	Low-Layer Split
LO	Local Oscillator
LOS	Loss of Signal
LR	IEEE 802.3 nomenclature referring to physical layer specifications having up to 10 km reaches.
LWDM	Local Area Network (LAN) WDM
MPI	Multi-Path Interference
MSA	Multi-Source Agreement
NANF	Nested Anti-resonant Fibre
NR	New Radio, RAN part of 5G system
NRZ	Non-Return to Zero modulation
O-band	The original fiber transmission band, around 1310 nm (aka “2nd window”)
OAN	Optical Auto Negociation
ODN	Optical Distribution Network
ONU	Optical Network Unit (for TDM-PON)
OLT	Optical Line terminal (for TDM-PON)
OpEx	Operational expenditure
OPP	Optical Path Penalty
P2MP	Point-to-multipoint
P2P	Point-to-point
PAM4	Pulse Amplitude Modulation, 4 levels
PBG	Photonic BandGap
Phy	Physical layer (optical)
PIC	Photonic Integrated Circuit
Pkt	Indicates a node for packet switching and aggregation. May include mapping CPRI to packet, TDM to packet, etc.
PTP	Precision Time Protocol
QAM	Quadrature Amplitude Modulation
QC	Quasi Coherent
QCR	Quasi Coherent Receiver
QC-EIC	Quasi Coherent Electrical IC
QPSK	Quadrature Phase Shift Keying
QSFP	Quadruple-density Small Form factor Pluggable
RAN	Radio Access Network
R-DDMI	Remote – Digital Diagnostics Monitoring Interface

ROSA	Receive Optical Sub-Assembly
RPM	Remote Performance Monitoring
RU	Radio Unit
SDO	Standards Development Organization
SNR	Signal to Noise Ratio
SFP	Small Form factor Pluggable
SSMF	Standard Single Mode Fibre
STO	Self-Tuning Optic
TDP	Transmitter Dispersion Penalty
TDECQ	Transmitter Dispersion Eye Closure Quaternary
TEC	Thermo-Electric Cooler
TIA	Trans Impedance Amplifier
TP	Test Point
TOSA	Transmit Optical Sub-Assembly
UC	Use Case
VFL	Visual Fault Locator
VHT	Very High Temperature (range)
VOA	Variable Optical Amplifier
VRAN	Virtual RAN
WDM	Wavelength Division Multiplexing. In a node, WDM indicates an active WDM equipment, also known as a WDM transponder
WL	WaveLength
WR	Wavelength Routed
WS	Wavelength Selected

4. Legend and nomenclature

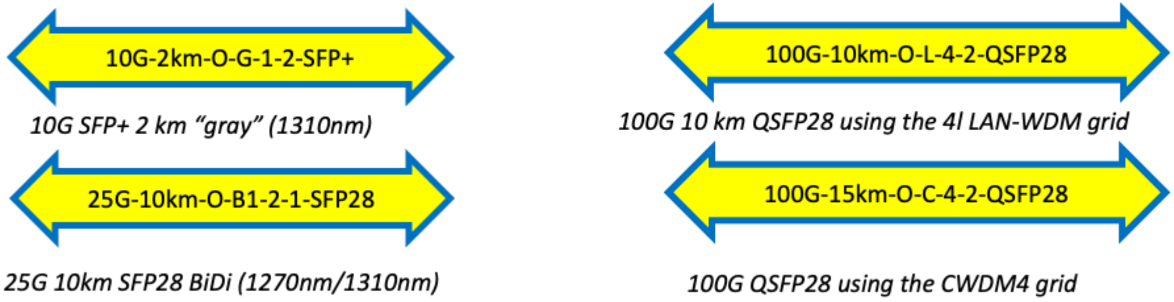
🟩 xyz	RAN Network Element
🟦 xyz	Transport node: WDM or Pkt
⬌ X-D-Y-Z-W-Z	Optical Pluggable of type X-D-Y-W-Z, industrial temperature range (“I-temp”)
⇔ X-D-Y-Z-W-Z	Optical Pluggable of type X-D-Y-W-Z, commercial temperature range (“C-temp”)
⏢	Optical (passive) multiplexer, industrial temperature range (“I-temp”)
⏢	Optical (passive) multiplexer, commercial temperature range (“C-temp”)
—	Fiber (generic)
⇄	Fiber pair
↔	BiDi fiber (single fiber strand)
●	Optical power splitter
⬌	Pluggable device with integrated Transport node functionality and optics

The optical pluggable type in the icons above is meant to provide an indication at a glance of the category to which the transceiver belongs. It is intended to be a compact and not all-encompassing description: detailed characteristics are provided in the optical Blueprints description in [MOPA-RBP] with further details in *[MOPA-RBP] Appendix A: Referenced Physical layer Standards Exceptions for MOPA Blueprints.* The different type fields are defined in Table 1.

X Bit rate	D Distance	Y1 Wavelength region(s)	Y2 WDM grid	Y3 Number of wavelengths / fiber strand	W Fiber mode 1=BiDi 2=dual	Z Form factor
10G 25G 50G 100G 200G 400G GPON XGSPON 25GSPON	2 km 5 km 10 km 15 km 20 km 40 km 80 km	O (1260-1360 nm) E (1360-1460 nm) S (1460-1530nm) C (1530-1565nm) L (1565-1625nm) "*" (all bands, only for CWDM)	G – gray (wavelength generic) B1 – BiDi 1270nm/1310nm B2 – BiDi 1270nm/1330nm B3 – BiDi xxxx / yyyy nm L – LAN-WDM (4.5nm) D – DWDM (100 GHz, 0.8nm) DL – DWDM with wavelocker (50 GHz, 0.4nm) C – CWDM (20nm)	1 2 4 6 8 12 16 48 96	1 2	SFP+ SFP28 SFP56 SFP112 QSFP+ QSFP28 QSFP56 QSFP-DD QSFP-DD56 SFP-DD SFP-DD56 DSFP DSFP56 (prefix T is used for tunable)

Table 1: Optical pluggables codes nomenclature[1].

Some examples of using this nomenclature are illustrated below:



10G SFP+ 2 km "gray" (1310nm)

100G 10 km QSFP28 using the 4l LAN-WDM grid

25G 10km SFP28 BiDi (1270nm/1310nm)

100G QSFP28 using the CWDM4 grid

Figure 1: Example of icons and codes for "client" pluggables.

---

[1] It should be noted that some values and variants are not yet used for the Blueprints in this paper, e.g. the distances 5, 20 and 80 km.

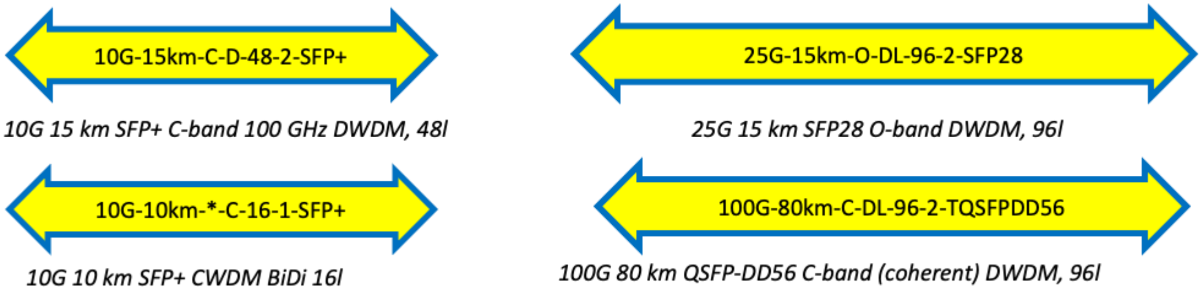


Figure 2: Example of icons and codes for "line" pluggables.

5. Summary of future technologies, capabilities, and components not yet available

This section discusses technologies and features that are not yet available in current products but are relevant to the evolution of the Blueprints described in the previous sections. The focus is on pluggable devices: other technological trends from which radio equipment could benefit, like co-packaged optics (CPO), are not covered by the current version of this paper.

5.1. Optical transceivers operating at high temperature

Optical transceivers operating at high temperatures are relevant to any equipment that may operate in a harsh environment, like the RUs in the Blueprints described in [MOPA-RBP]. Telecom transceivers share most of the characteristics developed for datacom applications, but with some important differences. The capability to operate at temperatures higher than 100 °C is probably the most important one, due to the higher density of integrated circuits in new generation radio equipment. Due to the operation in an uncontrolled environment, and limitations in weight and size, solutions commonly used in data centers, such as active cooling, are more difficult to apply in radio systems. High-temperature pluggable transceivers would allow the radio equipment to become smaller and lighter, with positive effects on the speed and cost of network rollouts.

The first industry to use integrated photonics was that of datacom transceivers, where the high volumes enable important investments in new technologies. Unfortunately, while silicon photonics modulators and photodetectors are tolerant to high temperatures, current commercial lasers for telecom applications are less so. Examples of solutions for lasers in high temperature systems:

- Continuous wave Quantum dot lasers, even with high power, are a quite mature technology. Direct modulation quantum dot lasers are a promising but not fully mature technology.
- External laser sources, placed away from the thermal hot spots, proposed today primarily for co-packaged optics.
- Improved material and laser structures, e.g 980 nm VCSELs used in the new [802.3cz] Multi-Gigabit Glass Optical Fiber Automotive Ethernet up to 125°C.

While resistance to high temperatures is important, another and important aspect of usability for a given pluggable is its power consumption. The lower the consumption the wider the range of mobile nodes it can be used for. Especially RU nodes can have strict limitations on maximal power consumption for the optics. The next section investigates how to lower the maximal power consumption.

5.2. Considerations on power consumption dependence from operating case temperature

While the worst-case power consumption is an important parameter to dimension, for example, the current that must be supplied to the pluggable by the voltage supply circuitry of the host, the operating case temperature at which the power consumption is highest is an extremely relevant parameter for thermal design of the host. Intuitively, it is much more desirable to have pluggables which consume higher power at a low case temperature rather than at a high case temperature. While the dependence of power consumption on case temperature may depend on several design details of the pluggable, if the transmitter is using a thermo-electric cooler (TEC) the laser chip operating temperature may be increased to achieve lower overall module power dissipation at high case temperatures. This would represent a novel engineering practice.

The intrinsic power consumption of the TEC is proportional to the temperature gradient between the cold and hot plate. If the laser chip temperature is much lower than the maximum operating case temperature, the TEC becomes the main contributor to the pluggable power consumption. Setting the laser chip operating temperature closer to the maximum case operating temperature of the pluggable decreases the TEC power consumption at high case temperatures, while increasing it at low case temperatures. Having a higher pluggable power consumption at cold case temperatures is less of an issue for thermal design; effectiveness of the approach depends on how high the laser chip operating temperature can be set without significant degradation in performance and reliability.

A typical description of the power consumption vs. operating case temperature for pluggables with a cooled transmitter is in figure 3:

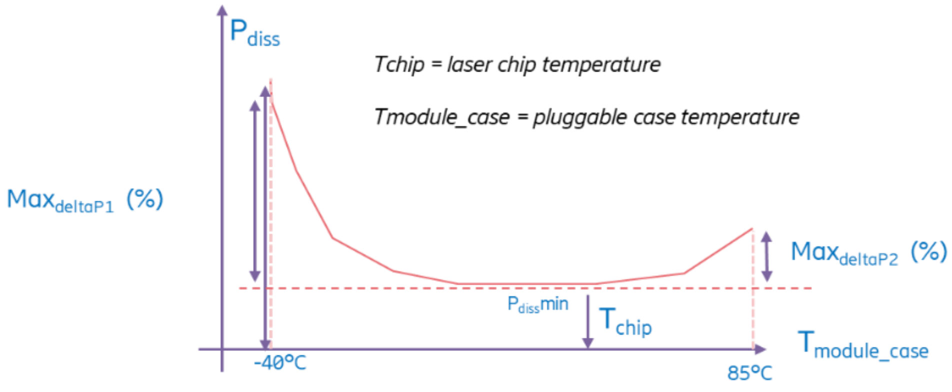


Figure 3: Typical Pdiss(Tmodule_case) with cooled transmitter

The key parameter is the laser chip operating temperature, and the higher it can be set without compromising on reliability, the more power consumption at high operating case temperature will be reduced. For a pluggable designed following this principle, a typical value for the extra power consumption at cold case temperature vs. ambient case temperature , MaxdeltaP1 ,can be around

100%, while a typical value for the extra power consumption at hot case temperature vs. ambient case temperature, MaxdeltaP2 can be around 70%..

An example of the results that can be obtained in the case of tunable optical pluggables can be found in section 6.11.

For pluggables with no TEC, also called “uncooled”, the typical power consumption vs. operating case temperature curve appears instead monotone as in figure 4:

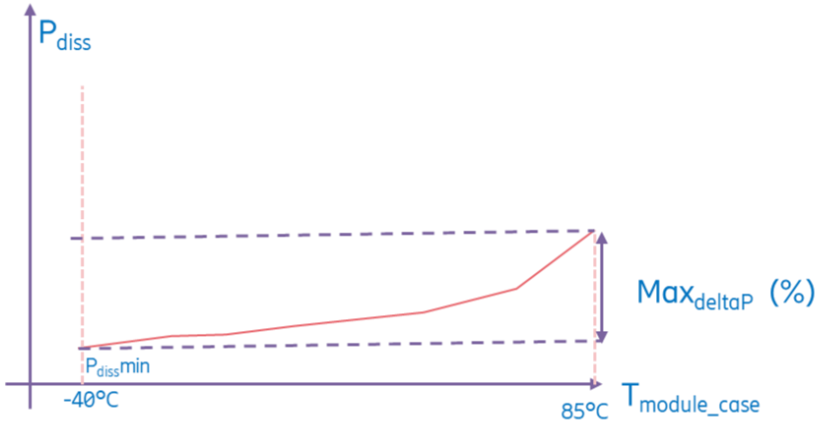


Figure 4: Typical Pdiss(Tmodule_case) of uncooled pluggable

In this case power consumption at hot case temperature will always be higher than power consumption at cold case temperature, and there are no variables to play with other than the selection of sub-components. A typical value for the power ratio at cold and hot case temperature, **Max_{deltaP},** is around 100%.

Sometimes, pluggables can also feature transmitters with partially regulated temperature, for example by use of a micro-heater to prevent the laser chip from operating at extremely low temperatures; a typical case is limiting detuning of the gain wavelength peak and the grating response wavelength peak in a DFB laser, both moving with chip temperature.
In this case,the curve resembles that of “uncooled” implementations at high temperature but as the case temperature falls below a given designed value, the micro-heater is turned on to keep the laser chip warm (see figure 5).

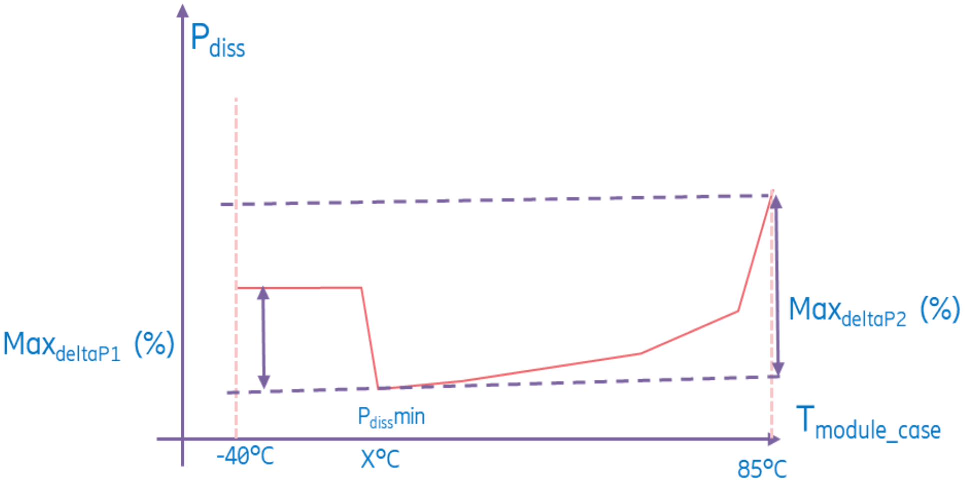


Figure 5: Typical Pdiss(Tmodule_case) with heated transmitter

Values of the power deltas depend on the choice of lasers and heaters, but also in this case it is safe to assume that the maximum power consumption will be at hot case temperature, and the only possibility to limit it is the selection of sub-components.

5.3. Cost effective high-capacity transceivers

Intensity-Modulated Direct-Detection (IM-DD) systems have been extensively used for mobile networks (as evident from this paper) and are simpler and more cost-effective alternatives to coherent systems. However, IM-DD systems suffer from limited distance and power budget performance at high bit rates due to the fundamental impact of chromatic dispersion and receiver sensitivity (while coherent detection discussed in the next section mitigates these impairments by taking advantage of electrical channel equalization techniques, which offer operation at much lower SNR). For 100 Gb/s, the practical limit today for IM/DD systems is approximately 40 km/20 dB in the O-band for non-WDM use. The success of 25 Gb/s in the access part of backhaul is expected to generate the need for single fiber solutions with 40 km reach and beyond, for example to extend the reach of the Blueprint 9.2.8 (passive DWDM) or with a link attenuation equal or higher than 20 dB, as in Blueprint 9.2.7 (gray/bidi). Extending the operation of NRZ optical interfaces beyond 25 Gb/s needs high accuracy tunable chromatic dispersion compensators, for example based on fiber gratings or silicon nitride micro-rings integrated in the TOSA/ROSA. Increasing the number of modulation symbols, as in PAM4, or using spectrally efficient line codes, such as optical duobinary or combined amplitude phase-shift, are other solutions but limited receiver sensitivity leads to implementation complexity and cost, which may become comparable to that of optical coherent modules. For how long the continued development of IM-DD optical pluggables for DWDM applications, based on one of the above solutions, remains cost-effective compared to optical coherent pluggables remains an open question. The new MOPA paper “Coherent lite for mobile networks” [MOPA-c-lite] explores the coherent option.

5.4. Pluggable optical amplifiers and dispersion compensators

Though tolerated at the CO and hub sites, optical amplifiers are not usually allowed at the RU and cell sites due to their large footprint, power consumption and cost. Compact optical amplifiers implemented in Pluggable Optical Line System (POLS) would be highly beneficial, in these aspects, for DWDM Blueprints where wavelength filters introduce a high insertion loss (e.g., Blueprints 8.3.3, 8.3.4, 9.2.8 and 9.2.4) and could allow the upgrade at 25 Gb/s or higher bitrate of all current 10 Gb/s installation, which is impossible today due to link attenuation constraints.

Similar considerations hold for Dispersion Compensating Modules (DCM) that are today quite bulky, adding to the link loss and latency. Pluggable implementations, possibly tunable to fit all practical network design cases and avoid inventory issues, would enable 25G transceivers to extend beyond 15 km and to continue to use cost effective IM-DD interfaces at bit rates higher than 25 Gb/s.

Bismuth doped fiber amplifiers can be one of the candidates to resolve the link budget issue in O-band DWDM.

5.5. Cost-effective tunable filters and wavelength switches

One drawback of current DWDM systems is the need to keep the inventory of all variants of transceivers and OADMs working at different wavelengths. This is impractical in mobile transport applications where installation times and cost must be minimal. Reconfigurable OADMs (ROADM) would relieve operators from installing and storing many variants of fixed OADMs, by replacing them with a single reconfigurable device. However, the ROADMs used in optical metro networks are based on high-performance but expensive Wavelength Selective Switches (WSS). Silicon micro-ring resonators could be a promising technology to realize pluggable and low-cost ROADMs. They apply, for example, to Blueprints 8.3.4 and 9.2.4.

Tunable optical filters enable new mobile transport architectures for the same Blueprints, replacing the OADM with a cost-effective power splitter, according to a broadcast-and-select architecture. Current tunable filters based on MEMS, liquid crystals or thin film filters are either too big or only support a limited number of DWDM channels, as in NG-PON2. New silicon photonics designs would offer decreased size and cost.

5.6. Self-tuning DWDM transmitters

As mentioned in [MOPA-RBP], it is highly desirable that all DWDM applications described in this document rely on tunable transceivers, for inventory simplification and consequent reduction of the operational costs.

In general, tunability has the following benefits;

- Only 1 part number is required instead of 96.
- Easier forecasting and inventory management.
- Reduces the potential for stranded inventory at the wrong/unused wavelengths.

Self-tunability is the capacity of one or a pair of modules to automatically tune into the required wavelength. An MSA for STO functionally has been formed [Smart Tunable MSA] that enables additional reduction in OpEx and CapEx:

- Plug and Play feature means less technician time in the field.
- No need to label or track fibers and no need to buy hundreds of tuning boxes to set the wavelength.

The self-tuning functionality will not require anything new from the host system and the host system can enable or disable this function.

5.7. Support of Tight Synchronization

As indicated in [MOPA-RBP], in a packet transport network using PTP for synchronization distribution, taking into account the internal delays of the pluggables helps in minimizing PTP timestamping inaccuracy.

The MOPA paper “Optical pluggable performance for tight time synchronization” [MOPA-sync] presents a detailed description of node level and link level aspects of accurate sync distribution via PTP, and of how the characteristics of optical pluggables can impact them. For this purpose, the paper proposes a classification of delays of optical pluggables. The paper also includes updates related to EEPROM data to estimate propagation delay contribution of a pluggable and propagation delay measurement principles. The MOPA paper “Implementation considerations about FEC and MII extensers for tight sync“ [MOPA-syncImpl] additionally provides recommendations for design choices to avoid inaccuracies.

A first step in standardization has been achieved by including the proposed parameters and their format into SNIA [SFF-8472] for single-lane SFP modules. Further work is planned for bringing similar delay parameters in the context of 4- and 8-lane optical modules.

5.8. 50 Gb/s xWDM 15 km LLS blueprint

50 Gb/s is the next data rate to be employed to address the increasing bandwidth requirement in LLS links. 50 Gb/s gray optics are already available in QSFP28 and SFP56 form factors. Similar to other rates, xWDM is likely needed for use cases such as those illustrated in [MOPA-RBP] (15 km RU-DU, passive DWDM over a single fiber Blueprint), [MOPA-RBP] (15 km RU-DU, passive DWDM bus over a single fiber Blueprint) and [MOPA-RBP] (15 km RU-DU, semi-active DWDM over a single fiber Blueprint).

The target characteristics are as follows:

- Up to 15 km P2P links
- SFP56 form factor

- Industrial temperature range (-40 °C to 85 °C)
- 48 channels.
- Wavelength grid and insertion loss budget are under study.

Implementations under study

Different implementations for 50 Gb/s WDM are currently under study while keeping in mind the network requirements described in this paper:

- Maximum distance of 15 km to accommodate the same requirement used for lower data rates and current infrastructure.
- SFP56 is the preferred form factor as it is beneficial to keep the same mechanical dimensions as lower data-rate transceivers.
- As described in [MOPA-RBP] “I-temp” operating temperature range and low power consumption are very important.

Since technologies are already available in the market and employed in gray optics, 25 GBaud PAM4 modulation format appears to be the most reasonable choice.

The increasing data rate makes it very challenging to meet the required performance. To fulfill these needs, different options are under evaluation to meet the insertion loss budget requirement and reduce chromatic dispersion impairments.

To have acceptable dispersion penalties, O-band could be adopted. It is generally known that O-band has a risk of FWM (Four Wave Mixing), especially when the wavelengths are close to the zero-dispersion wavelength of the fiber (1310 nm typ.[2]) and the grids are denser, but theoretically FWM can be managed by operating far enough from the zero-dispersion wavelength. Another consideration is that longer wavelengths distant from the zero-dispersion, such as 1370 nm, has a disadvantage in dispersion. Optimum wavelength grids, such as 1320 nm to 1350 nm, are under study.

In C-band, the dispersion penalty is a big challenge for 15 km distances at high data rates. One way to overcome this challenge is to implement dispersion compensation methods like DCM (dispersion compensation modules – e.g. based on dispersion compensation fiber or fiber Bragg gratings). EDC (electronic dispersion compensation) at the receiver, signal predistortion at the transmitter, ODC (optical dispersion compensation) at transmitter or receiver by means of photonic integrated circuits (PICs) or the use of modulation formats resilient to chromatic dispersion (duobinary and its extension: Combined Amplitude and Phase Shift keying (CAPS), Differential Quadrature Shift Keying (DQPSK)). All these techniques have their pros and cons, as discussed in [Paper1] and [Paper2], and further evaluation is needed to understand the most suitable one.

---

[2] Rec. ITU-T G.652 (11/2016) states in Tables 1 and 2 that the zero-dispersion wavelength is between 1300-1324 nm.

On the other hand, a coherent-transmission based solution in C-band is sufficient to overcome the dispersion challenge with no risk of FWM. As is commonly known, this solution also enables higher data rates such as 100 Gb/s, which will likely be a necessary data rate in LLS links in the future. In this case, however, since the DSP is indispensable for the implementation, power consumption of the 100G Coherent pluggable module is expected to be around 6W in a QSFP28 form factor over I-temp range at present (see [MOPA-RBP]). This is a major challenge to be addressed in order to adopt such an approach for radio units. It is also challenging to incorporate all the necessary components into an SFP56 form factor. Also due to the DSP, latency is another potential challenge which needs to be carefully evaluated especially for use in LLS link. (see Appendix B "*Optical pluggable performance for tight synchronization*"). To accommodate the needs of mobile applications, "Coherent Lite" is under consideration as described in [MOPA-c-lite].

Candidate O-band wavelength grid vs Four-wave mixing penalties

In order to assess the possible penalties arising from Four Wave Mixing (FWM) for O-band WDM, a simplified analytical model derived from [Paper3], [Paper4] and [Paper5] has been used for simulations. FWM penalties are known to get worse with lower amounts of chromatic dispersion, close spacing of wavelengths, and high optical power levels per wavelength launched into the fiber [Paper4, Paper5]. To estimate the order of magnitude of such penalties, we have used three scenarios, which are listed and illustrated below:

1) A "baseline" scenario, considering 12 wavelengths with 800 GHz spacing on the LAN-WDM grid.

2) An "overlay" upgrade scenario, in which 3x100GHz DWDM wavelengths are injected into each of the 12 LAN-WDM filter slots of the "baseline" scenario.

3) An "expansion" upgrade scenario, in which the original 12 x 800 GHz LAN-WDM wavelengths of the "baseline" scenario are not touched but 48 new wavelengths, with 100 GHz spacing on the DWDM grid are added right above of the LAN-WDM region (>1322 nm).

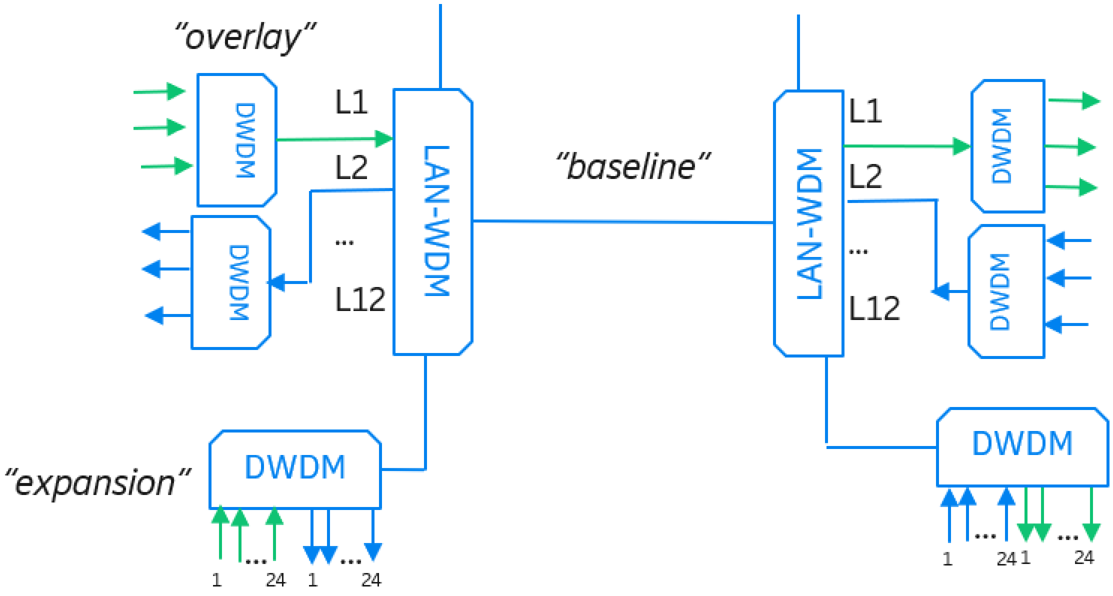


Figure 6: "baseline", "overlay" and "expansion scenarios.

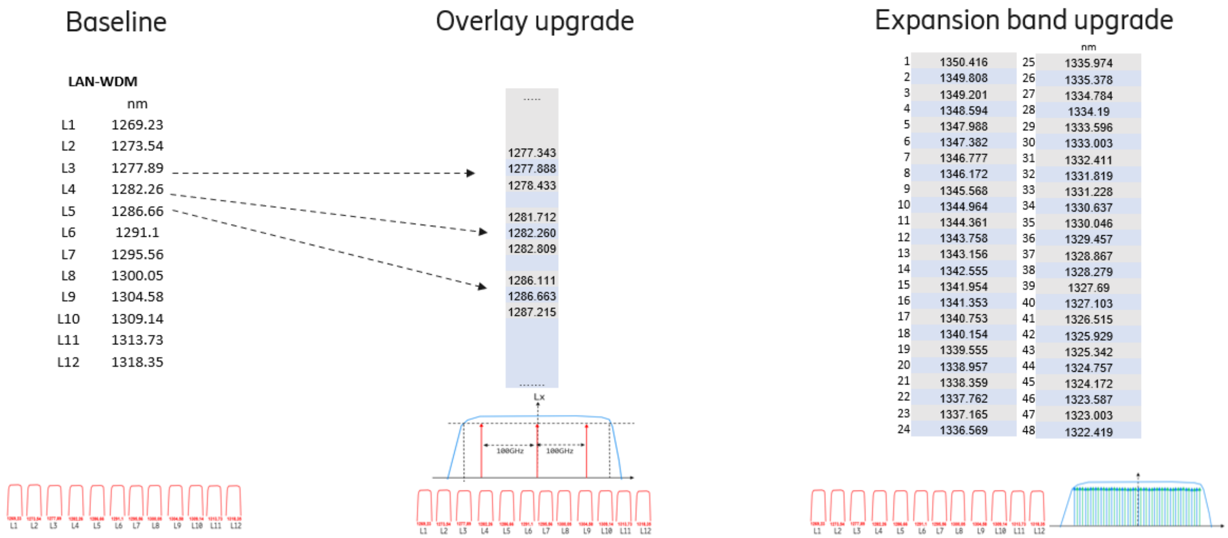


Figure 7: "baseline", "overlay" and "expansion" wavelength grids.

The simulation calculates the OSXR (optical signal to nonlinear crosstalk ratio) in a worst-case condition, assuming corner conditions with all FWM penalties coinciding:

- maximum transceiver output power and minimum optical filter losses,
    - These conditions result in a +2 dBm launch power per channel after WDM filters,

- nominal fiber distance of 15 km (for maximum cumulative effect),
- polarization alignment of all transmitted wavelengths,
- fixed spacing wavelength grids,
- channels operate on exactly the nominal wavelength.

A sweep of the optical fiber “zero dispersion” wavelength, in the allowed variation range dictated by ITU-T G.652 [G.652], is performed in order to exacerbate all possible ‘resonance’ conditions between the signal wavelength grid and the specific zero-dispersion wavelength value. Once OSXR is obtained, it can then be translated into BER under the simplifying assumption that crosstalk noise behaves as additive Gaussian noise. Then, assuming a target BER of 5E-5 (Reed-Solomon “KR” pre-FEC threshold), the FWM penalty in dB can be estimated. These simulations are shown in the figures below:

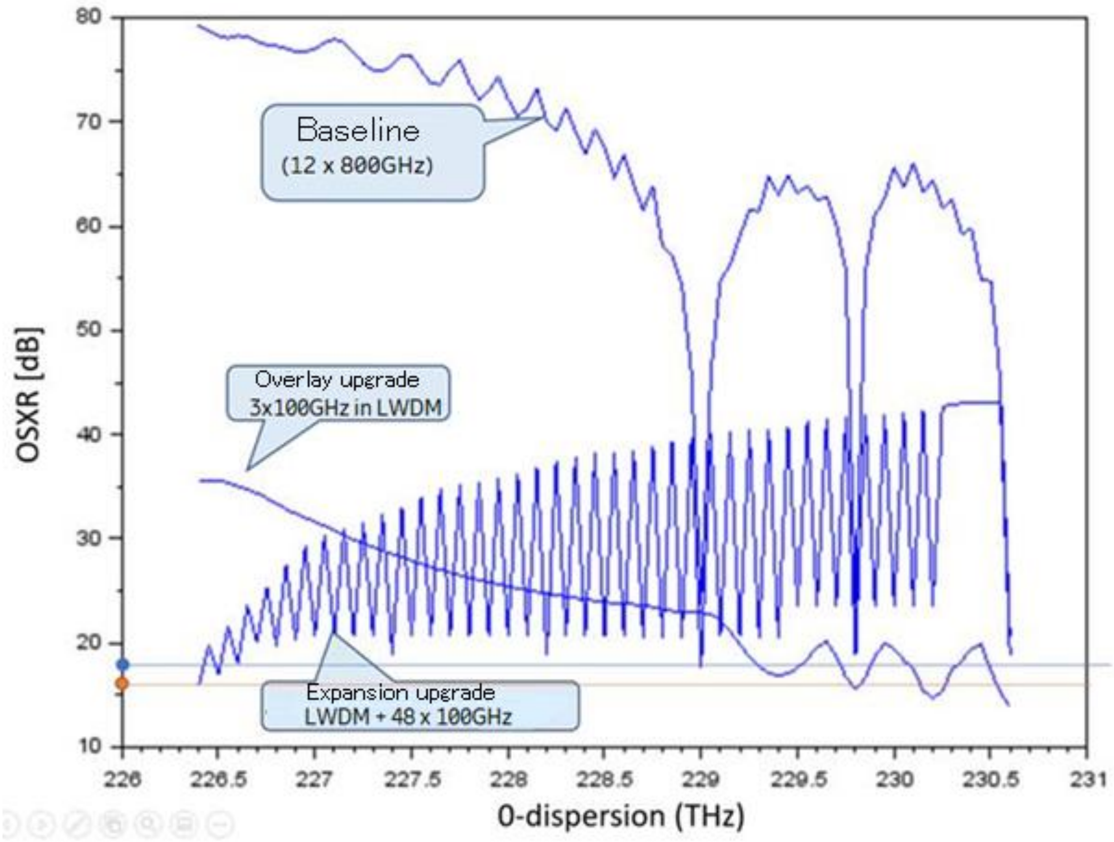
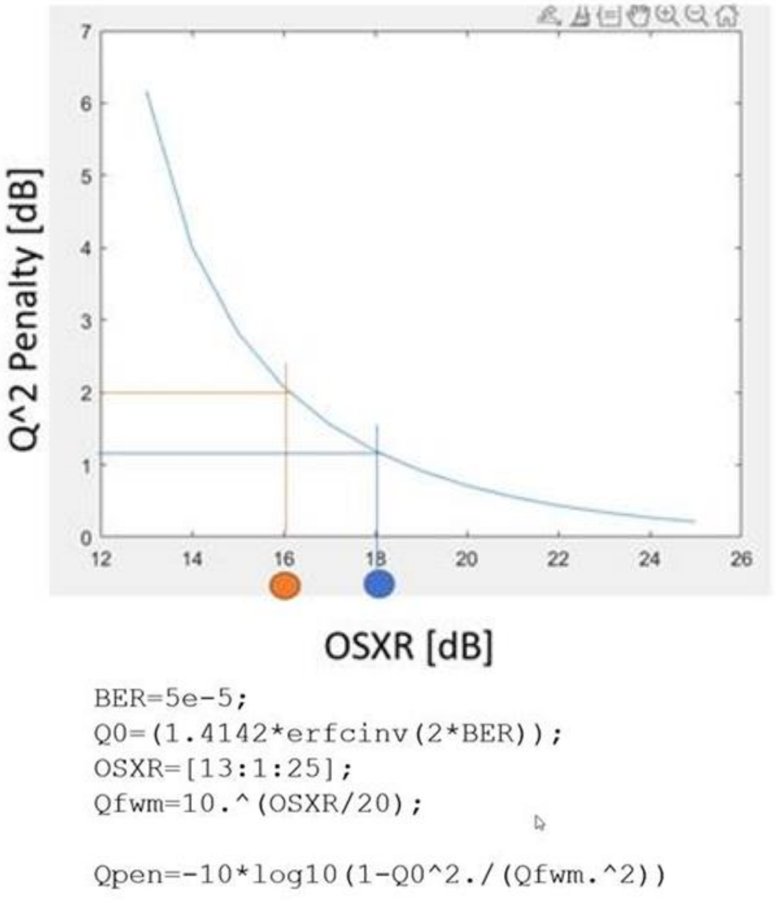


Figure 8: OSXR results obtained by sweeping the zero-dispersion wavelength all over the allowed range, for the three considered scenarios.



```
BER=5e-5;
Q0=(1.4142*erfcinv(2*BER));
OSXR=[13:1:25];
Qfwm=10.^(OSXR/20);

Qpen=-10*log10(1-Q0^2./(Qfwm.^2))
```

Figure 9: OSXR to penalty conversion under the assumption of additive Gaussian crosstalk noise.

As is shown in the figures above, the “baseline” 12 x 800 GHz LAN-WDM system exhibits three “notches” corresponding to different values of fiber zero-dispersion fiber wavelengths “resonating” with the fixed grid. In this instance, the OSXR is around 18 dB, corresponding to a 1dB penalty.
For the system in the “overlay” scenario, the combination of a denser wavelength spacing (100 GHz) together with the operating wavelengths in the vicinity of the fiber zero-dispersion wavelength, the OSXR is less than 16 dB worst case.
For the system in the “expansion” scenario, the effect of a denser wavelength spacing is compensated by the fact the signal wavelengths are relatively far from than the fiber zero-dispersion wavelength. As a result, the worst case OSXR is around 18 dB.

These simulations suggest a conservative worst-case OSNR from FWM effects in the “baseline” and “expansion” scenarios OSNR is around 18 dB, which corresponds to a penalty of about 1dB @ BER=5E-5. It should be noted that these simulations assume extremely unrealistic conditions, as it is very unlikely that all the possible worst-case conditions will occur simultaneously. It should also be noted that this worst-case penalty of 1dB could be further reduced by placing a limit on the maximum fiber launch power from the transmitter. Each dB of optical launch power reduction results in a 2dB improvement in the OSXR.

In summary: A LAN-WDM grid with its relatively wide spacing, does not suffer from significant FWM penalties. On the other hand, 100 GHz DWDM grids in the 1310 nm range would be more severely impacted by FWM; 100 GHz grids at wavelengths above 1322 nm do not appear to suffer from significant FWM penalties due to the higher levels of chromatic dispersion.

Preliminary Blueprint

Whichever solution is ultimately selected, per-channel flexibility and tolerance to various amounts of chromatic dispersion will be required for mobile applications. Moreover, as already mentioned, implementation of these WDM interfaces must fit in widely adopted pluggable format like SFP56 and reuse mature technologies like PAM4 modulation. To minimize the overall link insertion loss, one must carefully consider the number of wavelength channels and filter requirements.

The following table shows estimated loss budgets for C-band and O-band with maximum link distances of 15 km:

	Fiber Attenuation	**Connectors Insertion Loss**	**Maintenance Margin**	**Mux/DeMux Insertion Loss**	**Total Loss budget**
C-band DWDM 48ch	3.8 dB *	2 dB *	1 dB *	9 dB (2 x 4.5 dB)	15.8 dB
O-band DWDM 48ch	6.0 dB *	2 dB *	1 dB *	9 dB (2 x 4.5 dB)	18.0 dB

*Table 2: Preliminary Loss budget estimations for C-band DWDM and O-band DWDM. * Using the values of Table 4 in [MOPA-RBP].*

DSP-based pluggable modules are increasingly attractive for mobile applications although this function may introduce higher latency, costs and power consumption.

Analog CDR-based solutions can be beneficial in terms of power consumption and latency, however, the ability of these solutions to compensate for various link impairments remains an active area of investigation.

The table below summarizes a preliminary 15 km xWDM 50 Gb/s LLS blueprint:

Typical use cases	15 km RU-DU, passive DWDM over a single fiber Blueprint ([MOPA-RBP]) 15 km RU-DU, passive DWDM bus over a single fiber Blueprint ([MOPA-RBP]) 15 km RU-DU, semi-active DWDM bus over a single fiber Blueprint ([MOPA-RBP])
Distance	Typ Min 0 km; Typ. Max: 15 km
Channel Insertion Loss	18 dB in O-band, 15.8 dB in C-band (under study)
Chromatic Dispersion	< 65 ps/nm @ 1350nm * (< 270 ps/nm @ C-band**)
Mode, Nr ch., Wavelengths	Dual fiber pluggables, single fiber trunk: 48 wavelengths @ 100 GHz spacing
Temp. Range/Class	I-temp
Lifespan	15 years
Data rates	50 Gb/s
Form factor	SFP56
FEC, Mod format	yes, PAM4 (likely)
Power Class	Under study (PC4 / 2.5 W preferred, but 3.0W appears to be more reasonable target for tunable solutions)
Pluggables codes	50G-15Km-?-?-48-2-SFP56
Key technologies	Low-cost 50Gb/s EML DWDM without wavelength lockers, APD. Athermal AWG or TFF filters
Standards	ITU-T Q6/15 is evaluating the performance of 50G WDM systems to decide whether or not to start their standardization

Table 3: Preliminary 15 km xWDM 50 Gb/s LLS blueprint. (*) 1350 nm is an example of the longest possible wavelength to be adopted with an aim to limit FWM effects. The chromatic dispersion for 1350 nm is calculated using "$S_{omax}/4*L*(\lambda-\lambda_{omin}^4/\lambda^3)$*", where* S_{omax} *is the maximum zero dispersion slope (0.092 ps/nm*^{2}*/km), L is the maximum fiber length (15 km),* λ_{omin} *is the minimum zero dispersion wavelength (1300 nm),* λ *is 1350nm. "4 ps/(nm*km)" described in [MOPA-RBP] is not used here because 1350 nm is relatively far from the typical O-band wavelength. (**) This dispersion must be compensated using a DCM in the fiber link or an EDC function in the pluggable module, etc., which requires further evaluation.*

6. Summary of emerging technologies and future work

6.1. LLS using TDM-PON with separate ONU box

The industry has been exploring the possibility of using TDM-PON to provide connectivity between the RU and DU in a CRAN architecture with a Low Layer Split interface. Some of the challenges to accomplish this are bandwidth and latency.

- **Bandwidth**. LLS has higher bandwidth requirements than HLS. The RU interfaces are typically 10 Gb/s or 25 Gb/s rates. LLS variants that generate variable rate traffic can allow aggregation of several RUs on a 25G TDM-PON (and higher), provided the line rate is not fully used by each RU.
- **Latency**. The latency requirement for LLS is much tighter than HLS, on the order of 25-500 μs one-way [eCPRIreq]. Several efforts have been made to reduce the latency of TDM-PON in order to allow it to be used for certain distances. The methods include reduced burst sizes in the upstream and a real-time control interface (called Cooperative Transport Interface) between the DU scheduler and the OLT scheduler (called Cooperative DBA). These measures are specified in the following standards documents:
  - O-RAN CTI Specification [ORAN-CTI].
  - ITU-T G series supplement on Cooperative DBA [ITU G.Sup.71].

It should be noted that the Cooperative DBA and CTI concepts are still experimental and real-world conditions will be needed to assess their potential.

An illustration for TDM-PON for LLS using an external ONU is shown in Figure 10.

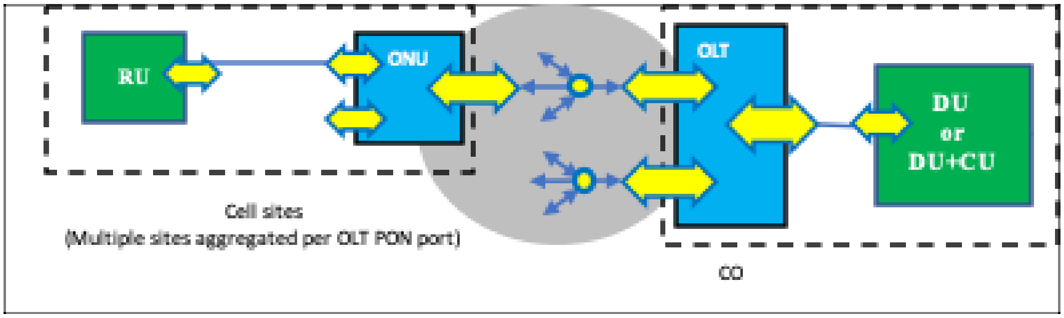


Figure 10: LLS using TDM-PON with a separate ONU box.

6.2. LLS using TDM-PON with pluggable ONU

An illustration for TDM-PON for LLS using a pluggable ONU is shown in Figure 11. The ONU functionalities must be built into the optical module itself.

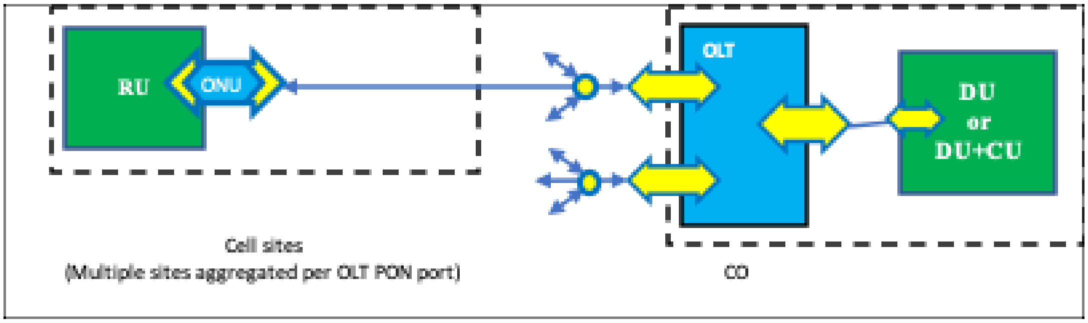


Figure 11: LLS using TDM-PON with a pluggable ONU module.

6.3. Higher speed TDM-PON technologies

The currently defined and available TDM-PON technologies above 10G per wavelength are 25GS-PON [25GSPON] for asymmetrical 25/10Gb/s and symmetrical 25 Gb/s, and Higher Speed PON (HSP) [G.9804.x] for asymmetrical 50/25 Gb/s and symmetrical 50G/50G. Work is on-going in ITU-T on Very High Speed PON (VHSP) beyond 50 Gb/s (100Gb/s, 200Gb/s). The use of these higher speed PONs will be gated by the availability and economic viability of new technology needed to make them possible.

6.4. LLS using semi-active DWDM wavelength multiplexed links over a power splitter ODN (WS-WDM-PON)

An architecture that is being explored by several operators who have an extensive power splitter PON network is an overlay of DWDM wavelengths on the same Power Splitter ODN (PS-ODN) to serve designated RUs that may be located within the area served by the TDM-PON. This is called WS (Wavelength Selective) WDM. because the desired downstream wavelength must be selected by the end node from among all the wavelengths arriving at that point. Some standardization work has been done on this architecture by ITU-T SG15 Q2 [G.989.x] but it is not a mainstream solution at this point.

NOTE: In some circles, the term PON (Passive Optical Network) is used to describe any point to multi-point architecture that involves a passive branching node, whether that is a Wavelength MUX or a Power Splitter. TDM-PON (sections 6.1, 6.2, 6.3) is the most common form of PON, but it is not the only type of PON. There can also be TWDM-PON and WDM-PON in which the users share a time slot, a wavelength or a combination of the two. Under this definition, the architecture is referred as a "WS-WDM-PON".

The dedicated wavelengths can be an effective way of meeting the high bit rate and low latency requirements of LLS while leveraging the existing PON infrastructure. The main difference of this Wavelength Selected WS-WDM-PON architecture from the typical semi-active DWDM wavelength architecture (Wavelength Routed WR-WDM-PON) is that a power splitter is used as the branching node rather than a wavelength Mux.
There are two added challenges for WS-WDM-PON:

- Higher insertion loss: typical PON optical budget classes range from 29 to 35 dB. Techniques that can help address this target include the use of FEC and higher optical power optics.
- Wavelength selection on the receive side: this will require a tunable filter at the RU end in addition to the tunable lasers that are part of the traditional DWDM optics.

On the other hand, it is assumed that fewer wavelengths will be needed per PON for WS-WDM-PON than for WR-WDM-PON since the ODN is expected to be shared as an overlay with other TDM-PONs that have existing PON end-points. In most cases, four wavelengths (and at most eight wavelengths) will be sufficient since most of the PON splitter ports are assumed to be serving other applications. The P2P overlay wavelengths can operate at 10 Gb/s or 25 Gb/s.
An illustration for this WDM architecture with a power splitter ODN is shown in Figure 12. What is not shown is the coexistence, on the same fiber, of other legacy TDM-PONs. There is no interaction between these, other than the fact they share a common fiber. They operate at independent wavelengths, just like there are many independent radio frequencies operating in the air at the same time, with no interaction between them.

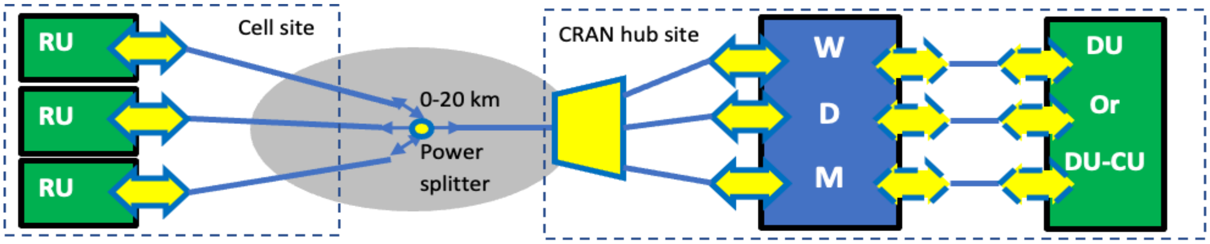


Figure 12: LLS using semi-active DWDM wavelength multiplexed links over a power splitter ODN (WS-WDM-PON).

6.5. Remote Optical Module management

Standardized methods to perform remote digital monitoring of devices are implemented in ITU-T Recommendation [G.698.4]. MOPA Technical Paper [MOPA-RemMon] has addressed this by proposing and describing a messaging channel, a frame structure, a memory map, and a protocol that together enable the management of optical modules at the two ends of an optical “black link”, either WDM or gray and single or dual fiber. The term “black link” means that the internal details of the link are not defined here. In the tunable DWDM case, the requirement for end-to-end operation of the messaging channel is that the two module transmitters are tuned to the correct wavelength(s) so that messages sent by one module’s transmitter will be received at the receiver port of the other module.

The mechanism in [MOPA-RemMon] reuses the head-to-tail message channel (HTMC) defined in [G.698.4] with focus on remote performance monitoring (RPM). A small set of Type of Message is defined for the purpose of sending special messages specifically for [SFF-8472] Transceiver Management register device addresses, pages and bytes (inventory and digital diagnostics data mainly). The memory map defined and associated with this specification is detailed in [SFF-8472] Rev 12.4.1 and above.

6.6. LLS data rate auto-negotiations

Optical Auto-Negotiation (OAN) refers to the capability of both endpoints in an optical link to establish the combination of transmitter and receiver digital and analog parameters that optimizes operation of the link in a heterogeneous environment where it’s not possible to duplicate the same deployment scenario and apply the same set of parameters every time. Auto-negotiation simplifies installation and reduces the need for strict cabling regimes, in situ resolution of PHY type and technology by negotiation, minimizing the need for human interaction and saving time and resources during system deployment.

A working auto-negotiation also adds much needed visibility and debug information during fault finding, giving insight into systems state in between the coarse signal detect of the optical pluggable and PHY and MAC layer link in operation.

The CPRI 7.0 [cpri7.0] standard describes a mechanism in clause 4.5.2 /4.5.3, a parallel detection scheme in which both peer-ends cycle through their respective PHY rates and FEC combinations. The case of CPRI links, CPRI 2.4G (Option-3) through 24Gb/s (Option-10) is relatively simple as host ASIC Serdes and optical pluggables can relatively quickly lock on to a new data rate,. Given that these data rates are supported by the hardware components, the convergence and recovery of valid data and clock typically occurs in microseconds.

There are no major concerns implementing a CPRI stack that complies with this mechanism. The caveat with the current defined scheme and time periods defined in the CPRI 7.0 specification is that there is no guaranteed convergence, nor stipulated convergence time.

With Ethernet-based fronthaul, eCPRI [eCPRI] is introduced with lower speeds, starting at 10.3 and 25.7 Gb/s. With relatively modest design changes, the specific Ethernet line data rates could be included in the CPRI parallel detect regime, which would enable continued interop with pure CPRI peer-ends.

With the introduction of 50 Gb/s operation, the space becomes more challenging, due to the evolution of host ASIC Serdes/CDR and changes to the internal architecture of optical pluggables: with the introduction of PAM-4 modulation, the electrical re-timer in the pluggable can be either an analog CDR or a DSP. Complexity of the retimer function in the pluggable increases with the bit rate, and the more complex the retimer becomes, the more the time for link adaptation and achieving lock on a specific bit rate can become long, in some cases in the range of tens of seconds that is long enough to disrupt the CPRI parallel detect mechanism. Thus, in the era of higher bit rates (50 Gb/s, 100 Gb/s, 200 Gb/s+) it is no longer feasible to have a detection based on the CPRI parallel detect mechanism.

With an increased focus on Ethernet based eCPRI fronthaul and the introduction of 100 Gb/s Ethernet, a mechanism to complement the CPRI parallel detect mechanism is needed.
This must reliably allow for a broader mechanism of auto-negotiation preferably from 2.5G CPRI with emphasis on Ethernet rates including 100 Gb/s and beyond eCPRI in a pluggable port with multiple capabilities.

One implementation alternative for optical auto-negotiation is to reuse the proven IEEE 802.3 [802.3] clauses 73, currently defined for auto-negotiation (AN) over electrical backplanes and direct attach copper (DAC), where different technology and PHY can be negotiated. See Figure 13. The AN method uses a low out-of-band 300 Mbaud Differential Manchester Encoding (DME) where clock and data is combined to form a simple two-level signal. This protocol is robust and includes a loop detection mechanism, and in addition supports vendor extensions with the Next page, allowing transmission of further pages to be sent. The simple encoding and low baud rate requires no or minimal RX or TX equalization or dedicated high speed CDR in either Host SOC or pluggable. Note the pluggable optics must be able to bypass any analog or DSP based CDR as 300 Mbaud is too low frequency, such functionality is available in SFP+ and SFP56 for 25 Gb/s Ethernet.

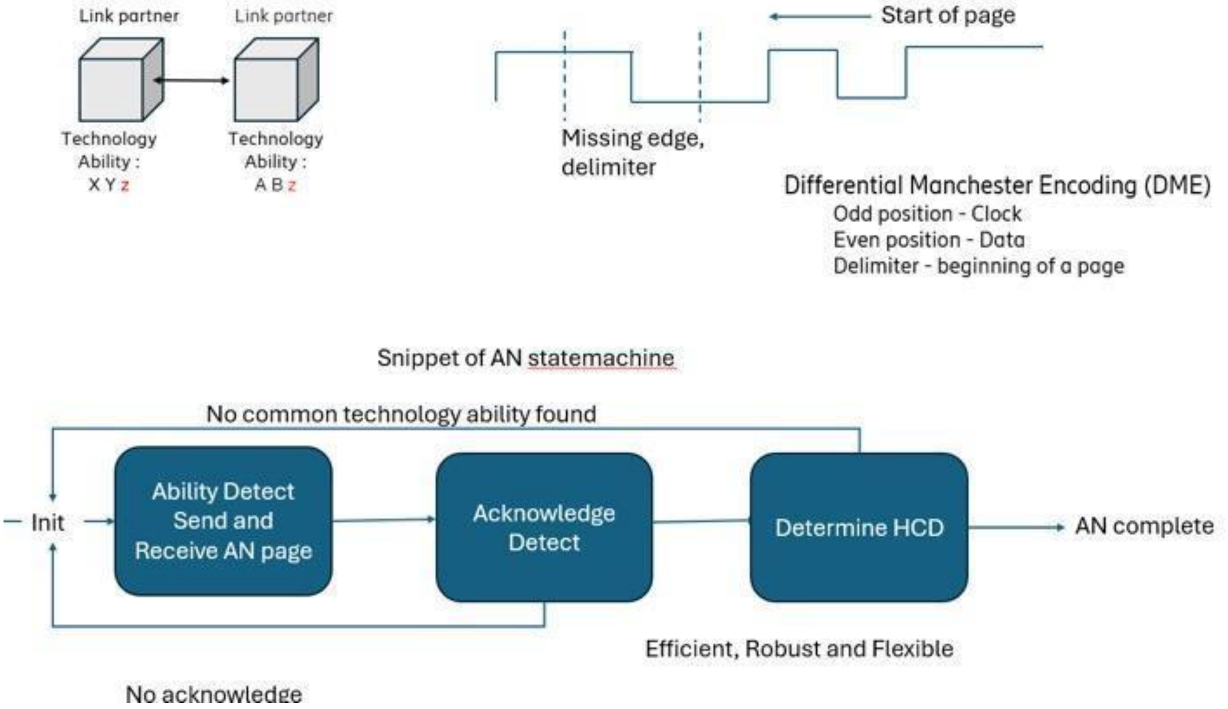


Figure 13: Illustration[3] of the auto-negotiation method in IEEE 802.3 [802.3] clause 73 .

---

[3] HCD = Highest Common Denominator

Another alternative signaling channel method is TX_Disable switching, i.e. using optical module transmitter function TX_Disable for modulation of transmitted bits, and the receiving optical module RX_LOS function for the detection [SFF8419]. Using the same DME scheme as IEEE 802.3 Clause 73 AN, and the practical baudrate limited by laser turn off/turn on times, [SFF 8419] table 6 may support up to 100baud depending on interface between AN state machine and optical module TX_Disable and RX_LOS detection circuitry. To allow for Optical Modulation Amplitude (OMA)-based RX_LOS detection mechanisms, the transmit side needs to ensure that during the laser ON period modulated data is sent.

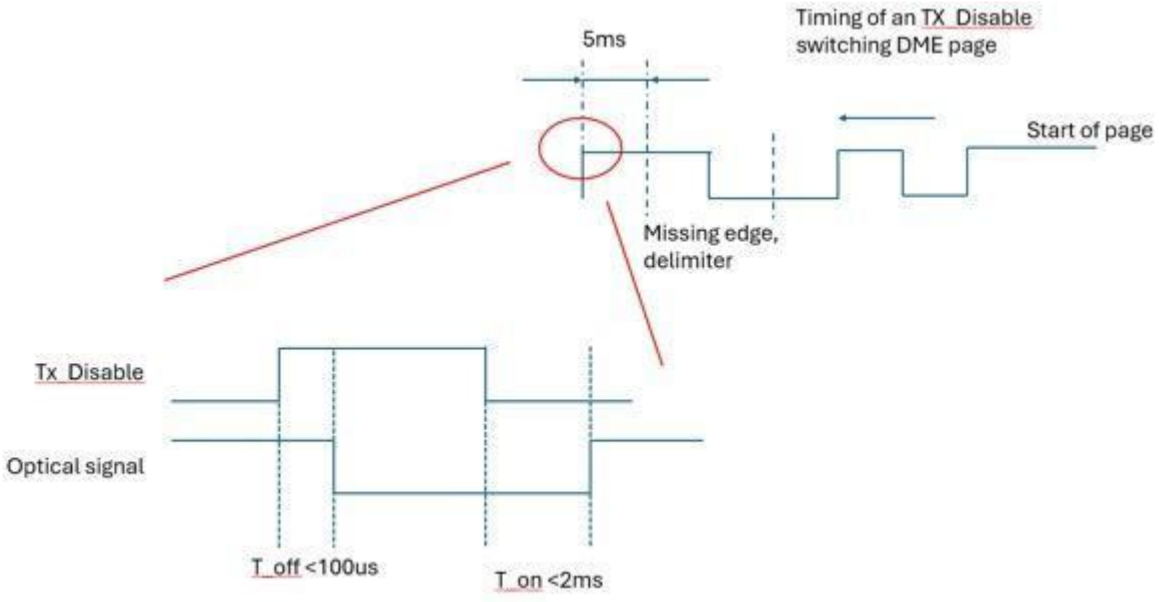


Figure 14: Illustration of theTX_Disable switching as a signaling channel for optical auto-negotiation

An optical AN scheme using TX-Disable switching even at 50 baud has many advantages, over trial and error or an adapted CPRI parallel detect with extended time scale, as Optical AN would always be able to converge on the best line rate in less than 3 seconds. This solution is described in [OAN-ECOC2025].

6.7.30-40 km LLS WDM solutions

MOPA Operator Advisory Board members, and others, have identified the need for 30+ km WDM solutions in mobile LLS. Currently, the longest WDM blueprints specified are 15 km (see [MOPA-RBP]). While commercial 10 Gb/s 40 km systems are available in the market (40 channels, 100 GHz, C-band), achieving 30-40 km with 25 Gb/s IM/DD WDM systems is technically challenging.
Using information from [MOPA-RBP] the resulting required loss budgets are as follows:

- 40 km: O-band 20 dB, C-band 15 dB
- 30 km (extrapolating between 20 and 40 km table values, assuming. 2 dB margin, 6x connectors): O-band 17 dB, C-band 12.5 dB
- Mux/Demux pair loss: DWDM 48 ch 11 dB, CWDM 6 ch 4.5 dB. LWDM (sect. 12.5): 4.5 dB for matched pairs (two variants) or 3.5 dB each side for one variant.

As examples, the resulting total loss for 40 km DWDM in C-band would be 26 dB and 30 km LWDM in O-band would be 21.5 dB for matched pairs or 24 dB for one variant.

Due to the higher loss in O-band, 30 km may be the current limit for cost-effective implementations as well as keeping SFP28 pluggables within a 2. 5W power dissipation envelope, either DWDM (where the grid should be above the ZDW as outlined in sect 12.5 and Annex A) or 12 channel LWDM. For LWDM, an APD receiver is needed, which may also allow for the higher loss case of one variant MUX/DeMUX [tanaka_3ca].

For C-band, chromatic dispersion compensation is required. Electronic Dispersion Compensation (EDC) is the preferred solution, which may allow 40 km DWDM operation. There are indications that SFP28 module power consumption with EDC could be within the target of 2.5 W for E-temp variant and plus a few tenths more below -20degC for I-temp variant. This is to be verified.
There's an interesting comparison between 25 Gb/s NRZ and 12.5 GBd PAM-4. Initial investigations for both EML and MZM transmitters indicate both are viable options: 12.5 GBd PAM-4 may offer lower power consumption while there's no PHY standard for 12.5 GBd PAM-4 systems.

6.8. 100 Gb/s IM/DD LLS WDM solutions

Extending the discussion in the previous section of IM/DD WDM systems, 100 Gb/s operation will be required as a future data rate in LLS systems.
Clearly, at such high data rates, coherent detection (see the MOPA paper on Coherent lite for mobile networks [MOPA-c-lite]) has a clear advantage in overcoming problems with chromatic dispersion and sensitivity. However, using IM/DD when possible is attractive from a footprint (SPFx form factor as required in RUs), power consumption and cost perceptive.
Continuing the example from the previous section, a 15 km 12-channel LWDM system in O-band would require a total loss budget of 16 dB for one variant MUX/DeMUX and 12.5 dB for matched filters. This appears to be achievable using similar technology as in the recent work on 100 Gb/s 40 km BiDi in ITU-T G.9806 Amd 3 and IEEE 802.3dk.

6.9. 100G retimed and linear technology outlook

As introduced in [MOPA-RBP], the next data rate and form factor after 50 Gbps SFP56 is 100 Gbps SFP112.

In order to better understand the 100 Gbps technology and its availability, a survey was sent out to the MOPA members in a previous iteration of this document. (Note that the survey will need to be updated in terms of availability of technical implementations.) The responses are summarized below.

One of the aspects of the survey was to understand the status of retimed and linear implementations. The Figure below illustrates the differences between retimed, LPO and LRO implementations, where the latter remove the DSP or CDR in both Tx and Rx parts or just in Rx part, respectively. The benefit of this would be optical pluggables with lower power consumption and cost, with the drawback of more complex signal integrity engineering including with the host system.

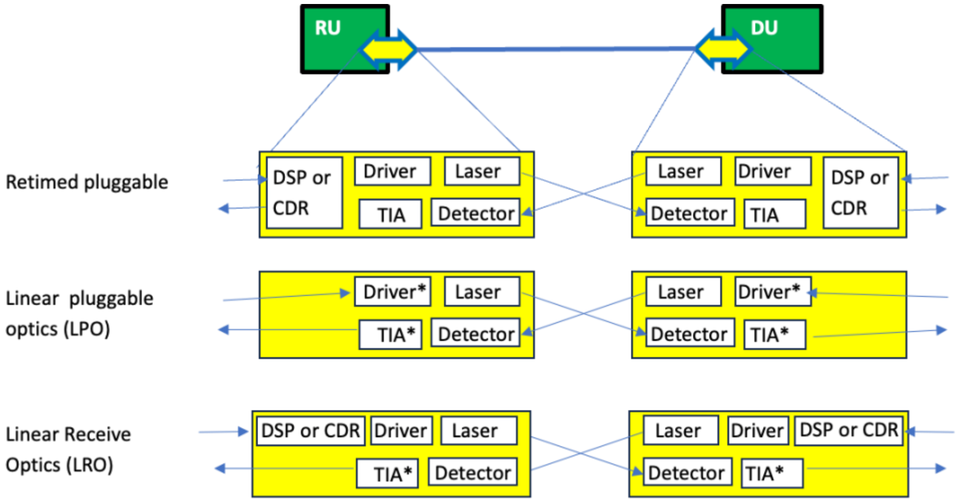


*Figure 15: Illustration of retimed, linear (LPO) and linear receive (LRO) optical pluggables in an LLS example with RU and DU. * Indicates that the laser Driver and TIA (transimpedance amplifier) in the linear implementations may be enhanced with channel equalization capabilities.*

SFP112 signal recovery / integrity features: Several indicate analog CDR but also DSP with equalization is mentioned.

Power consumption:

- **Retimed LR** 10 km: Responses: several stated the ambition to reach the target of 2.5 W, but also 3.5 W and 2.4-3W are indicated.
- **Retimed ER** 40 km: 3.5 W, 2.4-3W and 3-3.5W are indicated.
- **BiDi:** same as dual fiber
- **FR** 2 km: 1.9-2.5W is indicated.
- **LRO:** 1.4-2W is indicated for LR/ER/BiDi.
- **LPO:** 1-1.5W is indicated for FR/LR.

Temperature range: all pluggable options are planned to be available in C-, E- and I-temp.

Multi-rate operation: In general, pluggables implementations will support multi-rate operation, where lower data rates may be supported with CDR bypass.

Enhanced features and management: The responses indicated that SFP112G CDR based pluggables will support BER test, electrical loopback, optical loopback capabilities, while this may not be supported on LPO/LRO modules. The LPO MSA has published a white paper on diagnostic features supported by LPO modules, including link level BER and SNR metrics It's indicated that SFP112G with CDR based will support tight sync class C, while tight sync support with LPO is supported since the latency through the module is minimal. Regarding Diagnostic features, supported functions mentioned are: Tx/Rx amplitude or SNR Monitor and Eye Monitor. LPO modules are inherently rate agnostic and are expected to support rate negotiation which is defined by end-point support. Additional definition of optical rate negotiation in a MOPA environment would be beneficial to ensure interoperable solutions.

6.10. Hollow-core fiber for mobile networks

It has since long been identified that compared with conventional glass fiber [G.652], optical fibers with air/vacuum waveguide results in low attenuation and latency. However, the central question has been how such fibers, i.e. hollow core fibers (HCF) could contain the light to the core. With photonic-crystal fibers, or photonic bandgap fibers (PBG) [NaturePBG], the light is contained to the core but the losses are high and the bandwidth is relatively narrow. Following more than a decade of focused work on nested anti-resonant (NANF) HCF by several groups, a team at Microsoft (which in 2022 acquired the University of Southampton spin-off Luminesity), reported a record low 0.1 dB/km loss at OFC 2024 [HCF-OFC24].

In addition to low loss and low latency (about 1/3rd less than glass fiber), NANF-HCF offers low non-linearity (1/1000th vs glass fiber) and low and flat chromatic dispersion (2-4 ps/(nm*km)) in the band the HCF is designed for (O-band, C-band, etc).

Table 4 summarizes the pros and cons of HCF for mobile networks:

Characteristic	Glass fiber (G.652D)	HCF-DNANF	HCF impact on fronthaul optical link
Signal speed (group velocity) & Latency	(3*108/1.46) = 2.05*108 m/s	(c0 / Group index Group index ≈ 1) 3*108 m/s 33% lower latency	15 km fronthaul latency-induced limit becomes 22 km
Loss	0.2-0.4 dB/km	0.1-0.2 dB/km ~30-50% lower loss	Longer reach with same optics
Chromatic dispersion	~2-5 ps/nm*km O-band ~18 ps/nm*km C-band	2-4 ps/nm*km	Lower cost/lower power consumption for same reach
Rayleigh Backscattering	Main loss factor, limits lasers and bidi transmission	No backscattering in air	Lower cost and power consumption for composition electronics No laser isolator needed. Bidi channels on nominally same wavelength (same SFPs) (needing circulator or splitter)
Non-linearity	Launch power per channel limited to +5-+10 dBm in C-band, typically for stimulated Brillouin scattering, self-phase and cross-phase modulation.	No practical limit	50% longer amplifier span in metro, long-haul and submarine
Cost, maturity	Very mature, ~40 years in the field	Limited field experience. Some deployments from 2025.	5+ years out. Cabling, splicing, connectors industrialization needed Installed fiber there for a long time

Table 4: Characteristics of HCF for mobile networks

It can be noted that currently Microsoft [MS-HCF25] and China Mobile [CM-HCF25] are starting to deploy HCF in commercial networks, albeit in small volumes.

Some operators are studying HCF as an emerging technology in their lab. The benefits are still being investigated, with some indications being lower latency and reduction of Raman scattering for a QKD context. Deployment is not foreseen for the short term.

In the end of 2025, ITU-T SG15 started correspondence and planing around HCF, noting improvements to the loss values (0.05 dB7M @ 15050 nm reported by YOFC at OFC’25) length of single drawing (83 km reported by Linfiber at ECOC’25), connection loss (HCF-HCF：<0.1dB with fusion connection, HCF-SMF：<0.3dB with cold connection), etc.

6.11. Power consumption reduction technologies and methods

In the scope of 25G DWDM tunable optics , MOPA has investigated the feasibility of attaining a lower power 25G tunable suitable for legacy RAN platforms. Current designs, see e.g. MOPA Blueprint 8.3.4, typically consume around 2.5W, which newer platforms can handle, but many older systems support a lower value, for example only up to 2W. A small study was conducted to explore whether tunable optics can achieve power consumption below 2.5W across different temperature ranges (-40°C to 85°C or -20°C to 85°C). Two strategies were examined: limiting the operating temperature range to reduce power consumption, and lowering transmitter output power, each with trade-offs in applicability or transmission reach.

Test results revealed that power consumption increases at colder temperatures, with up to 15% higher consumption at -40°C compared to -20°C, and approximately 10% higher at -40°C than at 85°C. Figure 16 illustrates the power consumption profiles for 6 samples tested at -40°C and then -20°C across 48 DWDM channels (100GHz spacing).

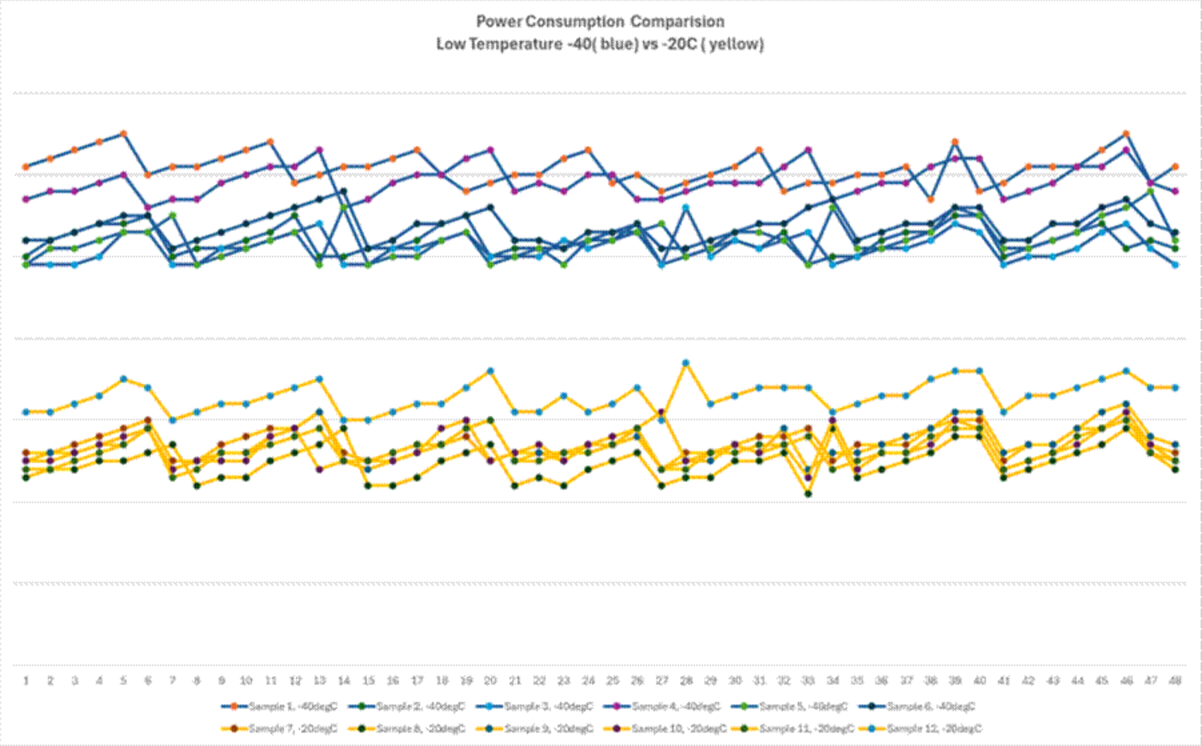


Figure 16: Power Consumption Comparison at Low Temperatures

Similarly, higher transmit power calibration increased power consumption, with up to a 6.5% difference between low (-2 dBm) and high (2 dBm) settings. The percentages might vary depending on the transceiver design and power dissipations profile, but we expect the conclusion to be similar. Figure 17 shows a sample that has been calibrated at different Tx power levels and the power consumption profile associated with each.

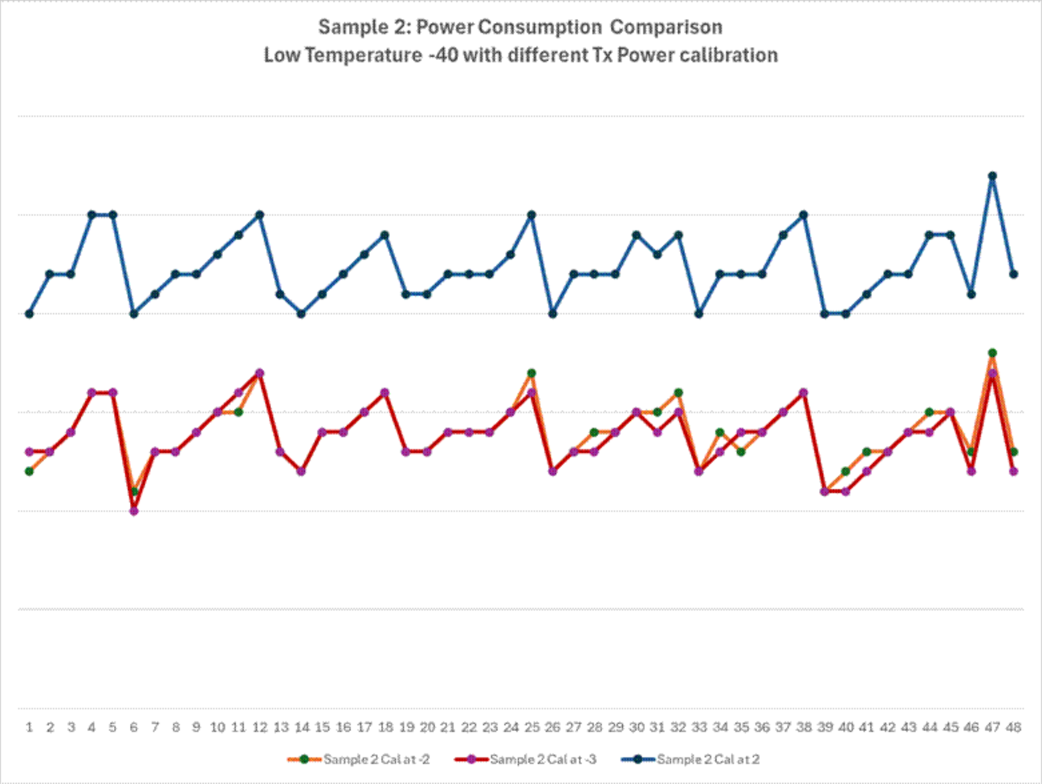


Figure 17: Power Cunsumption Comparison at different Tx power calibrations

The findings suggest that defining a power consumption profile with higher limit from -40° to -20° at 2.5W and a lower limit from -20° to +85° at 2.0W (these temp limits and power consumption numbers are examples only, in line with the considerations in 6.1.2,) , and/or reduced transmit power could be viable paths to lowering power consumption. It is important to note that RAN vendors need the -40C operating temperature limit for modules to target deployments in harsh weather conditions. The lower transmitter output power is still expected to meet the applicable MOPA DWDM blueprints such as 8.3.4. These changes could influence MOPA blueprints and lead to new power class definitions for SFP28 modules, ultimately supporting more cost-effective cooling solutions and energy-efficient deployment across RAN architectures.

6.12. Quasi-Coherent Receiver Technology

Introduction

Quasi-coherent receiver (QCR) technology is an optical heterodyning technique that relies on advanced analog RF signal processing to compensate for chromatic dispersion [JLT-QCR1, JLT-QCR2]. It thus provides a DSP-free method of increasing the dispersion limited reach of IMDD systems. In addition, due to its inherent wavelength selectivity, it enables WDM over a point-to-multipoint ODN without the need for WDM-demultiplexers.

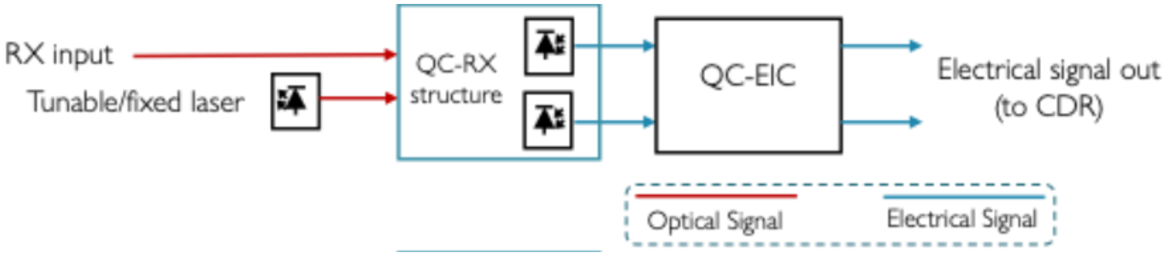


Figure 18: Functional block diagram of a Quasi-Coherent (QC) receiver.

As shown in Figure 18, the optical signal is mixed with the light from the LO laser. The Quasi-Coherent Electronic Integrated Circuit (QC-EIC) consists of a trans-impedance amplifier (TIA) stage, an chromatic dispersion compensation (CDC) analog RF-filter, an envelope detector that converts from radio frequency (RF) to baseband data, and an output buffer that conditions the signal for an off-the-shelf clock and data recovery (CDR) chip.

In contrast to conventional coherent detection, QC-receivers do not require a DSP. It operates on the principle of optical heterodyning where a frequency offset (typically 30-50 GHz) eliminates the need for carrier-phase recovery and phase diversity in the receiver structure, thereby removing the need for a DSP. On the downside, QC is only suitable for amplitude modulated signals, such as NRZ and PAM4. Polarization multiplexing can in principle be used, but would require would require either DSP-based butterfly equalizers or optical polarization tracking techniques to work. QC is therefore best viewed as an upgrade to IMDD systems – not as a competitor or alternative to “full” coherent.

An additional advantage – especially for mobile networks – is that since there is no DSP, the latency is the same (and low) as for IMDD.

Receiver Architecture

A functional block diagram of the QCR is shown in Figure 18. The weak, incoming optical signal is combined with a relatively high power optical local oscillator (LO) and detected by two pairs of balanced PIN photodetectors. The LO is frequency off-set from the signal by typically 20-50 GHz depending on the data rate and the design of the QC-EIC. This means that the photocurrent is not a baseband signal as it would have been if detected by a standard IMDD receiver. Rather, it is an RF signal centred on the intermediate frequency between the signal and LO. This signal requires demodulation e.g. by an envelope detector before being compatible with standard IMDD clock and data recovery (CDR) chips. This is provided by the QC-EIC along with electrical transimpedance amplification and chromatic dispersion compensation (CDC).

The QC-EIC provides a standard non-return-to-zero (NRZ) differential signal compatible with off-the-shelf clock-and-data recovery (CDR) circuits. Polarization diversity is implemented in the SiPh Photonic Intergrated Circuit (PIC) to provide independence to the polarization of the incoming signal.

Analog (near-zero latency) chromatic dispersion compensation (CDC)

Chromatic dispersion is a frequency domain distortion leading to time domain pulse broadening. It can be viewed as a linear group-delay variation across the optical spectrum. In other words, the different spectral components constituting the optical signal travels through the fiber at different speeds. Since the optical signal is a double sideband signal, this leads to a phase shift between corresponding frequency components of the upper and lower sidebands. When this phase shift reaches 180 degrees, that frequency is cancelled by destructive interference in an IMDD detector, which in the frequency domain can be viewed as a "folding" around the optical carrier. This leads to notches in the IMDD spectrum. As the fiber distance increases these notches move down in frequency. When a notch reaches the Nyquist frequency (approximately half the symbol rate of the optical signal), the signal can no longer be recovered by an IMDD receiver without advanced signal processing in the form of a DSP. For 25 Gbps NRZ signals, this happens at approximately 12-15 km standard SMF transmission depending on the amount of frequency chirp from the transmitter.

With QCR, the double sideband signal is converted from optical to RF without folding the upper and lower sidebands around the carrier. It is therefore possible to compensate for chromatic dispersion using analog RF phase filters that have near-zero latency and power consumption. As an example, C-band transmission at 25 Gbps at distances of up to 40km have been demonstrated using this technique. This same approach can be extended to high baud-rates and PAM4 modulation formats. For 50 Gbps PAM4, 20 km reach in the C-band is achievable.

Performance

Figure 19 shows measurements of QCR for 25 Gbps NRZ C-band signals transmitted over 0, 20 km and 40 km SSMF. Best performance is observed after 20 km, which is the setting point of the built-in chromatic dispersion compensation. Receiver sensitivity after 40 km is -20 dBm. These results are achieved using standard EML transmitters and a standard 25 Gbps NRZ CDR chip from Semtech.

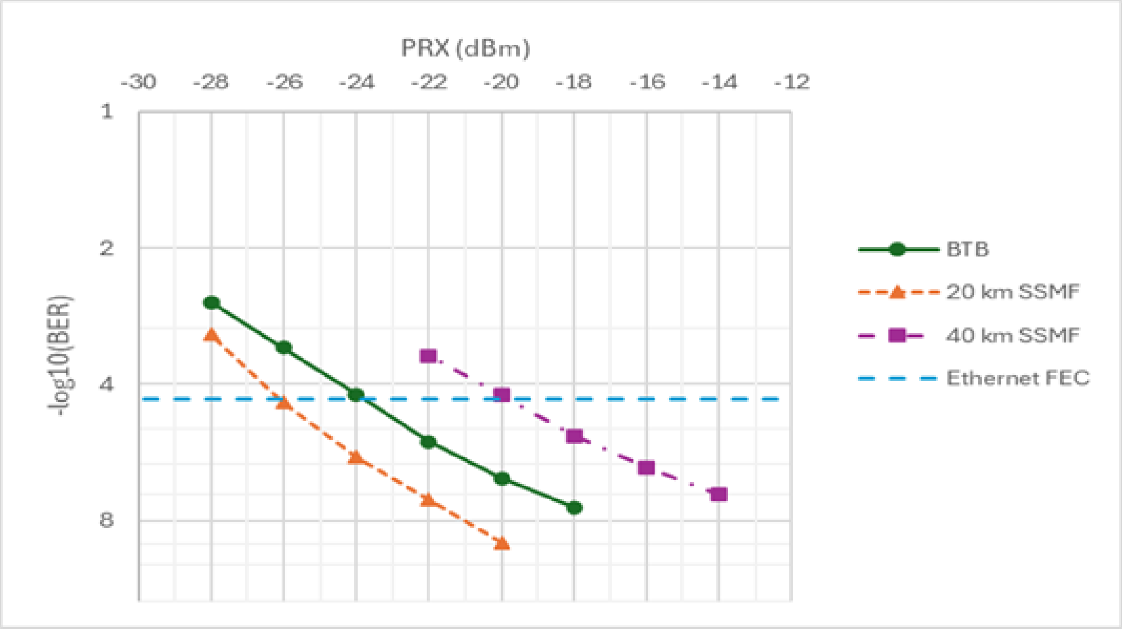


Figure 19: Measured bit error ratio (BER) vs receiver input power for 25 Gbps NRZ signals received by Quasi-Coherent receiver after 0, 20 km and 40 km SSMF transmission in the C-band

Table 5 shows a pros/cons comparison table between IMDD, QCR and DSP enabled coherent.

	IMDD	**IMDD w/ eCDC**	**DSP Coherent**	**QCR**
25 Gbps C-band reach	15 km	40 km	+1000 km	40 km*
50 Gbps PAM4 C-band reach	10 km	N/A	+1000 km	20 km*
Cost	low	medium	high	medium
Power consumption	Less than 3W (I-temp) for SFP28/56	Less than 3W (I-temp) for SFP28	Above 5W	Less than 3W (I-temp) for SFP28/56
Latency	low	low	high	Same as IMDD

*) Longer reach under development

Table 5: Comparison IMDD - IMDD w eCDC - DSP Coherent - QCR

6.13. Single-laser (wavelength) DSCM-based coherent communication for Adaptive and Flexible Bi-directional (Bi-Di) transmission over single fiber

Single fiber transmission capability is desirable in Radio Access Network (RAN) transport, as illustrated in Figure 20. It offers better usage of available fiber, where fiber is scarce, as it halves the number of required fibers. It provides better timing and synchronization for 6G, and more importantly, removes potential time synchronization error. Furthermore, it provides compatibility with passive optical networks (PONs) architecture, and finally, it secures faster replacement after events such as fiber cuts compared to dual-fiber architecture [MOPASync]. In coherent systems over single-fiber, the transceivers (TRx) with single laser architecture, enabling single-wavelength transmission, is also preferable to be employed in such networks, due to the low-cost envelope and ease thermal management.

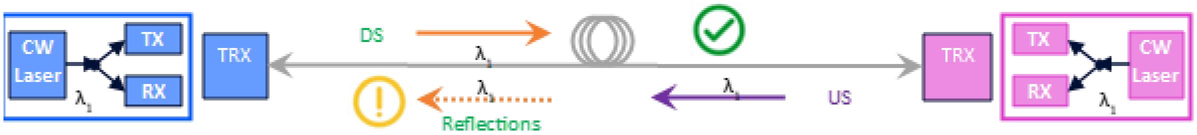


Figure 20: Single-fiber transmission using single laser transceiver (TRx)

Coherent communications either use a single carrier or use Digital SubCarrier Multiplexing (DSCM). The use of DSCM allows for lower symbol rates and flexible bandwidth allocation.
XR technology [JLT-XR1], [JLT-XR2] is a DSCM-based coherent communication solution, in which coherent TRxs use a single-laser and support single-fiber transmission, might address the requirements and challenges of RAN transport. It utilizes digital subcarrier multiplexing (DSCM) signaling scheme consisting of 16 digital subcarriers (DSCs). Each DSC has a ~4 GBaud signal with a bandwidth (BW) of ~4GHz, offering in total 400 Gb/s signal over ~67 GHz BW, including a guard-band of ~300 MHz between the DSCs. The DSCM scheme also enables to realize single fiber solutions for up to 200G, in which half of the DSCs can be allocated for only downstream (DS), and the other half would be for only upstream (US) transmission.

The DSC allocation of an XR signal depending on the modulation format (QPSK or 16-QAM) is depicted for 100 Gb/s single-fiber P2P applications in Figure 21, in which 12.5G (QPSK) or 25G (16-QAM) per DSC x 8 or 4 DSC are used for DS and US, separately. In both scenarios, the HUB has a free-running laser, whereas the LEAF laser gets locked to its HUB laser, i.e., leading to <+/-300 MHz frequency offset compensated in digital signal processing (DSP). It is worth noting that the back-reflected DSCs do not overlap with the signal (DSCs) of interest and the DSCs are processed in parallel in DSP. In such applications, the performance is mainly limited by back reflections in case of pre-amplification due to analog front-end, specifically TIA and ADC quantization noise.

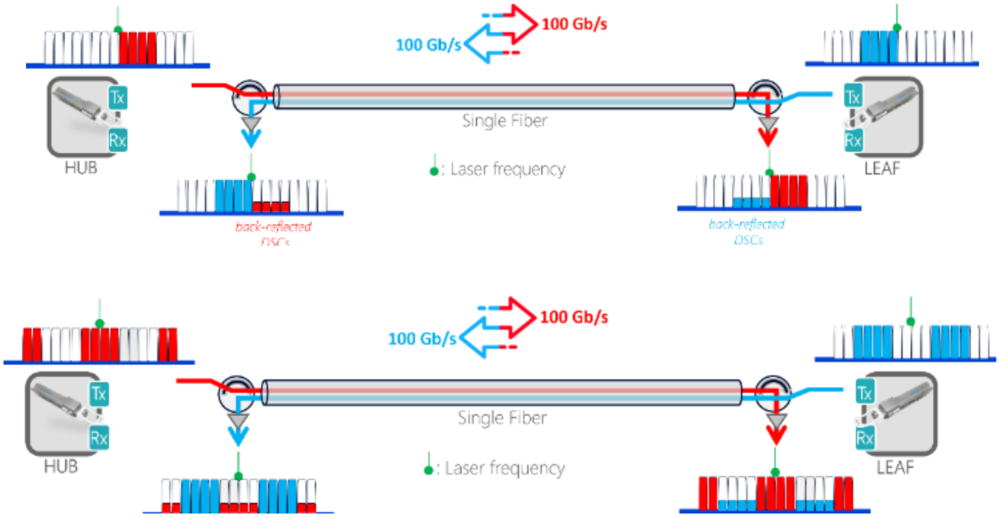


Figure 21: (top) P2P 100 Gb/s 16-QAM (bottom) QPSK single-fiber applications using XR technology

The same architecture can also support 200 Gb/s per direction by increasing the number of DSCs from 4 to 8 if the modulation format is chosen to be 16-QAM. If the application of interest requires higher link budgets and/or longer transmission distances, QPSK signaling is preferable but the total capacity per direction is limited to 100Gb/s since all available DSCs are used.

The impact of reflections with possible strategies to mitigate them in a bidirectional transmission (BiDi) link over single-fiber using (-laser, -wavelength) was investigated. This scenario is useful for the next generation beyond 5G (B5G) and 6G mobile transport, where reflections (discrete and distributed) might play a major role under the aforementioned assumptions.

We compared two transceiver solutions: digital-subcarrier multiplexing (DSCM) based (Open XR [Open XR] optics) and single carrier (ZR like optics). In the first solution DSCM creates virtual channels that can, for example, be aggregated with passive couplers, thus avoiding the electronic aggregation layer, as illustrated in Figure 22.

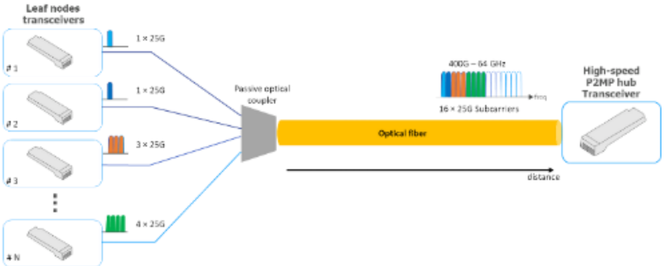


Figure 22: Optical aggregations, realized with a passive optical coupler of signals generated by multiple transceivers

In addition, DSCM-based transceivers can significantly increase the flexibility of the spectrum allocation

– thanks to the embedded granularity provided by the subcarriers, and enable mitigation of reflections, by interleaving the digital subcarriers in frequency domain. We demonstrated this using the testbed shown in Figure 23. The experiment was carried out in a lab. The discrete reflections were emulated and thus controlled by a variable optical attenuator (VOA); while the distributed reflections were just caused by the propagation over fiber.

We tested two approaches to mitigate reflections: (i) by interleaving the subcarriers – note this can be also realized by single carrier transceivers, but it requires two lasers; (ii) by optimizing the power of the individual transceivers.

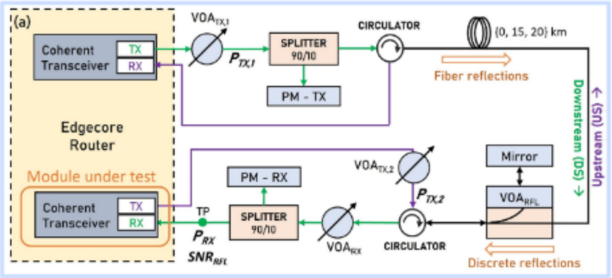


Figure 23: BiDi experiment, including discrete and distributed reflections

Figure 24 (right) shows the key result obtained and presented at ECOC 2024. The full-mode (complete overlapping in frequency, black curve) is the common solution that can be also realized with traditional P2P transceivers; while the half-mode (interleaved in frequency, blue curve) is a clear benefit of the DSCM approach. This last solution presents an almost negligible power penalty caused by both types of reflections.

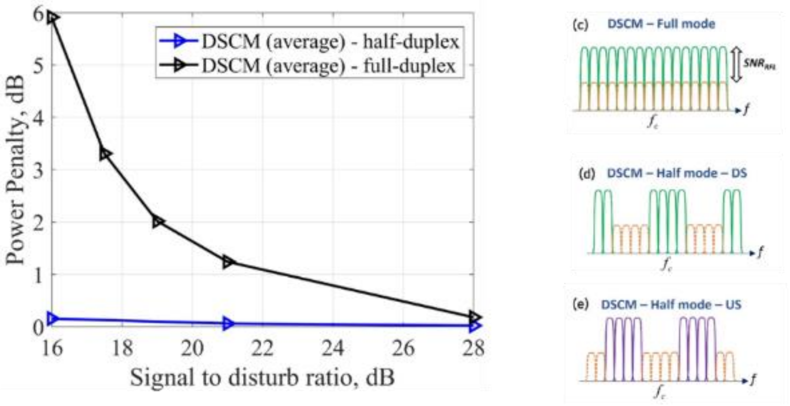


Figure 24: (left) Power penalty vs Signal to disturb ratio for full-mode (black) and half-mode (blue); (right) scenarios considered.

The last results are reported in Figure 25. The left-hand side shows a typical front haul testbed realized with DSCM-based transceivers. Here, a single hub transceiver can receive multiple signals (here subcarriers) from several leaf nodes. The plot on the right shows an example of optimization based on the heuristic variation of the individual powers of the modules – obtained by tuning the VOAs at the leaf nodes. [ECOC25-XR] describes a first version of a more advanced physical layer-based optimization.

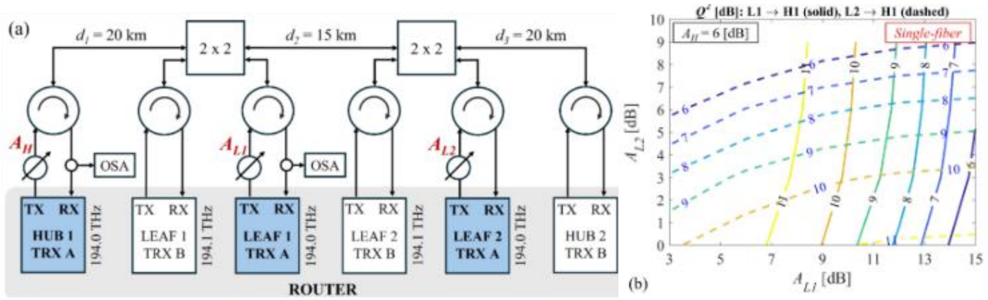


Figure 25: Setup and exemplary of multi-power optimization

7. Summary of technologies for operational purposes

Operations of advanced networks such as mobile optics constitutes a high cost for operators. Thus, new technologies that can simplify and lower the cost of operations, for example by being faster and/or less resource demanding, are very important.
The term "new" does not necessarily refer to the novelty of the optoelectronics themselves, but to their use and integration for addressing specific operational needs in real deployments. This leads to pluggables that have extra functionality on top of the data transport itself.

7.1. Automatic identification of optical line

The challenge

One of the major service outages is optical fiber cut. As an example, in South Korea it has been estimated that more than 500 cases occur per year, mostly at excavation sites.
Engineers have to repair the cuts by splicing the right fibers together, but this is made more complex and error-prone when only relying on cable colour codes, leading to incorrect splicing and delays in service restoration. Also, excessive cable pulling can sometimes damage the cable connections inside the enclosure.

Without clear physical labeling of the cables and their fibers a lot of time is spent in identifying them and in finding out which fibers must be matched. One manual method is to inject visible red light into the cables from both remote ends to visually pair the fibers to be spliced together. The drawback of the approach is that it requires simultaneous presence of field workers at the accident site and at the end stations on both sides. It also limits the distance to the propagation distance in fiber of red light of 5-6 km, well below the 20-30km reach of mobile transport.

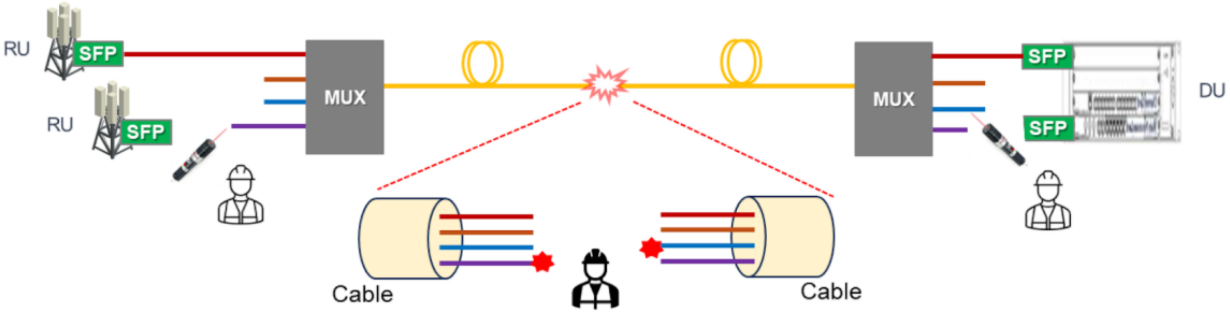


Figure 26: using red light for matching fiber pairs

The solution

A more swift and automated way to identify individual fibers is for each optical module to transmit a unique identifier during loss of transmission and read the corresponding identifier from a broken fiber at the accident site. Such transmission can be very low speed (e.g. 5 kbit/s) and carry the serial number of the optical module on the host system.
At the location of the cut, a given pair of fibers is plugged into a dedicated optical receiver, their identifiers are read and transmitted to the field engineer's smartphone by bluetooth. The smartphone application compares the line identification information with the operator's NMS system to identify the system associated with the optical line and displays the results.

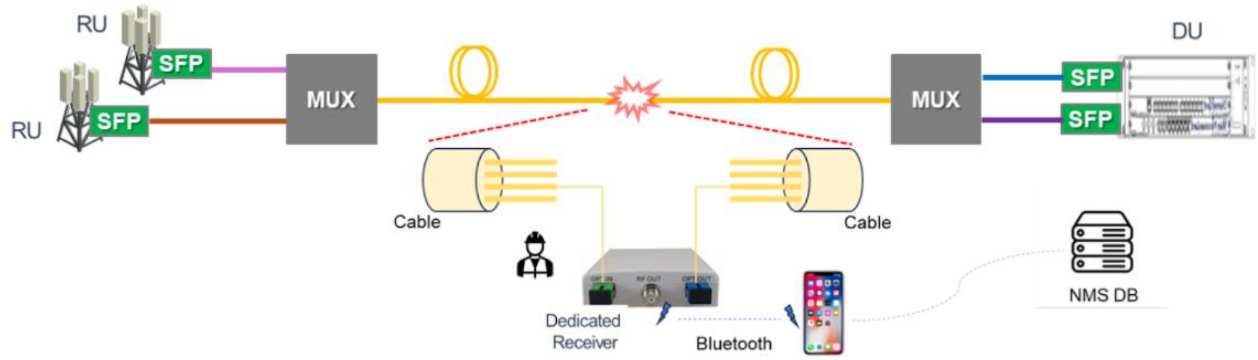


Figure 27: using OOB identifier for matching fiber pairs

The same solution is also useful during initial installation process, where the information of transport system connected to a given optical cable can be remotely identified at the Fiber Distribution Frame, which is located at some distance away from the transport system.

The functionality has been entirely implemented by SKT by firmware update of the optical pluggables, without requiring hardware modifications or changes at the host system side.
The solution can be also used in the context of multiple WDM wavelengths or multiple PON ONUs per fiber, by employing a random slot transmission scheme. Each transmitter selects a random slot position in every given fixed period, leading to randomness in collisions, whose invalid signals are discarded by checking the CRC of the messages.

Current use and next steps

The concept has been implemented by SKT in various kinds of the optical pluggables for the optical access network and deployed in the field. The range of optical pluggables is expected to expand further including 10Gbit/s BiDi and G-PON.

A second version of the field optical receiver has been developed in the form of a clip-on coupler, eliminating the need for fiber connectorization in the field.

7.2. In-field detection of device by means of pluggable identifier

Challenge

An operational challenge during installation and maintenance (at the customer premises or at access points in the fiber plant) is the detection of improper fiber handling or defects that degrade the light transmission (causing light leaks). Another challenge is similar to the case of fiber cuts mentioned in section 7.1, namely the identification of the device attached to a given fiber for trouble-shooting or repair purposes. In the case of PON the device is the ONU, in the case of mobile fronthaul the device is the RU or DU.

The solution

A solution to both challenges has been elaborated by Orange by integrating a red (650nm) LED in the optical module of the device. A first use case is to add the red LED in a PON ONU module, creating a TriOSA. The use of the red signal use is twofold.

Firstly, it enhances the reliability by helping a technician as visual fault locator (VFL) during installation and maintenance. The light is flashing for easy detection.

Secondly, the VFL can be modulated with a unique ONU identifier, allowing to identify the remote user on a faulty link. The detection of the light modulation and reading of the ID is done by pointing the smartphone camera to the light source (fiber end, severely bent fiber, faulty splice, ...).
So the red light serves two purposes; a quick visual inspection, and identification of the customer affected. An error-free transmission at 18 bit/s over 6km has been demonstrated.

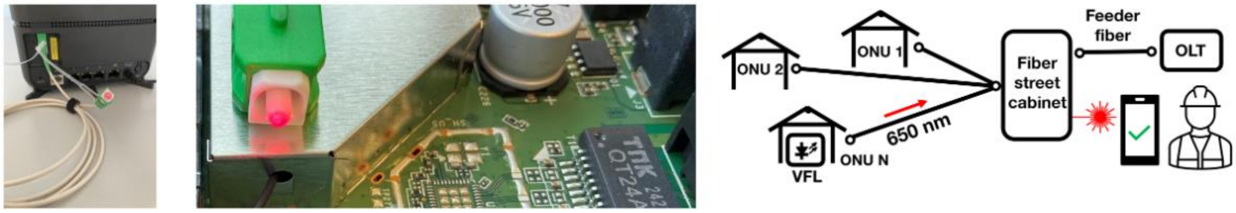


Figure 28: integrated red LED as VFL

- 650 nm TX modulated by an Arduino Uno.
- Modulation voltage = 2 Vpp

Detection and decoding

- Mobile application running on Android smartphone (Samsung S20).
- Camera frame rate = 60 frames/s
- App sampling frequency = 32 Sa/s
- The measure of the intensity of the light in a four-dimension space (R, G, B and time) is performed in the red square.
- The measure is started and stopped manually.

Figure 29: Integrated TriOSA carrying ONU ID and read-out on smartphone app

In customer premises, the VFL allows the technician to verify the integrity and continuity of the optical signal (no breaks, bends, bad splices, etc.).
The same VFL is used at the street cabinet to check the connection and modem ID from the user premises to the street cabinet hosting the coupler, without the need for an appointment with the customer. Note that most fiber optic breaks or patching issues occur between the customer outlet and the street cabinet's coupler.
A standalone version of the VFL is used by the technician to check the fibers being used and when a splice point is crossed (building splice, sidewalk splice, etc.). It can also be used at the optical central office during specific operations (equipment swap, OLT repair) to control the links between each PON port of the OLT and the cable heads which are in different technical rooms including crossings of patching elements.

Besides PON deployments, the same technique is also applicable to point-point pluggable modules for (short reach) mobile xhaul at both the RU side and the network node side. The integrated VFL helps a technician in deployment and maintenance, like during equipment swaps or repair operations. Uses cases are RU identification without needing to climb the tower (a single tower can have a patch panel for multiple fiber connections, e.g. 3 RUs x 2 SFPs x 2 fibers (duplex) giving 12 fibers per tower), remote inventory of fiber and connected equipment (RUs, DUs), etc. The VFL can be integrated in duplex modules and in BiDi modules.

Current use and next steps:

The VFL is available both in Orange’s GPON fiber gateway “LiveBox S”. Next steps are to include the VFL in the OLT MPM (Multi PON Module GPON+XGS) optics to allow identification of central-office side fiber, and in Point-point modules.

8. Conclusions

Optical solutions are essential enablers for the global mobile network rollouts, as they bring capacity and performance needed for 5G and future 6G transport. Some solutions are dedicated to facilitate operations (during installation and repair events).

The review in this paper of multiple relevant technological developments in the context of mobile transport aims to provide a common view and understanding of their potential as future solutions for Mobile Blueprints.

9. References

[OptConn] S. Dahlfort, et al. "5G Mobile Pluggables - Blueprints for Global Deployments", https://opticalconnectionsnews.com/webinars/optical-connections-webinar-series-5g/

[MOPA-NT] MOPA Technical Paper – New Technologies

[MOPA-RBP] MOPA Technical Paper – Requirements & Blueprints

[MOPA-MO] MOPA Technical Paper – Market Outlook

[802.3cz] IEEE 802.3cz Physical Layer Specifications and Management Parameters for Multi-Gigabit Glass Optical Fiber Automotive Ethernet

[MOPA-c-lite] MOPA Technical paper " Coherent lite for mobile networks", Version 1.0, March 25, 2024, https://mopa-alliance.org/papers-and-presentations/

[Smart Tunable MSA] Self-Tuning Optics Interoperability Specification v2.0, smarttunable-msa.org

[MOPA-sync] MOPA Technical paper "Optical pluggable performance for tight synchronization", Version 1.0, March 25, 2024, https://mopa-alliance.org/papers-and-presentations/

[MOPA-syncImpl] MOPA Technical paper "Implementation considerations about FEC and MII extensers for tight sync". Version 1.0, Sept 22, 2024, https://mopa-alliance.org/papers-and-presentations/

[SFF-8472] "Specification for Management Interface for SFP+", Rev 12.5, August 1, 2025

[Paper1] E. Forestieri, M. Secondini, L. Potì and F. Cavaliere, "High-Speed Optical Communications Systems for Future WDM Centralized Radio Access Networks," in Journal of Lightwave Technology, vol. 40, no. 2, pp. 368-378, 15 Jan.15, 2022, doi: 10.1109/JLT.2021.3131399.

[Paper2] P. Iovanna et al., "Optical Components for Transport Network Enabling The Path to 6G," in Journal of Lightwave Technology, vol. 40, no. 2, pp. 527-537, 15 Jan.15, 2022, doi: 10.1109/JLT.2021.3117122.

[Paper3] "FWM simulations in O-band", Dora van Veen & Vincent Houtsma, Nokia Bell Labs – contribution to the P802.3ca IEEE Task Force: https://www.ieee802.org/3/ca/public/meeting_archive/2016/07/van_veen_3ca_1_0716.pdf

[Paper4] N. Shibata, R. P. Braun, and R. G. Waarts, "Phase-mismatch dependence of efficiency of wave generation through four-wave mixing in a single mode optical fiber," IEEE J. Quantum Electron., vol. 7, pp. 1205-1210, July 1987.

[Paper5] K. Inoue, "Four-wave mixing in an optical fiber in the zero-dispersion wavelength region," J. Lightwave Technol., vol. 10, pp. 1553-1561, Nov. 1992.

[G.652] ITU-T Rec. G.652 "Characteristics of a single-mode optical fibre and cable". Nov 2016

[eCPRIreq] CPRI. "Transport Network V1.2 (2018-06-25) Requirements Specification Common Public Radio Interface: Requirements for the eCPRI Transport Network"

[ORAN-CTI] O-RAN Technical Specification WG4.CTI-TCP.0-v01.00 "Cooperative Transport Interface Transport Control Plane Specification", 2020 (v2 2021 pending).
O-RAN Technical Specification WG4.CTI-TMP.0-v01.00 "Cooperative Transport Interface Transport Management Plane Specification", 2020 (v2 2021 pending)

[G.Sup.71] ITU-T series G Supplement 71 "OLT Capabilities for supporting CO DBA" (publication pending)

[25GSPON] 25G PON MSA group, "25GS-PON Specification: 25 Gigabit Symmetric Passive Optical Network" v2.0, Aug 2021

[G.9804.x] ITU-T Rec. G.9804.1 Amd2, G.9804.2 Amd2, G.9804.3 Amd2 "Higher speed passive optical networks (HSP)"

[G.989.x] ITU-T Rec. G.989.1, G.989.2, G.989.3 “40-Gigabit-capable passive optical networks (NG-PON2)

[G.698.4] ITU-T Rec. G.698.4 “Multichannel bi-directional DWDM applications with port agnostic single-channel optical interfaces”, June 2018[MOPA-RemMon] “MOPA Remote Performance Monitoring Specification”, v1.0, May 21, 2023. See https://mopa-alliance.org/papers-and-presentations/

[cpri7.0] See http://cpri.info/spec.html

[eCPRI] See http://www.cpri.info/downloads/eCPRI_v_2.0_2019_05_10c.pdf

[802.3] https://www.ieee802.org/3/

[SFF-8419] “Specification for SFP+ Power and Low Speed Interface”, Rev 1.3 June 11, 2015

[OAN-ECOC2025] https://ecoc2025.abstractserver.com/program/#/details/sessions/54

[tanaka_3ca] https://www.ieee802.org/3/ca/public/meeting_archive/2016/11/tanaka_3ca_1_1116.pdf

[NaturePBG] Jonathan C. Knight “Photonic crystal fibres” Nature volume 424, pages 847–851 (2003), 14 August 2003

[HCF-OFC24]. OFC 2024. Post deadline paper Th4A.8

[MS-HCF25] https://techcommunity.microsoft.com/blog/azurenetworkingblog/the-deployment-of-hollow-core-fiber-hcf-in-azure’s-network/4395340

[CM-HCF25] https://www.lightreading.com/cable-technology/chinese-operators-get-cracking-on-hollow-core-fiber

[JLT-QCR1] J. A. Altabas et al., "Real-Time 10 Gbps Polarization Independent Quasicoherent Receiver for NG-PON2 Access Networks," in Journal of Lightwave Technology, vol. 37, no. 2, pp. 651-656, Jan, 2019, doi: 10.1109/JLT.2018.2880361.

[JLT-QCR2] J. A. Altabas, et al., "DSP-Free Real-Time 25 GBPS Quasicoherent Receiver With Electrical SSB Filtering for C-Band Links up to 40 km SSMF," in Journal of Lightwave Technology, vol. 38, no. 7, pp. 1785-1788, April, 2020, doi: 10.1109/JLT.2019.2963787

[JLT-XR1] Welch, D., Napoli, A. et al. (2021). Point-to-multipoint optical networks using coherent digital subcarriers. Journal of Lightwave Technology, 39(16), 5232-5247

[JLT-XR2] Welch, D., Napoli, A. et al. (2023). Digital subcarrier multiplexing: Enabling software-configurable optical networks. Journal of Lightwave Technology, 41(4), 1175-1191.

[Open XR] “Open XR Signal Specification”, OXR.SigSpec.01.00, Sept. 2024, https://openxropticsforum.org/documents

[ECOC25-XR] Single-Fiber Single-Wavelength Bidirectional Digital Subcarrier Point-to-Multipoint Coherent Systems for Beyond 5G Transport”, P. Torres-Ferrera et al., ECOC 2025