Mobile Optical Pluggables Alliance (MOPA)

Technical paper – Requirements & Blueprints

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1. Executive summary

From the International Mobile Telecommunications (IMT) visions for consecutive generations of mobile systems (see the 2020 vision [M2083] for 5G and the 2030 vision [M2160] for 6G) and resulting global and national efforts, the spectrum allocations for mobile systems are growing. This together with innovative and high bandwidth consuming applications drives transport network capacity growth, resulting in an urgent and significant need for high-capacity and cost-effective optical solutions as part of those mobile transport networks.

Consequently, there is a need for a shared and common view of the optical solutions needed for mobile transport [OptConn]. This has several benefits:

- Technological and architectural: fewer and better suited architectures and technologies.
- Cost: operators, system vendors and optical pluggables suppliers can better focus on the most relevant needs.
- Availability: having the right solution commercially available at the right time and at the right cost.

An improved common understanding and focus can be achieved by making *mobile optical blueprints* resulting in:

- Clear optical pluggable needs for operators, systems vendors and pluggable suppliers.
- An eco-system ensuring timely, cost-efficient, and optimized architectures.

By *mobile optical blueprint* we mean a network solution description documenting a use case with the optical pluggables and passive optical components (wavelength division multiplexing (WDM) mux, splitter, etc.) implementing that use case, with high-level optical and pluggables requirements.
The Blueprints in this paper—nineteen in total—cover all globally relevant deployment variants for distributed radio access networks (DRAN), centralized RAN (CRAN) and virtualized RAN (VRAN) for the links connecting the radio units (RUs) with distributed units (DUs), DUs with centralized units (CUs), and CUs with the mobile core.

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

- **Requirements & Blueprints [MOPA-RBP]:** General functional requirements, and mobile optical blueprints for C-RAN, D-RAN and VRAN, based on available technologies.
- **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 technologies in the context of mobile applications.

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

From the International Mobile Telecommunications (IMT) visions for consecutive generations of mobile systems (see the 2020 vision [M2083] for 5G and the 2030 vision [M2160] for 6G) and resulting global and national efforts, the spectrum allocations for mobile systems are growing. This together with innovative and high bandwidth consuming applications drives transport network capacity growth, resulting in an urgent and significant need for high-capacity and cost-effective optical solutions as part of those mobile 5G transport networks.

MOPA aims to develop a shared and common view of the optical solutions needed for mobile transport. This vision is described in three Technical Papers consisting of:

- **Requirements & Blueprints [MOPA-RBP]:** General functional requirements, and mobile optical blueprints for C-RAN, D-RAN and VRAN, based on available technologies.
- **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 technologies in the context of mobile applications.

This Requirements & Blueprints technical paper outlines the authors’ view of the functional requirements for optical pluggables intended for use in mobile RAN equipment. It clarifies the capabilities these pluggables must provide and reduces barriers to adoption by specifying the development priorities relevant to the RAN environment, helping avoid investment in solutions with little or no demand. The goal is to enable robust, competitive optical components and solutions for mobile networks, ultimately benefiting end users.

By mobile transport we mean networks to connect RAN equipment such as RUs, DUs and CUs, including eNodeB and gNodeB, and also transport equipment such as cell site gateways and active WDM equipment dedicated to mobile traffic[1].

This paper organizes and integrates existing standards and implementation agreements produced by Standards Development Organizations (SDO), Industry Fora and multi-source agreements (MSAs), where the Blueprints cover the different technical aspects, forming a broad description of optical solutions useful and important for mobile transport networks.

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[1] In this document, RAN node terminology is reused from [TS38306], [TS38470] and [GSTR-TN5G].

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 Negotiation
AOC	Active Optical Cable
APC	Angled Polished Connector
AWG	Arrayed Waveguide Grating (optical DWDM multiplexer)
B5G	Beyond 5G
BiDi	Bi-Directional (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 wavelength (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 wavelength (aka “2nd window”)
OAN	Optical Auto Negotiation
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
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

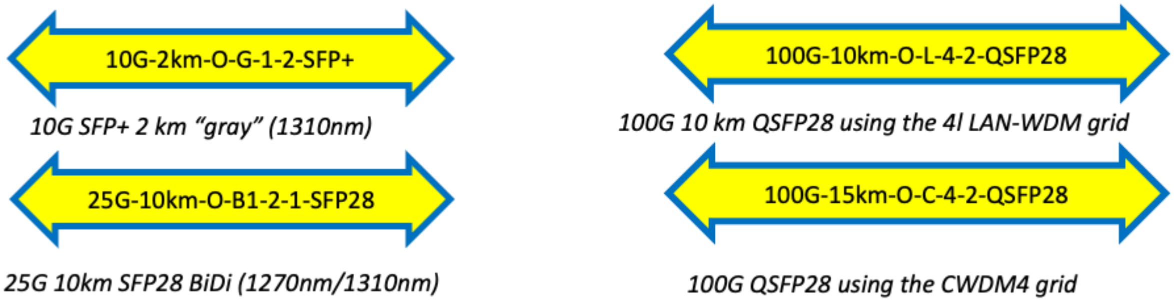
🟩 xyz	RAN Network Element
🟦 xyz	Transport node: WDM or Pkt
⬌ X-D-Y-Z-W-Z	Optical Pluggable of type X-D-Y-W-Z, industrial temperature range (“I-temp”)
⬌ X-D-Y-Z-W-Z	Optical Pluggable of type X-D-Y-W-Z, commercial temperature range (“C-temp”)
⏢	Optical (passive) multiplexer, industrial temperature range (“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 Sections 6, 7, and 8, with further details in *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[2].

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.

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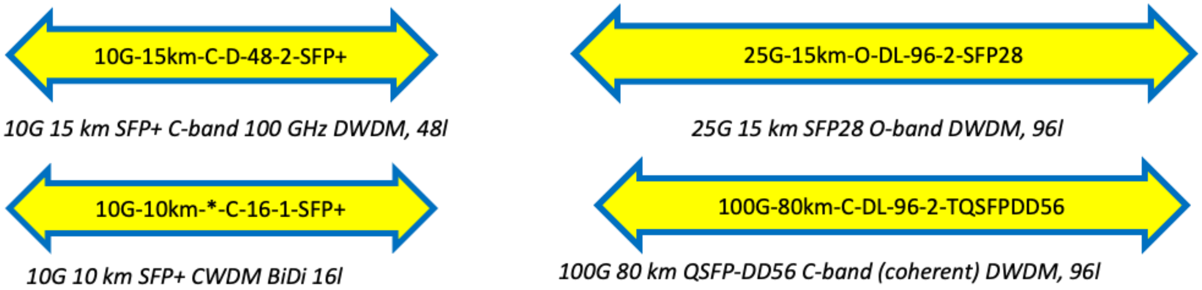
[2] It should be noted that some values and variants are not yet used for the Blueprints in this paper, e.g. the distances 5, 20 and 80 km.



10G 15 km SFP+ C-band 100 GHz DWDM, 48l

25G 15 km SFP28 O-band DWDM, 96l

10G 10 km SFP+ CWDM BiDi 16l

100G 80 km QSFP-DD56 C-band (coherent) DWDM, 96l

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

5. Generic optical solutions requirements in mobile transport networks

This section outlines specific requirements characterizing “radio-grade” optical solutions.

5.1. Operating temperature and power consumption classes

In mobile transport networks, optical pluggable modules can be used in RUs or packet nodes that are located outdoors, which require a wide operating temperature range. While DUs may be deployed in temperature-controlled locations, especially for CRAN, it might be beneficial from an inventory, planning, and testing perspective to use wide operating temperature optical pluggables for Dus as well. Using wide temperature optics for indoor applications can add cost during the initial phases of the technology and product life cycle, but history and consolidated trends in the industry indicate that this cost addition disappears over time.

The typical requirement for outdoor-grade optical pluggables is the so-called “industrial case operating temperature range”, or “I-temp” for short, ranging from -40 °C to +85 °C. It should be noted that this applies to both SFPx and QSFPx formfactors (see for example blueprint 7.3.7).

It is identified that a lower bound of -20 °C could provide cost advantages in certain scenarios: the definition of such scenarios and the intended transceiver behavior between -40°C and -20°C case temperature is for further study.

For certain applications with a high density of dissipated power, it could also be necessary to exceed the upper temperature limit, which may require alternative solutions. One such “higher than I-temp” class is very high temp (VHT), which extends the upper temp limit to 95 °C. In this paper, we assume I-temp for all pluggables unless otherwise stated.

Following the methodology described in [OIF-Thermal], the module maximum power consumption is classified in terms of so-called power levels or power classes, see Table 2. The respective limits are to be satisfied to facilitate the implementation and thermal management on host units.

Form factor	PC 1 [W]	PC 2 [W]	PC 3 [W]	PC 4 [W] [3]	PC 5 [W]	PC 6 [W]
SFP/+/28	1	1.5	2.0	> 2.0	-	-
DSFP/SFP-DD	1	1.5	2.0	2.5	-	-
SFP56	1	1.5	2.0	2.5	-	-
SFP112[4]	1	1.5	2.0	3.5	5.0	-
QSFP28	1.5	2.0	2.5	3.5	4.0	4.5 [5]
QSFP-DD	1.5	3.5	7.0	8.0	10	12

Table 2: Power consumption classes (PC) for pluggables, using the methodology in [OIF-Thermal].

The form factors and power classes of Table 2 will be used for the Blueprints outlined in this paper. Apart from thermal aspects, it's important not to exceed these values because they are used to dimension the electrical power supply of the host boards.

5.2. Power saving mechanisms

Equipment sleep modes are being investigated in the industry and being standardized, for example for radio units (RUs). The resulting implications/requirements for pluggable optics for a RU are not yet clear. What can be said for the optical pluggable is that the total module wake-up time depends on the complexity of the optics, where for today's designs, simpler transmitters without a TEC may require hundreds of milliseconds while tunable lasers may require several seconds. Without the optical link, the timing synchronization of the RU cannot be maintained (i.e. holdover times are often practically zero).

5.3. EMI and EMC

EMI and EMC requirements at module level are critical, given the possible proximity of optical pluggables to RF receivers: in order to provide enough margin for system-level tests, it's not uncommon to require margin figures of 6 dB to 12 dB on top of the applicable transceiver-level standards in [ETS-EMC] and [FCC15], where FCC Part 15 Class B should be the target on a node level.

Careful design of the pluggable is required to minimize the impact on system-level EMI and EMC performance. The choice of materials, mechanical tolerances, internal placement of components and RF absorbing materials are all aspects to be considered. A potentially critical area inside pluggables is the connection between the laser driver or modulator driver and the laser or modulator, respectively: it is the point in the signal chain where the voltage swing is highest, and the rise/fall times are shortest. Implementations using a driver integrated with the modulator/laser inside the TOSA offer better EMI/EMC suppression but add complexity; in the case where the driver is stand-alone or integrated inside the retimer/DSP, particular care must be taken with that specific interconnect (e.g. impedance matching, length of the wires / flex circuit) [EMI_EMC].

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[3] In SFF-8472, the single-lane transceiver power level 4 allows for greater than 2W.

[4] See SFF-TA-1031.

[5] BiDi DWDM QSFP28 can have up to 7 W power consumption.

5.4. Latency

Particular care must be taken to limit the worst-case latency introduced by the optical pluggable (due to the DSP, serialization, FEC encoding, decoding, and other manipulations like interleaving). As a general criterion, a contribution to single-ended latency on the order of a few μs can be tolerated.

5.5. Synchronization

It is also important that potential sources of PTP (Precision Time Protocol) timestamping inaccuracy are tightly controlled. Any effect, deterministic or stochastic, potentially leading to uplink/downlink propagation delay asymmetry, directly impacts the time error budget. The acceptable contribution of pluggables in point-to-point links to overall uplink/downlink delay asymmetry should be less than a few ns. For TDM-PON systems the delay is inherently asymmetric, and these delay asymmetries is mitigated by a termination of PTP at the OLT, the use of TPS-TC (Transport Protocol Specific – Transmission Convergence), and generation of PTP at the ONU side. See the MOPA Technical Paper – New Technologies [MOPA-NT] for further discussion.

5.6. Support for multiple bit rates

The specific nominal bit rates which must be supported are part of the detailed Blueprints descriptions. In general terms, transceivers using internal re-timer ICs are expected to support "re-timer bypass" functions, to allow operation at lower bit rates.

5.7. Form factor standards

The aforementioned form factors are expected to be fully compliant with the relevant SFF MSA specifications in Table 3.

Name	Main specification	Low-speed and general electrical specifications	High-speed electric specification	Common management specification
SFP+	SFF-8083	SFF-8419	SFF-8418	SFF-8472, SFF-8690
SFP28	SFF-8402	SFF-8419	CEI-28G-VSR, IEEE 802.3, 109B.3.2,4	SFF-8472, SFF-8690
SFP56	SFF-8402	SFF-8419	CEI-56G-VSR, IEEE 802.3, 135G.3.2,4	SFF-8472, SFF-8690
SFP112[6]	SFF-8402	SFF-8419	CEI-112G-VSR, IEEE 802.3, Annex 120	CMIS[7]
DSFP	DSFP MSA		CEI-28G-VSR	ACMIS (abridged CMIS)
QSFP28	SFF-8665	SFF-8679	CEI-28G VSR, IEEE 802.3 83E.3.2,4	SFF-8636
QSFP-DD	QSFP-DD MSA		CEI-56G VSR, IEEE 802.3 120E.3.2,4	CMIS (common management interface spec)

Table 3: Pluggable form factors and their standards.

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[6] see [SFF-TA-1031]: "SFP2 modules may use SFF-8472 or CMIS for management. For higher speeds as 50 Gbps or 100 Gbps, the Common Management Interface Specification (CMIS) is recommended."
[7] CMIS offers management extensions for wavelength tunability.

Digital diagnostic monitoring (DDM) in SFF-8472 and SFF-8636 is important for observability of optical links, and the *internally calibrated* approach is almost ubiquitous in line card implementations. Remote DDM is an emerging requirement and standards are in development. See the technical paper "New Technologies" for a more detailed discussion [MOPA-NT].

5.8. Connectors: UPC, APC

Solutions must be able to work on outdoor fiber plants based on UPC/LC single mode connectors: thus, they must be able to tolerate a maximum discrete optical return loss of -50 dB[8] [IEC61753]. The only exception to this rule is represented by PON solutions, which can also be based on APC/LC single mode connectors in some cases. Unless stated otherwise in the detailed Blueprints descriptions, UPC/LC single mode connectors are assumed.

5.9. Tunable and automatic self-tunable DWDM pluggables

Currently, DWDM networks utilize either fixed wavelength or wavelength tunable transceivers. 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 (no need to label or track fibers, only a single part number is required instead of 48[9] or 96, easier forecasting and inventory management, less potential for stranded inventory at unused wavelengths). Sub-optimal solutions, where the transceiver is able to tune over a subset of wavelengths, can be an acceptable temporary solution, if the cost gap between full-tunable transceivers and fixed wavelength transceivers remains large. The topic of self-tunable transceivers is discussed in the MOPA Technical Paper – New Technologies [MOPA_NT].

5.10. Loss budget (channel insertion loss) and chromatic dispersion

In this document we focus on single-mode fiber. Compared to multi-mode fiber, single-mode fiber has clear advantages for the outside plant fiber with its much higher bandwidth-distance product, better tolerance to fiber bends, and lower cable cost. Pluggables for multi-mode fiber can be lower cost than corresponding ones for single-mode fiber, but that cost has historically vanished with volume. Moreover, I-temp tends to be challenging for low-cost multi-mode transmitters. Multi-mode can be interesting for short distance temperature-controlled data center environments. i.e., when using short patch-cords and active cables.

There are many standards for loss budgets, also called channel insertion loss, used in standards documents and the industry. Examples for cabled fiber and splice attenuation include:

- ITU-T G.652 [G.652] Table I.1: Cabled concatenated links incl splices: 0.5 dB/km 1260-1360 nm, 0.275 dB/km 1530-1565 nm
- Commercial example for SMF-28: max 0.35 dB/km 1285-1330nm, max 0.20 dB/km @ 1550 nm (excl. splices).

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[8] It should be pointed out however, that such low values are difficult to assure in field environments, where return loss values of 35 dB are more realistic.

[9] Used in this paper, reference [G.698.2] specifies a 48 channel 100 GHz grid with min central frequency of 191.4 THz, and max central frequency of 196.1 THz.

- ITU-T G.671: Fusion splice active alignment: 0.3 dB.
- ITU-T G.sup39: Cables installed after 2003, Fiber att. average 0.349 dB/km @ 1.3um, 0.205 dB/km @ 1.55um (incl. splices every 2 km).

For connectors (typ. LC assumed in this paper), examples include:

- ITU-T G.671: max 0.5 dB 1260-1360 nm.
- Commercial products: 0.25 - 0.5 dB.

The values above will, in many cases, over-engineer the optics, leading to higher component costs. Instead, this paper suggests a pragmatic approach to find a balance between high quality/reasonable margin and cost: 0.4 dB/km 1260-1360 nm (i.e., O-band), 0.25 dB/km 1530-1565 nm (i.e. C-band), connector loss of 0.5 dB.

We assume there are up to four intermediate connector jumps for distances up to 20 km. For 40 km, since such long links may pass additional flexibility points, we assume up to six connector jumps.

In addition, it is customary for operators to allocate a small margin for maintenance reasons (e.g., degradation of fiber, new splices, bad connectors or minor fiber bends). Consequently, the following loss budget values will be used in this paper:

Distance	**Fiber attenuation O-band (1260-1360 nm)**	**Fiber attenuation C-band (1530-1565 nm)**	**Connectors Insertion Loss**	**Maintenance Margin**	**Total Loss budget - P2P O-band**	**Total Loss budget - P2P C-band**
≤ 2 km	0.8 dB	0.5 dB	2 dB (4x)	0 dB	2.8 dB	2.5 dB
10 km	4 dB	2.5 dB	2 dB (4x)	1 dB	7.0 dB	5.5 dB
15 km	6 dB	3.8 dB	2 dB (4x)	1 dB	9.0 dB	6.8 dB
20 km	8 dB	5 dB	2 dB (4x)	1 dB	11.0 dB	8.0 dB
40 km	16 dB	10 dB	3 dB (6x)	2 dB	20.0 dB *	15.0 dB

*Table 4: Loss budget values used in this paper. The total loss budget is sometimes called Channel insertion loss. *The sum of the connector loss and margin is capped at 4 dB.*

It should be noted that,

- The above values do not take into account the transmitter and dispersion penalties etc., which are in addition to the loss values for a complete power budget specification. Thus, this paper does not deal with power budget specifications and the related transmitter and receiver requirements.
- The above total loss values are higher than those for IEEE 10GBASE-ER, 25GBASE-ER and 4WDM-40, due primarily to the maintenance margin. For further details, see Appendix A: Referenced Physical layer Standards Exceptions for MOPA Blueprints.

For 10G, we assume a BER of 10e-12, while for 25G and 100G we assume a BER of 5e-5. The latter assumes using FEC with RS(528, 514), i.e., the so-called “KR” FEC. The FEC functionality is implemented in the host system, not in the pluggable module.

In some cases, a wavelength mux is required. Commercial devices have insertion loss values in the range of 4.6 to 6.0 dB depending on the type (AWG vs TFF) and design. For networks that employ a point-to-multipoint fiber infrastructure with passive power-splitting, i.e., a TDM-PON fiber network, the insertion loss of splitters must be added to the insertion loss values indicated for P2P fiber in Table 4.

Nominal wavelength mux and power splitter insertion losses are shown in Table 5 below.

Component	**CWDM Mux DeMux 6ch (TFF) matched pair**	**LWDM Mux DeMux 12ch (TFF) matched pair***	**DWDM Mux DeMux 48 ch (AWG), Unit**	**DWDM fixed OADM 6 ch (TFF) Pass / AddDrop, Unit**	**Power splitter 1:2,4,8,16,32,64**
Insertion loss [dB]	4.5	4.5	5.5	0.6 / 3.0	3.5, 7, 10.4, 13.9, 17.4, 21

*Table 5: Insertion loss values for passive optical components used in this paper. *Matched pair requires different units on each side. If the same unit is required, the loss per side is 3.5 dB for a total of 7 dB for the pair.*

With a similar line of thinking, the value for Chromatic Dispersion (CD) used in this paper is 18 ps/(nm*km) for the C-band and 4 ps/(nm*km) for the O-band. An appropriate Optical Path Penalty (OPP) must be included in the network design to account for the impairments over a fiber distance taken together with any CD mitigation capabilities.

5.11. Lifespan of optical pluggables

Whatever the functional split and the architecture, antenna sites in RAN will remain geographically scattered as they must ensure the intended radio layer coverage. The number of antenna sites and their variety are very large: some antenna sites can be quite difficult and expensive to access, for instance tall cell towers. Geographical distribution of antenna sites also makes spare parts management and logistics an important operational cost. Therefore, lifespan and reliability of optical transceivers for RAN cannot be relaxed to a point where they adversely impact whole network operation costs.

The lifetime of optical transceivers, defined as the period of time for which all requirements must be fulfilled, must be at least 15 years.

During the lifetime, it is also very important that the number of random failures expressed in FITs (number of failures per billion device hours) at high case operating temperatures is very low. If converted from FITs to MTBF and expressed in years, the typical reliability figure required at high case temperature is normally *one order of magnitude larger* than the ‘lifetime’ figure.

5.12. Firmware update of optical pluggables

There are some cases where the firmware in the EEPROM memory of optical pluggables needs to be updated in the field, for example:

- Error fix. Examples include problems reading diagnostics and laser wavelength misalignment due to inaccurate look-up table values in the memory to account for aging the laser.
- New Standard (e.g. SFF) revisions with new functionality and/alignment with host software revisions.

There are two distinct cases of firmware updates:

- In the case of optical pluggables in a DU, firmware updates could be considered to be done locally in the sense that they are done in a relatively controlled environment with easy access to manual intervention if anything goes wrong.
- In the case of optical pluggables in a RU, firmware updates could be considered to be done remotely in the sense that the locations are often more difficult and costly to visit in case of problems.

From a system vendor perspective,

- Remote in-service firmware updates are typically not supported due to risk of high costs in case of failures (site visits, mast climes, network downtimes etc.). A safer approach is to view the firmware as part of the optical pluggable.
- A module firmware modification will void existing type approvals and respective equipment operation certificates/warranties.

5.13. Optical module system vendor qualification, interoperability and the role of MOPA

System vendors of network equipment, such as RAN and transport equipment, need to ensure the network and system function and performance during the agreed life span – from contractual and/or public relations and/or critical infra perspectives. This also includes pluggable optics being an integral part of the overall system. For an optical pluggable to function as intended in a system/box a number of qualification tests must be met:

1. Meet the applicable available standards and specifications.
2. Fulfill additional functionality not standardized.
3. Module performance is consistent over subcomponent and design changes.
4. Unit variability (i.e. by tests, quality control and audits confirm the module performance variation due to component and manufacturing variation).
5. Function as intended with the specific system/box for that specific network function and deployment type(s).

An industry effort such as MOPA feeds into 1 and 2 above, and in the case of MOPA, specifically for mobile optical pluggables. Areas 3 and 4 above require a continuously adapting testing organization, which is outside the scope of MOPA. Number 5 requires system vendor expertise, continuously evolving with new products and features.

There is a common misconception/expectation that industry work and documentation, such as MOPA and other industry organizations, can produce specifications that include all the necessary information to qualify any optical pluggable for any system box. The main complication is that the combined host equipment (e.g. RU or DU) and optical pluggable system function and performance, for example regarding EMI, must be tested together for the specific combination. Both host equipment and optical pluggables have continuous updates to hardware, firmware and software that may impact the combined function and performance. While many combinations may work for the base functionality at room temperature during a limited time, the target for critical infrastructure such as mobile networks, must be that all functionality works for all the environmental conditions it is specified for during its entire life span.

From the above, it is fair to conclude that using “any pluggable for any system” is not feasible in the general case, as integration testing and type approval are essential to guarantee system performance, quality, and stability. The simple answer to the question “Why can’t I just take any optical pluggable and use it in my system box?” is that one wouldn’t know how well the optical pluggable works for that system box over the intended life span. In case of any problems, the system vendor cannot help trouble-shooting the problem since the optical pluggable is unknown with regards to its system related behavior. And to answer the follow-up question of “What should I do if there is a problem with a (by the systems vendor) non-qualified optical pluggable in my system?” The response would be that the first action would be to replace the non-qualified optical pluggable with an optical module qualified by the system vendor since this is helping the system reliability and the system vendor troubleshooting task.

5.14. Connectivity Solution Alternatives

Individual connectivity solutions are the outcome of technical and commercial trade-offs. Several implementation options are available for fiber optical data links:

1. Pluggable transceiver module at both ends of a detachable fiber cable using standardized connectors
   Attached cable assembly.
   - Active Optical Cable (AOC) assembly consisting of pluggable transceivers at both ends and nondetachable fiber cable.
   - Direct Attach Cable (DAC) / Active Copper Cable (ACC) assembly of pluggable modules (passive or active) and nondetachable copper cable.
2. Pluggable transceiver module with connector fitted fiber pigtails at both ends and an optional detachable fiber cable using standardized connectors.
3. Combination of options 1 and 3.

As an alternative to pluggable optical modules for very short distances (up to a few tens of meters), attached cables can be used, for example, between DU and Pkt nodes (see the DU to Pkt links in section 9.2 *Backhaul and HLS optical blueprints*). Such attached (integrated) cables can come with SFP connectors ports at both ends, QSFP ports at both ends, or break-out solutions with, for example, 4x SFP connectors ports at one end and 1x QSFP at the other. The motivation for using attached cables is typically lower cost, when applicable, and fewer points susceptible to manual handling errors.

In the case of attached electrical cables, they are typically called Direct Attached Cables (DAC) or Active Copper Cable (ACC) and can be passive or active, respectively. Passive variants come at low power and low cost but are limited to very short distances, a few meters, putting requirements on the host system's Serdes to be able to drive passive DACs. Active ones have come with electrical amplification/equalization and offer somewhat longer distances but at higher cost and power consumption.

Active Optical Cables (AOCs) offer longer reach compared to DAC or ACC (10s of meters, in some cases up to 100 meters), but usually at higher cost than DAC. Typically, AOCs are less bulky and provide improved EMI resilience. While the Test Points 1 and 4 (TP1 and TP4 in IEEE terminology, see [IEEE 802.3]) of AOCs may follow the main and electrical standardized specifications, see Table 3, the EEPROM data may be less rich than optical pluggables. In general, the overall characteristics of attached cables are not standardized.

6. Mobile Optical Solution Blueprints for LLS in Distributed RAN (DRAN)

6.1. Overview

DRAN is the original RAN deployment and is the most popular deployment method where the DU and RU are in proximity, often within a cell site. The figure below illustrates a simplified DRAN architecture.

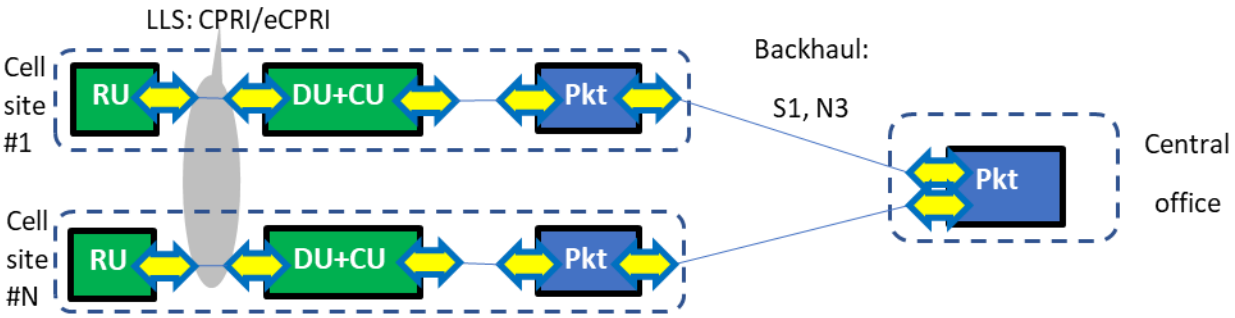

Figure 3: DRAN architecture with RAN nodes, transport nodes and optical pluggables.

Following the above, most of the DRAN DU-RU links are less than 300 m, with a significant number of links extending up to a few kilometers, as shown in Figure 4.

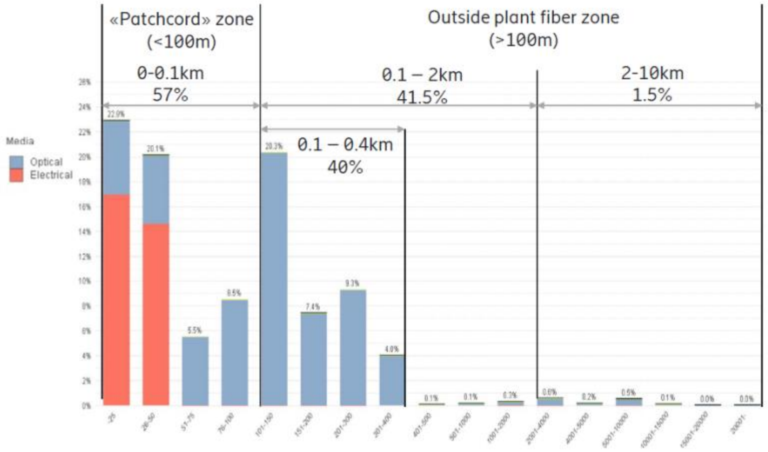

Figure 4: *LLS link length distribution.*
(source: Ericsson, by characterizing millions of LLS links in live networks).

The typical rooftop installation for macro base stations consists of three radios, with three antennas, each covering a 120° sector, to provide omni-directional coverage. This structure is replicated on the same site when several frequency bands must be supported: for instance, in 4G/LTE a typical deployment is *3x2* (three sectors, two frequency bands). Thus, the number of RU pluggables required at a cell site tends to be a multiple of 3 or 6, with the same for the number of fibers or WDM channels (when used). For 4G/LTE-E deployments, considering typical radio configurations and capacities, the required LLS capacity per sector usually does not exceed 10 Gb/s.

With the adoption of 5G, capacity requirements have increased but the re-architecting of the radio base stations have exposed more bandwidth-efficient LLS transport interfaces, thus limiting the potential explosion of capacity. For 5G NR deployments, considering early radio configurations and capacities, the required LLS capacity per sector usually does not exceed 25 Gb/s today but the adoption of AAS and higher frequency bands will push the required LLS capacity further [GSTR-TN5G].

The two typical scenarios of fiber resources availability in DRAN are reported below:

In the majority of cases, DUs (or DU+CU) are located in close proximity of the RUs (cell towers or rooftop installations) and the fiber interconnect length is relatively short, on the order of few hundred meters: in this scenario not only is the fiber an abundant resource: it is often considered a *consumable* (patch-cords) part of a site cabling solution. Duplex fiber short reach pluggables, which are very cost-effective, can be used.

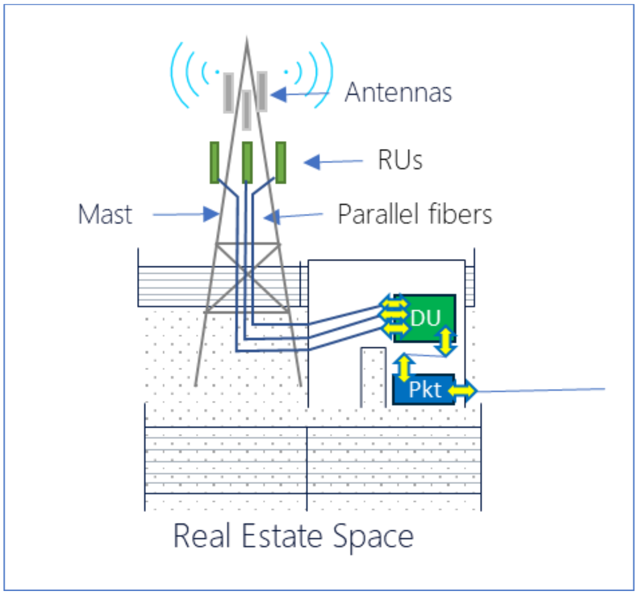

Figure 5: Cell site illustration for the DRAN fiber abundance case.

There are other cases in which the DUs (or DU+CU) and the RUs are not co-located due to, for example, real estate constraints[10]. In these cases, optical patch-cords cannot be used, and dark fiber (typically part of a large cable running in an underground duct) must be used. In this case, it may be beneficial to deploy single-fiber BiDi pluggables, allowing the use/lease of a single dark fiber strand instead of two.

For DRAN deployments, considering the short distance, it is relatively uncommon to find scenarios with a lack of fiber resources. Still, solutions to save fiber count are of interest if the added cost is low, for example BiDi or using fewer higher speed ports rather than multiple ports of lower speeds, daisy-chaining, etc.

10 km is traditionally considered the *shortest distance of interest* for transport networks. However, as is evident from Figure 10, the fiber distances in DRAN deployments are typically much shorter. Reducing the reach requirements may allow reduced costs by using inherently cheaper laser sources. This happened, for instance, with the use of Fabry-Pérot (FP) lasers, creating in LLS applications the typical “up to 2 km” solution space which is also seen in ITU-T specs for intra-office and IEEE 802.3 for data center interconnects.

It can be noted that even for DRAN where RU and DU equipment is typically collocated resulting in short fiber links, 10 km class optics may still be used, either because the potential shorter class optics devices do not offer any cost advantage (leading the market not to develop or standardize such optics), or that the operator prefers the fewest number of variants, or that the link distance or loss happens to be just too much for 2 km optics. This results in the 6.2.2 blueprint.

Scenarios requiring 10G BiDi are currently covered with 15 km-capable lasers due to the lack of suitable Fabry-Pérot lasers with the proper wavelengths (B2: 1270 nm, 1330 nm). Reach-reduced BiDi pluggables at 25 Gb/s can be realized by reusing the DFB laser with the proper wavelengths (B2: 1270 nm, 1330 nm), currently in use for 15 km 10 Gb/s BiDi. This is an example of trading fiber reach for extra penalties introduced by the higher speed modulation.

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[10] One common example is when the DUs are located in the basement of a building and the RUs on the rooftop of another building, one or more blocks away.

6.2. DRAN Optical Blueprints

6.2.1. 2 km RU-DU direct parallel fibers, dual fiber Blueprint

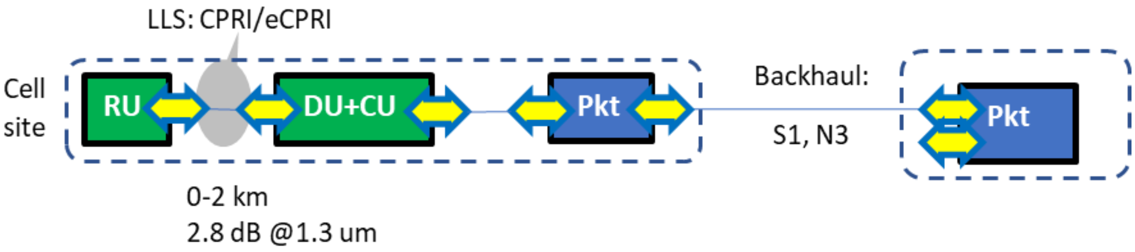

Figure 6: 2 km RU-DU direct parallel fibers Blueprint.

2 km RU-DU Direct parallel fibers Blueprint			
Typical UC	DRAN DU to RU; DU to cell site router intra-site; DU and/or cell site router to microwave element intra-site. Up to 2 km. The BiDi use cases, which are high volume, are covered by 10 km optics (6.2.2. blueprint)		
Distance (*)	Typ Min 0 km; Typ. Max: 2 km		
Channel IL	2.8 dB O-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm.		
Temp. Range/Class	I-temp, VHT cases also exist		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	50 Gb/s
Form factor	SFP+	SFP28	SFP56
FEC, Mod. format	No, NRZ	Yes, NRZ	Yes, PAM4
Power Class	PC2 (1.5 W)	PC2 (1.5 W)	PC2 (1.5 W)
Pluggables codes	10G-2km-O-G-1-2-SFP+	25G-2km-O-G-1-2-SFP28	50G-2km-O-G-1-2-SFP56
Key technologies	-	Low-cost 25G DFB (e.g., reuse 10G 10 km). New low-cost tech like 25G FP.	TBD
Standards	IEEE 802.3, Clause 52	IEEE 802.3, Clause 114	IEEE 802.3, Clause 139
Market status and outlook	Mature	Mature	Introduced

Table 6: 2 km RU-DU direct parallel fibers Blueprint. (*) From Figure 4, distances up to 2 km are expected to cover a large majority of the deployments.

6.2.2. 10 km RU-DU direct parallel fibers, dual and BiDi fiber Blueprint

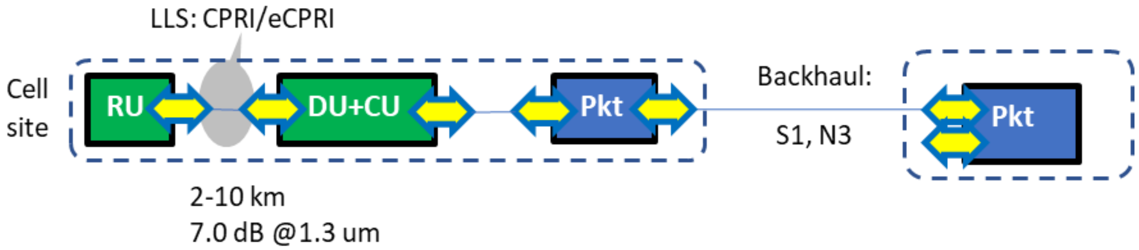

Figure 7: 10 km RU-DU direct parallel fibers Blueprint.

10 km RU DU Direct parallel fibers Blueprint			
Typical UC	DRAN DU to RU. 2-10 km. (This blueprint covers that case when 2 km optics are not available or preferred, or does not meet the distances and/or loss requirements even for short DRAN links)		
Distance (*)	Typ Min 2 km; Typ. Max: 10 km		
Channel IL	7.0 dB O-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm. BiDi O-band 1270nm/1330 nm.		
Temp. Range/Class	I-temp		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	50 Gb/s
Form factor	SFP+	SFP28	SFP56
FEC, Mod format	No, NRZ	Yes, NRZ	Yes, PAM4
Power Class	PC2 (1.5 W)	PC2 (1.5 W)	PC2 (1.5 W)
Pluggables codes	10G-10km-O-G-1-2-SFP+ 10G-10km-O-B2-2-1-SFP+	25G-10km-O-G-1-2-SFP28 25G-10km-O-B2-2-1-SFP28	50G-10km-O-G-1-2-SFP56 50G-10km-O-B2-2-1-SFP56
Key technologies	-	Low-cost 25G DFB	TBD
Standards	IEEE 802.3, Clauses 52 & 158 ITU-T G.9806 (Amend 2) See Appendix A Tables 5,6,7	IEEE 802.3, Clause 114 & 159 ITU-T G.9806 (Amend 2) See Appendix A Tables 5,6,7	IEEE 802.3, Clauses 139 & 160 ITU-T G.9806 (Amend 2) See Appendix A Tables 5,6,7
Market status and outlook	Mature	Mature	Introduced

Table 7: 10 km RU-DU direct parallel fibers Blueprint. (*) For DRAN, distances between 2 and 10 km are expected to be much fewer than those ≤ 2km.

7. Mobile Optical Solution Blueprints for LLS in Centralized RAN (CRAN)

7.1. Overview

Centralization of DUs to a single common location drives the need to cover longer fiber distances to connect with the RUs: typical values span for a few kilometers up to 20 km. Specifically, the majority of cases will be below 10 km, almost all below 15 km, and very few cases up to 20 km.

Figure 8 depicts the centralization of the DU and optionally the CU to a hub site. It should be noted that there are three conceivable categories of solutions involving the presence/absence of transport equipment at each end. These are:

1. Active-Active: there is transport equipment at both ends (e.g., Cell site #1)
2. Semi-Active: there is transport equipment only at the hub location. At the cell site, the optical module is plugged directly into the RU (e.g., Cell site #2)
3. Passive-Passive: there is no transport equipment. The optical modules are plugged directly into the RAN equipment at both extremity (e.g., Cell site #3).

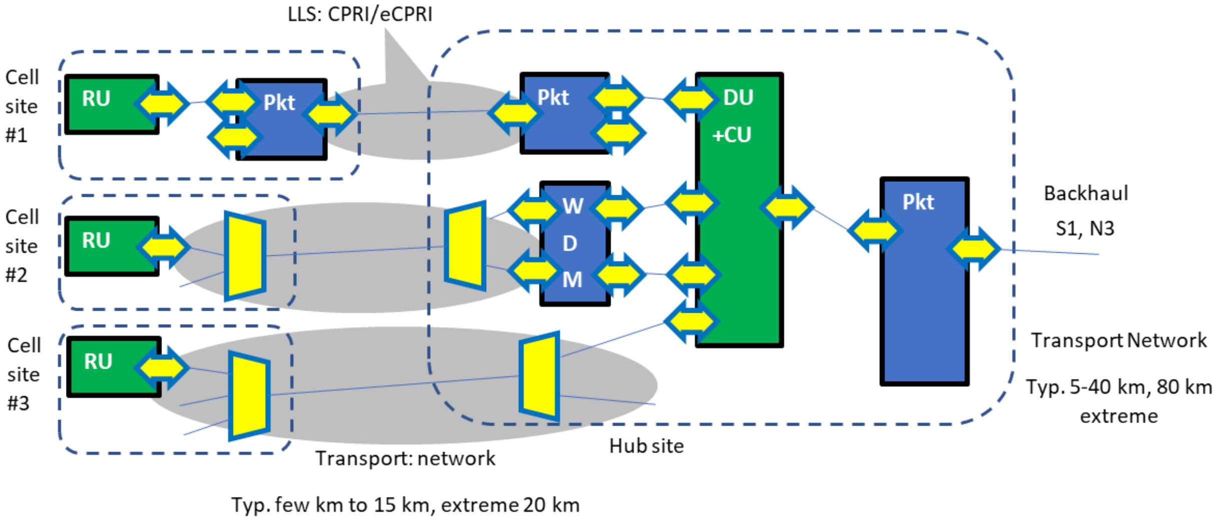

Figure 8: CRAN architecture with RAN nodes, transport nodes and optical pluggables. Cell site #1 shows a case with packet aggregation, Cell site #2 shows a case with semi-active WDM, and Cell site #3 shows a case with passive WDM aggregation.

In CRAN, the site cabling scenario (described for DRAN), which can be solved with optical patch-cords, is clearly not applicable: instead, an installed fiber plant must be used. Availability of fiber varies greatly with region and the local policies and market regulations.

There are scenarios in which fiber is a relatively abundant resource, for example, in cases where the network operator also owns fiber assets, or because the cost for leasing fiber resources from third parties is relatively low. In other scenarios, typically in dense urban areas and in unregulated markets, fiber is a scarce resource with high value: its lease costs can be high, driving fiber-lean solutions.

Duplex fiber solutions are used in the "fiber abundant" cases and when the cost of fiber is low. However, in many cases it is very attractive to use optical BiDi pluggables to reduce the number of fibers by two vs dual fiber pluggables.

When the fiber reduction enabled by BiDi is not enough, a way to use fiber resources more efficiently is to use WDM technologies. There are three main technologies used in fronthaul, with different techno-economic characteristics. CWDM is particularly successful in scenarios where chromatic dispersion is not a big problem, i.e. for low bit rates (<10G) or if the grid is limited to the six O-band wavelengths close to the zero-dispersion wavelength of the fiber. DWDM in C-band, with 100 GHz spacing, is a better choice when scalability to 48 wavelengths is required, up to 25 Gb/s per wavelength; chromatic dispersion management becomes the key issue for scaling to higher capacity per wavelength. LAN-WDM or LWDM, 12 wavelengths with 800 GHz spacing in the O-band, is emerging as an interesting option between CWDM and DWDM: more scalable than O-band CWDM but less than C-band DWDM, less issues with chromatic dispersion as the wavelengths are much closer to the zero-dispersion wavelength region of fiber. Different fiber scarcity scenarios and different requirements on maximum distance/maximum bit rate can make one of the three options preferable.

There are, conceptually, two flavors of WDM transport, one that uses a wavelength mux as the branching node in the field and one that uses a power splitter in the field [G989].

- *WR-WDM:* this is the more prominent solution and is referred to as Wavelength Routed (WR) since the downstream wavelengths are routed by the wavelength mux at the branching node. There are a number of standardization efforts for this generic architecture (e.g., ORAN, ITU-T SG15 Q6 and ITU-T SG15 Q2 [G.989.x] and [G.9802.x])). Blueprints for this option are presented in Sections 7 and 8.
- *WS-WDM:* Further discussion on this topic can be found in the MOPA Technical Paper – New Technologies [MOPA-NT].

A final observation should be made regarding the architectures that use WDM. The branching node—whether a wavelength multiplexer or a power splitter—may be placed either at the cell site or elsewhere in the outside plant. Both placement options are supported, and while diagrams may show one or the other, the chosen location does not impact the system's functionality.

Packet aggregation enables the use of high-speed gray optics to reduce the fiber count. Single-fiber, BiDi, high bit-rate interfaces couldn't be designed in an inexpensive and simple way in the era of 4x25 Gb/s-based 100 Gb/s implementations, but the rise of single lambda 100 Gb/s solutions have paved the way for simple BiDi (e.g., 1270 nm/1310 nm) single-fiber implementations.

The combination of high bit-rates and WDM provides a way to scale capacity, for cases where it is not possible to meet the requirement of the number of fiber resources with BiDi optics. Today, coherent pluggables (transceivers based on optical coherent transmission technology) are not cost-optimized for use in CRAN, but direct-detect alternatives are few and their limited performance is placing more demands on the optical infrastructure: the definition of cost reduction opportunities for coherent pluggables should be addressed by new industry agreements. The same 100G+ bit rate solutions will of course also be useful to support future capacity growth in DRAN.

7.2. Evolution of WDM systems over different bands

As capacity demands grow and additional RUs are deployed at cell sites, operators are increasingly turning to optical wavelength bands beyond the traditional C-band used in DWDM systems. A key challenge in adopting new bands is the existing installed base of WDM multiplexers. As noted in [MOPA_NT], using WDM multiplexers equipped with expansion ports enables incremental addition of new wavelength bands when needed—for example, adding O-band DWDM to an existing LAN-WDM system or integrating O-band DWDM with an existing C-band DWDM deployment.

7.3. CRAN Optical Blueprints

Note for 7.3.2: *Using DWDM to address fiber scarcity in CRAN deployments is common. Fully tunable DWDM modules provide operational advantages (see Section 5.9), though fixed-wavelength versions may still be used when cost considerations make them preferable.*

Note for 7.3.3: *15-kilometer optics may not be available for BiDi, dual-fiber solutions, or both. In such cases, 20-kilometer optics shall be used as the alternative option.*

7.3.1. 15 km RU – DU direct parallel fibers, dual and BiDi fiber Blueprint

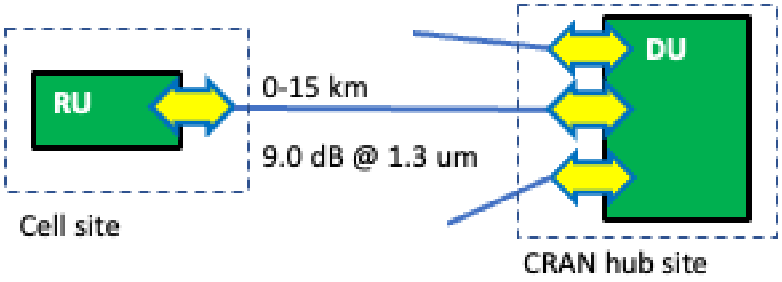

Figure 9: 15 km RU-DU direct parallel fibers Blueprint. Note for 7.3.3.

15 km RU DU Direct parallel fibers Blueprint			
Typical UC	CRAN DU to RU		
Distance	Typ Min 0 km; Typ. Max: 15 km (Note 8.3.2)		
Channel IL	9.0 dB O-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm. BiDi O-band 1270nm/1330 nm.		
Temp. Range/Class	I-temp		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	50 Gb/s
Form factor	SFP+	SFP28	SFP56
FEC, Mod. format	No, NRZ	Yes, NRZ	Yes, PAM4
Power Class	PC2 (1.5 W)	PC2 (1.5 W)	PC2 (1.5 W)
Pluggables codes	10G-15km-O-G-1-2-SFP+ 10G-15km-O-B2-2-1-SFP+	25G-15km-O-G-1-2-SFP28 25G-15km-O-B2-2-1-SFP28	50G-15km-O-G-1-2-SFP56 50G-15km-B2-2-1-SFP56
Key technologies	-	Low-cost 25G DFB	TBD
Standards	IEEE 802.3, Clause 158 See Appendix A Tables 9,10	IEEE 802.3, Clause 159 See Appendix A Tables 9,10	IEEE 802.3, Clause 160 See Appendix A Tables 9,10
Market status and outlook (*)	Mature	Mature	Introduced

Table 8: 15 km RU-DU direct parallel fibers Blueprint. (*) For CRAN, the fiber abundant case is a medium-size market.

7.3.2. 10 km RU – DU, passive CWDM over a single fiber Blueprint

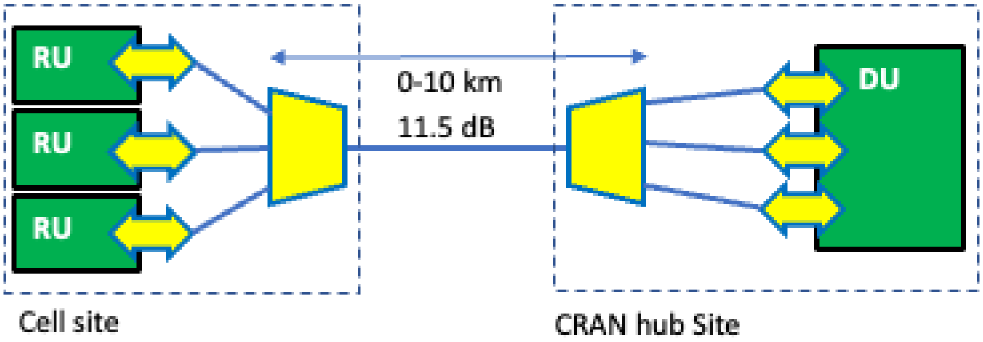

Figure 10: 10 km RU-DU CWDM passive wavelength multiplexed, P2P or P2MP Blueprint.

10 km RU-DU CWDM Blueprint		
Typical UC	CRAN DU to RU. Up to 10 km CWDM P2P or P2MP links up to 3 SFP+ pairs using the same single trunk fiber	
Distance	Typ Min 0 km; Typ. Max: 10 km	
Channel IL	7.0 dB O-band for the fiber (for typ. max distance), 4.5 dB per WDM mux/demux pair: Total 11.5 dB	
Mode, Nr ch., WL	Dual fiber pluggables, single fiber trunk: Wavelength pairs (DU/RU): 1271/1291, 1311/1331, 1351/1371 nm (i.e. the six shortest wavelengths from [G.694.2])	
Temp. Range/Class	I-temp	
Lifespan	15 years	
Data rates	10 Gb/s	25 Gb/s
Form factor	SFP+	SFP28
FEC. Mod format	No, NRZ	Yes, NRZ
Power Class	PC3 (2.0 W)	PC3 (2.0 W)
Pluggables codes	10G-10km-*-C-6-2-SFP+	25G-10km-*-C-6-2-SFP28
Key technologies	-	
Standards	ITU-T G.695. See Appendix A Table 12	
Market status and outlook	Mature	Mature, complements 10G

Table 9: 10 km RU-DU CWDM Blueprint.

7.3.3. 15 km RU – DU, passive LWDM over a single fiber Blueprint

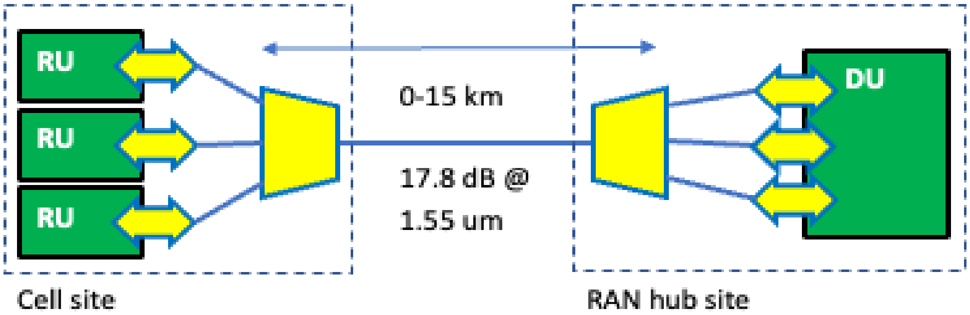

Figure 11: 15 km RU-DU LWDM passive wavelength multiplexed, P2P or P2MP Blueprint

10 km RU-DU CWDM Blueprint		
Typical UC	CRAN DU to RU. Up to 15 km LWDM P2P (all RUs at the same location together with the optical multiplexer) links up to 12 pluggable pairs using the same single trunk fiber.	
Distance	Typ Min 0 km; Typ. Max: 15 km	
Channel IL	9 dB O-band for the fiber (for typ. max distance), 3.5 dB for WDM mux/demux filters: Total 16 dB (same variant filter are assumed but also matched filters are possible, 4.5 dB per pair)	
Chromatic Dispersion	-81.5 to +25 ps/nm	
Mode, Nr ch., WL	Dual fiber pluggables, single fiber trunk: 12 wavelengths @ 800GHz (4.5 nm) spacing	
Temp. Range/Class	I-temp	
Lifespan	15 years	
Data rates	10 Gb/s	25 Gb/s
Form factor	SFP+	SFP28
FEC. Mod format	No, NRZ	Yes, NRZ
Power Class	PC3 (2.0 W)	PC3 (2.0 W)
Pluggables codes	10G-15km-O-L-12-2-SFP+	25G-15km-O-L-12-2-SFP28
Key technologies	Low-cost EML DWDM, without wavelength lockers. Athermal TFF filters	
Standards	ITU-T G.698.5 (formerly G.OWDM) , Tables 8.2 and 9.1	
Market status and outlook	Emerging	Emerging

Table 10: 15 km RU-DU LWDM Blueprint.

7.3.4. 15 km RU-DU, passive DWDM over a single fiber Blueprint

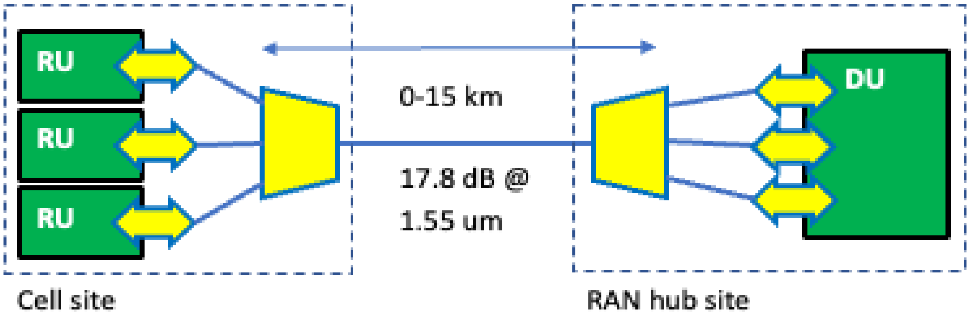

Figure 12: 15 km RU-DU, DWDM passive wavelength multiplexed, P2P or P2MP Blueprint.

15 km RU-DU DWDM Blueprint		
Typical UC	CRAN DU to RU. Up to 15 km DWDM P2P (all RUs at the same location together with the optical multiplexer) or P2MP (the RUs are located in slightly different locations, with the optical multiplexer at one of those, or another location) links up to 24 SFP+ pairs using the same single trunk fiber.	
Distance	Typ Min 0 km; Typ. Max: 15 km	
Channel IL	6.8 dB C-band for the fiber (for typ. max distance), 5.5 dB per WDM mux: Total 17.8 dB	
Chromatic Dispersion	270 ps/nm	
Mode, Nr ch., WL	Dual fiber pluggables, single fiber trunk: 48 wavelengths @ 100GHz (0.8nm) spacing	
Temp. Range/Class	I-temp	
Lifespan	15 years	
Data rates	10 Gb/s	25 Gb/s
Form factor	SFP+	SFP28
FEC, Mod format	No, NRZ	Yes, NRZ
Power Class	PC4 (2.5 W)	PC4 (2.5 W)
Pluggables codes	10G-15km-C-D-48-2-SFP+	25G-15km-C-D-48-2-SFP28
Key technologies	Low-cost EML DWDM, without wavelength lockers. Athermal AWG and TFF filters	
Standards	ITU-T G.698.1, Table 8.3. See Appendix A Table 13	-
Market status and outlook (See Note for 7.3.2)	Mature	Mature

Table 11: 15 km RU-DU DWDM Blueprint.

7.3.5. 15 km RU-DU, passive DWDM bus over a single fiber Blueprint

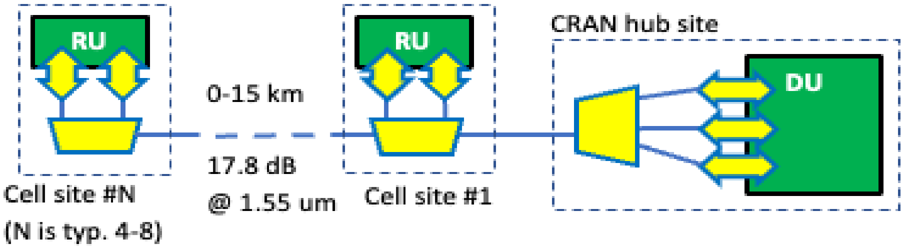

Figure 13: 15 km RU-DU, DWDM passive wavelength multiplexed bus Blueprint.

15 km RU-DU DWDM bus Blueprint		
Typical UC	CRAN DU to radio unit (RU). Up to 15 km DWDM bus or horseshoe topologies with one headend at DU side and multiple add/drop RU sites. Links up to 24 SFP+ pairs using the same single trunk fiber. - Flexible use of the available loss budget up to 17.8 dB. (*) - Max number of added/dropped channel at each OADM: 6 - Number of OADMs : Up to 8. (*Typical 4-6, deployments with 7-8 are few)*	
Distance	Typ Min 0 km; Typ. Max: 15 km	
Channel IL	6.8 dB C-band for the fiber, 0.6 dB per OADM pass, 3.0 dB for add/drop (up to 8 OADMs): Max total 17.8 dB	
Chromatic Dispersion	270 ps/nm	
Mode, Nr ch., WL	Dual fiber pluggables, single fiber trunk between MUX and OADM: 48 wavelengths @ 0.8nm/100GHz spacing.	
Temp. Range/Class	I-temp	
Lifespan	15 years	
Data rates	10 Gb/s	25 Gb/s
Form factor	SFP+	SFP28
FEC	No	Yes
Power Class	PC4 (2.5 W)	PC4 (2.5 W)
Pluggables codes	10G-15km-C-D-48-2-SFP+	25G-15km-C-D-48-2-SFP28
Key technologies	Low-cost EML DWDM, without wavelength lockers. Athermal AWG and OADM TFF filters.	
Standards	ITU-T G.698.1, Table 8.3. See Appendix A Table 13	-
Market status and outlook (See Note for 7.3.2)	Mature (while not very common)	Mature (while not very common)

Table 12: 15 km RU-DU DWDM bus Blueprint. (*) The 17.8 dB value comes from the 7.3.5 Blueprint. Flexible use means that the total loss budget is not calculated as a sum of the fiber and filter losses, but specified as a system limit, that a system design can use a combination of fiber and filter losses up to that value.

7.3.6. 15 km RU-DU, semi-active DWDM over a single fiber Blueprint

This Blueprint is a combination of Blueprints 7.3.4 for the DWDM part, and 6.2.1 for the WDM node to DU optics. In addition to those use cases, this Blueprint offers a WDM demarcation node.

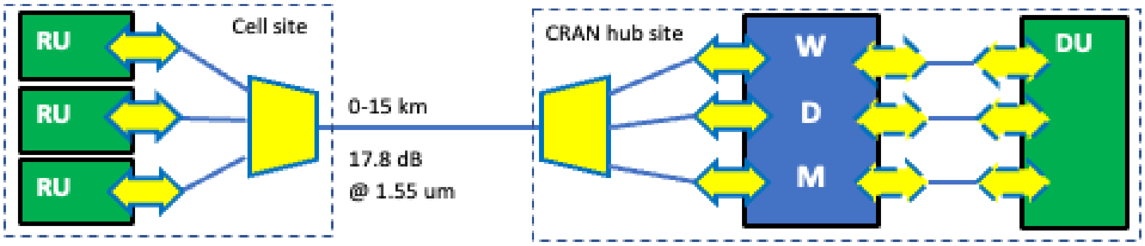

Figure 14: 15 km RU-DU semi-active wavelength multiplexed, P2P or P2MP Blueprint. The intraoffice pluggables at the hub site may be C-temp as indicated by dashed borders.

15 km RU-DU semi-active DWDM Blueprint		
Typical UC	CRAN DU to RU. Up to 15 km DWDM P2P (all RUs at the same location together with the optical multiplexer) or P2MP (the RUs are in slightly different locations, with the optical multiplexer at one of those, or another location) links up to 24 SFP+ pairs using the same single trunk fiber	
Distance	Typ Min 0 km; Typ. Max: 15 km	
Channel IL	6.8 dB C-band for the fiber (for typ. max distance), 5.5 dB per WDM mux: Total 17.8 dB	
Chromatic Dispersion	270 ps/nm	
Mode, Nr ch., WL	Dual fiber pluggables, single fiber trunk: 48 wavelengths @ 0.8nm/100GHz spacing	
Temp. Range/Class	I-temp	
Lifespan	15 years	
Data rates	10 Gb/s	25 Gb/s
Form factor	SFP+	SFP28
FEC, Mod format	No, NRZ	Yes, NRZ
Power Class	PC4 (2.5 W)	PC4 (2.5 W)
Pluggables codes	10G-15km-C-D-48-2-SFP+	25G-15km-C-D-48-2-SFP28
Key technologies	Low-cost EML DWDM, without wavelength lockers. Athermal AWG and TFF filters	
Standards	ITU-T G.698.1, Table 8.3. See Appendix A Table 13	-
Market status and outlook (See Note for 7.3.2)	Mature	Mature

Table 13: 15 km RU-DU semi-active DWDM Blueprint. Same table as used for blueprint 7.3.4 for the DWDM part.

7.3.7. 2 km RU-DU packet multiplexing, dual fiber Blueprint

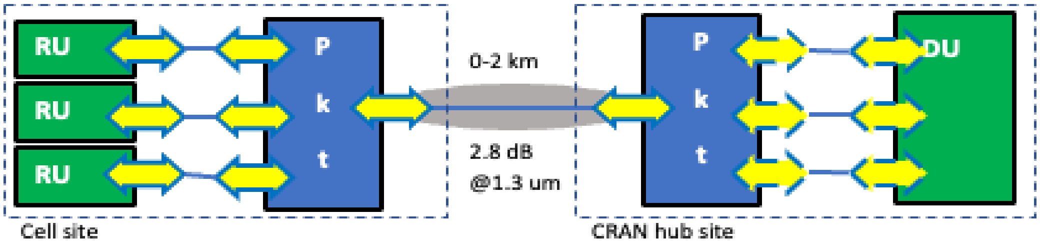

Figure 15: 2 km RU-DU, packet multiplexing, P2P or P2MP Blueprint. The link specified has a gray background. There may be additional intermediate Pkt nodes between the depicted Pkt node and DU, for example in case of cloud RAN deployments at the hub site. The intraoffice pluggables at the hub site may be C-temp as indicated by dashed borders.

2 km RU-DU packet multiplexing Blueprint		
Typical UC	DU to RU via packet-multiplexed interconnect, up to 2 km fiber between packet nodes. P2P (all RUs at the same location together with the optical multiplexer) or P2MP (the RUs in slightly different locations, with the packet multiplexer at one of those, or another location). Short reach 10G/25G optical links (<2km, see Blueprint 7.3.2) or direct attach copper cables (DAC) between Pkt node and the corresponding DU/RU.	
Distance	Typ Min 0 km; Typ. Max: 2 km	
Channel IL	2.8 dB O-band (For typ. max distance)	
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm.	
Temp. Range/Class	I-temp	
Lifespan	15 years	
Data rates	25 Gb/s	100 Gb/s
Form factor	SFP28	QSFP28
FEC, Mod. format	No, NRZ	Yes, PAM4 or NRZ for 4WDM
Power Class	PC4 (2.5 W)	PC4 (3.5 W)
Pluggables codes	25G-2km-O-G-1-2-SFP28	100G-2km-O-G-1-2-QSFP28 or 100G-2km-O-C/L-4-2-QSFP28
Key Technologies	-	Low-cost integrated 4x25G WDM or single lambda 100G Tx and Rx.
Standards	IEEE 802.3, Clauses 114	IEEE 802.3, Clause 140 or CWDM4 MSA,
Market status and outlook (*)	Mature	100G 4WDM-10 mature for mobile transport; single lambda 100G ramping

Table 14: 2 km RU-DU packet multiplexing Blueprint. (*) Higher data rates (e.g. 400Gb/s) are the next logical step.

7.3.8. 15 km RU-DU packet multiplexing, dual or BiDi fiber Blueprint

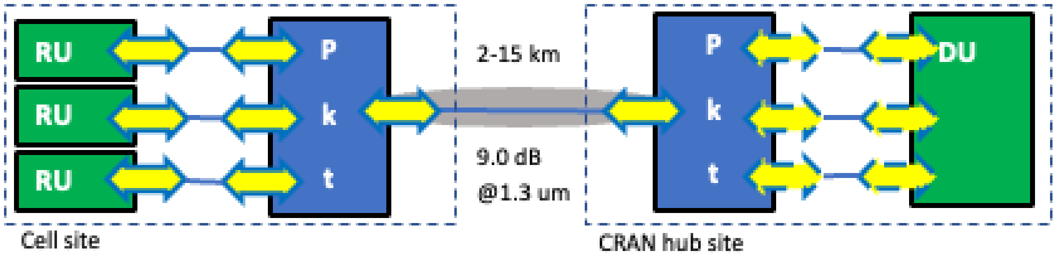

Figure 16: Same as Blueprint 8.3.7 for the 15 km case with dual or bidi fiber.

15 km RU DU packet multiplexed links Blueprint		
Typical UC	Same as Blueprint 8.3.7 for the 15 km case with dual or bidi fiber.	
Distance	Typ Min 0 km; Typ. Max: 15 km (See Note for 7.3.3) (*)	
Channel IL	9.0 dB O-band (For typ. max distance)	
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm. BiDi O-band 1270 nm/1330 nm.	
Temp. Range/Class	I-temp	
Lifespan	15 years	
Data rates	25 Gb/s	100 Gb/s
Form factor	SFP28	QSFP28
FEC, Mod. format	Yes, NRZ	Yes, PAM4 or NRZ for 4WDM
Power Class	PC4 (2.5 W)	PC4 (3.5 W)
Pluggables codes	25G-15 km-O-G-1-2-SFP28 25G-15 km-O-B2-2-1-SFP28	100G-15 km-O-G-1-2-QSFP28 or 100G-15 km-O-L-4-2-QSFP28 100G-15 km-O-B2-2-1-QSFP28
Key Technologies	-	Low-cost integrated 4x25G WDM or single lambda 100G Tx and Rx. BiDi: 1270 nm/1330 nm BOSA with single lambda 100G.
Standards	IEEE 802.3, Clause 159. See Appendix A Tables 9.10	100G Lambda MSA or 100G-4WDM-20 MSA, ITU-T G.9806 (Amend 3). See Appendix A Table 11
Market status and outlook	Mature	Dual fiber 100G 4WDM-20 mature for mobile transport; single lambda 100G emerging.

Table 15: 15 km RU-DU packet multiplexing Blueprint. (*) For 100G, 10 km may be more cost-effective, while 15 km is desirable for CRAN LLS deployment cases.

8. Mobile Optical Solution Blueprints for Backhaul and HLS

8.1. Overview

The mobile backhaul transport network connects the RAN segment with the mobile core segment and has a tiered hierarchical packet aggregation architecture [GSTR-TN5G]. The mobile HLS transport network connects the DUs and the CUs within the RAN. In both cases, the requirements regarding the transport traffic in terms of latency, delay variance and throughput are less stringent compared with LLS.

The figures below show the overall architectures for backhaul and HLS for DRAN and VRAN, and CRAN. The term *multi-service* is used generically to indicate any type of WDM, packet, TDM, etc., transport network used for different types of services, such as mobile access, enterprise site connectivity, residential connectivity, etc.

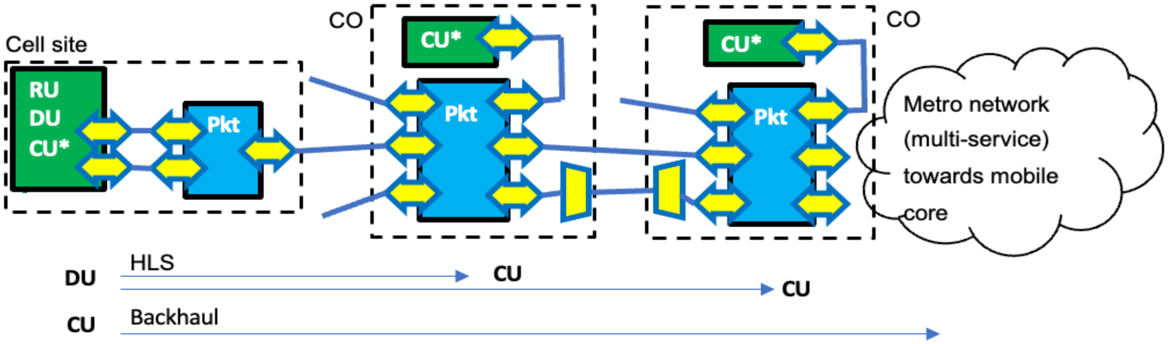

Figure 17: Backhaul and HLS for DRAN and virtual RAN. CU indicates possible locations for the CU, at the cell site, or at the closest CO. The latter constitutes the VRAN case. The pluggables at the CO sites may be C-temp as indicated by dashed borders for the intraoffice ones.*

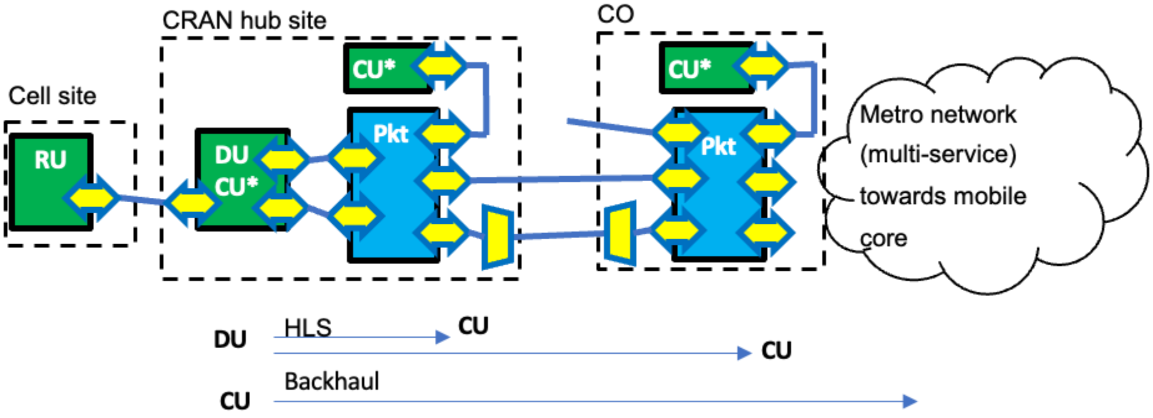

Figure 18: Backhaul and HLS for CRAN. CU indicates possible locations for the CU, at the CRAN hub site, or at the CO. The latter constitutes the VRAN case. The pluggables at the CRAN hub and CO sites may be C-temp as indicated by dashed borders for the intraoffice ones.*

Both DRAN backhaul and CRAN LLS can experience fiber abundance or fiber scarcity in the access part (i.e., between the cell site and the hub site). When fiber is relatively abundant, it allows for point-to-point parallel fiber links to the individual cell sites, possibly with duplex or BiDi fiber solutions. In scenarios where fiber is more scarce, cost-effective solutions like WDM and TDM-PONs are attractive. TDM-PONs are based on bidirectional use of a common single feeder fiber which is shared between multiple cell sites by a passive splitter and individual but shorter drop fibers. A single optic in the OLT is shared over multiple ONUs in the cell sites. More information about TDM-PONs and the different standards can be found in [TDM-PON].

This backhaul access network segment, sometimes called *Lo-RAN*, is located between the cell site packet node and the first level of aggregation. See the blueprints in the next section for current data rates.

In the backhaul aggregation segment, sometimes called *Hi-RAN (right-hand side of Figure 17 and Figure 178)*, which also applies to CRAN backhaul, the typical distances range from 10 km to 40 km, with a non-negligible minority of links demanding even longer reach and different scenarios of fiber resources availability. See the blueprints below for current and future data rates. Presently, unamplified DWDM links at 25G per channel are challenging to make cost-effective beyond 15 km. However, as technology evolves, there’s a need for up to 40 km links as stated above.

Except for the packet nodes at cell sites, other packet equipment is hosted in a temperature-controlled indoor environment, and it is possible to use optical pluggables supporting the so-called *C-temp*, with operating case temperatures in the 0° C to 70° C range.

8.2. Backhaul and HLS Optical Blueprints

8.2.1. 2 km DRAN intraoffice backhaul, direct parallel fibers, dual fiber Blueprint

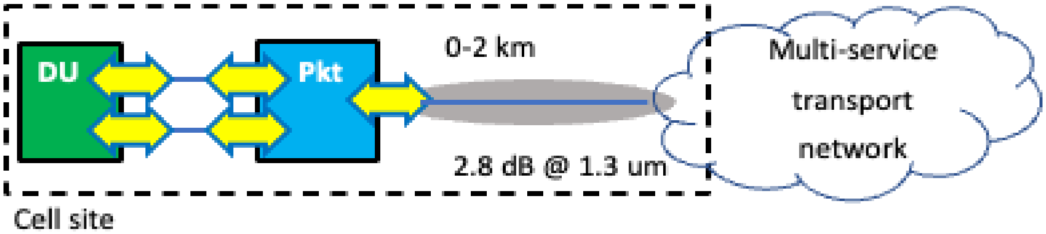

Figure 19: 2 km DRAN intraoffice backhaul direct dual fiber Blueprint. The link specified has a gray background. In cases where the cell site DU is collocated with the CU, backhaul is illustrated. If the CU is located at another location, HLS is illustrated.

2 km intraoffice backhaul Blueprint			
Typical UC	DRAN cell site packet node to leased line service, e.g., AAV with local (i.e., box at cell site) demarcation node, providing the transport to the metro transport network.		
Distance	Typ Min 0 km; Typ. Max: 2 km		
Channel IL	2.8dB O-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm		
Temp. Range/Class	I-temp		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	100 Gb/s
Form factor	SFP+	SFP28	QSFP28
FEC, Mod. format	No, NRZ	Yes, NRZ	Yes, PAM4 or NRZ for 4WDM
Power Class	PC2 (1.5 W)	PC2 (1.5 W)	PC4 (3.5 W)
Pluggables codes	10G-2km-O-G-1-2-SFP+	25G-2km-O-G-1-2-SFP28	100G-2km-O-G-1-2-QSFP28 or 100G-2km-O-C-4-2-QSFP28
Key technologies	-	Low-cost 25G DFB	Low-cost integrated 4x25G WDM or “single lambda” 100G Tx and Rx.
Standards	IEEE 802.3 Cl 52 See Appendix A Table 1	IEEE 802.3 Cl 114 See Appendix A Table 1	IEEE 802.3 Cl 140 See Appendix A Table 4
Market status and outlook	Mature and relatively common case	Emerging	Emerging

Table 16: 2 km intraoffice backhaul Blueprint.

8.2.2. 10 km DRAN backhaul, direct parallel fibers, dual and BiDi fiber Blueprint

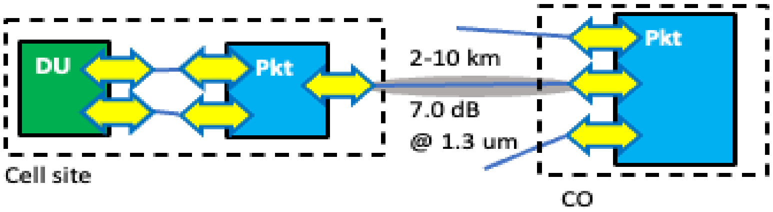

Figure 20: 10 km DRAN backhaul with direct parallel fiber, dual or BiDi Blueprint. The link specified has a gray background. In cases where the cell site DU is collocated with the CU, backhaul is illustrated. If the CU is located at another location, HLS is illustrated.

10 km DRAN backhaul direct parallel fiber Blueprint			
Typical UC	DRAN cell site packet node to CO packet aggregation node. In some deployments, the CO side uses a p2p OLT (demarcation point equipment, not shown in the figure above) interfacing the fiber plant.		
Distance	Typ Min 2 km; Typ. Max: 10 km		
Channel IL	7.0 dB O-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm. BiDi O-band 1270nm/1330 nm.		
Temp. Range/Class	I-temp		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	100 Gb/s
Form factor	SFP+	SFP28	QSFP28
FEC, Mod. format	No, NRZ	Yes, NRZ	Yes, PAM4 or NRZ for 4WDM
Power Class	PC2 (1.5 W)	PC2 (1.5 W)	PC4 (3.5 W)
Pluggables codes	10G-10 km-O-G-1-2-SFP+ 10G-10 km-O-B2-2-1-SFP+	25G-10 km-O-G-1-2-SFP28 25G-10 km-O-B2-2-1-SFP28	100G-10 km-O-G-1-2-QSFP28 or 100G-10 km-O-C/L-4-2-QSFP28 or 100G-10 km-O-B2-2-1-QSFP28
Key technologies	-	Low-cost 25G DFB	Low-cost integrated 4x25G WDM or single lambda 100G Tx and Rx. BiDi: 1270nm/ 1330nm BOSA with single lambda 100G.
Standards	IEEE 802.3 Cl 52 & 158, G.9806 (Amend 2) See Appendix A Tables 5,6,7	IEEE 802.3 Cl 114 & 159, G.9806 (Amend 2) See Appendix A Tables 5,6,7.	IEEE 802.3 Cl 140 & 88, ITU-T G.9806 (Amend 3) See Appendix A Table 8
Market status and outlook (*)	Mature and relatively common case.	Emerging, complement to 10G.	Few cases but emerging.

Table 17: 10 km DRAN backhaul direct parallel fiber Blueprint.
(*) The fiber abundant 10 km case is common for DRAN backhaul.

8.2.3. 40 km DRAN backhaul, direct parallel fibers, dual and BiDi fiber Blueprint

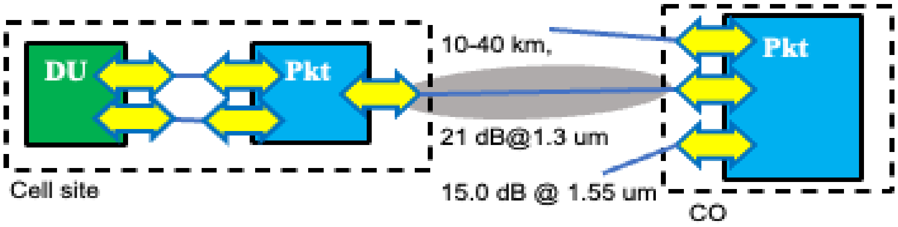

Figure 21: 40 km DRAN backhaul direct parallel fiber, dual or BiDi Blueprint. The link specified has a gray background. In cases where the cell site DU is collocated with the CU, backhaul is illustrated. If the CU is located at another location, HLS is illustrated.

40 km DRAN backhaul direct parallel fiber Blueprint			
Typical UC	DRAN cell site packet node to CO packet aggregation node.		
Distance	Typ Min 10 km; Typ. Max: 40 km (*)		
Channel IL	20.0 dB O-band, 15.0 dB C-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: for 10G: C-band. For 25G and 100G O-band. BiDi O-band 1270nm/1330 nm.		
Temp. Range/Class	I-temp		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	100 Gb/s
Form factor	SFP+	SFP28	QSFP28
FEC, Mod. format	No, NRZ	Yes, NRZ	Yes, PAM4 or NRZ for 4WDM
Power Class	PC4 (2.5 W)	PC4 (2.5 W)	PC4 (3.5 W)
Pluggables codes	10G-40 km-C-G-1-2-SFP+ 10G-40 km-O-B2-2-1-SFP+	25G-40 km-O-G-1-2-SFP28 25G-40 km-O-B2-2-1-SFP28	100G-40 km-O-G-1-2-QSFP28, or 100G-40 km-O-L-4-2-QSFP28 or 100G-40 km-O-B2-2-1-QSFP28
Key technologies	-	Low-cost 25G EML	Low-cost integrated 4x25G WDM or single lambda 100G Tx and Rx. BiDi: 1270nm/1330nm BOSA with single lambda 100G.
Standards	IEEE 802.3 Cl 52 & 158 See Appendix A Tables 14,15	IEEE 802.3 Cl 114 & 159 See Appendix A Tables 14,15	100G Lambda MSA, IEEE 802.3 Cl 88, ITU-T G.9806 (Amend 3). See Appendix A Tables 14,15
Market status and outlook (**)	Mature and relatively common case.	Emerging, complement to 10G.	Few cases but emerging.

Table 18: 40 km DRAN backhaul direct parallel fiber Blueprint. (*) 40 km is challenging for 25G and 100G. (**) The fiber abundant 40 km case is common (while less than 10 km) for DRAN backhaul.

8.2.4. 15 km DRAN backhaul, passive DWDM bus over a single fiber Blueprint

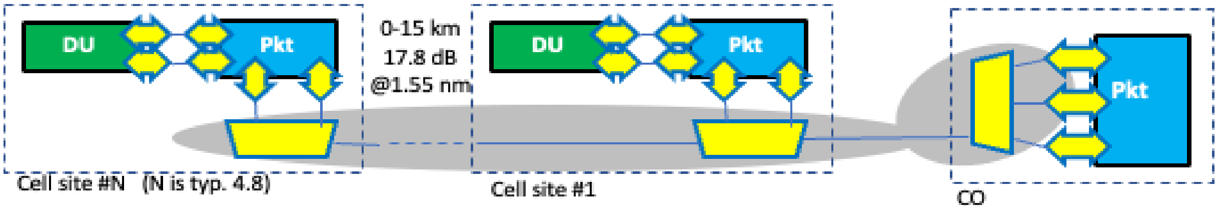

Figure 22: 15 km DRAN backhaul, DWDM passive wavelength multiplexed bus Blueprint. The link specified has a gray background. In cases where the cell site DU is collocated with the CU, backhaul is illustrated. If the CU is located at another location, HLS is illustrated.

15 km DRAN backhaul DWDM bus Blueprint		
Typical UC	DRAN cell site packet node to CO packet aggregation. Up to 15 km DWDM bus or horseshoe topologies with headend CO(s) and multiple add/drop cell sites. Up to 24 ch on a single trunk fiber. - Flexible use of the available loss budget up to 17.8 dB.(*) - Max number of added/dropped channels at each OADM: 6. - Number of OADMs : Up to 8. (*Typical 4-6, deployments with 7-8 are few*)	
Distance	Typ Min 0 km; Typ. Max: 15 km	
Channel IL	6.8 dB C-band for fiber, 0.6 dB per OADM pass, 3.0 dB add/drop (up to 8 OADMs): Max tot. 17.8 dB	
Chromatic Dispersion	270 ps/nm	
Mode, Nr ch., WL	Dual fiber pluggables, single fiber trunk MUX to OADM: 48 wavelengths @ 100 GHz (0.8 nm) spacing.	
Temp. Range	I-temp	
Lifespan	15 years	
Data rates	10 Gb/s	25 Gb/s
Form factor	SFP+	SFP28
FEC, Mod format	No, NRZ	Yes, NRZ
Power Class	PC4 (2.5 W)	PC4 (2.5 W)
Pluggables codes	10G-15 km-C-D-48-2-SFP+	25G-15 km-C-D-48-2-SFP28
Key technologies	Low-cost EML DWDM, without wavelength lockers. Athermal AWG and OADM TFF filters.	
Standards	ITU-T G.698.1 Table 8.3. See Appendix A Table 13	
Market status and outlook (See Note 7.3.1)	Mature.	Maturing but few cases.

Table 19: 15 km DRAN backhaul DWDM bus Blueprint.
(*) Same comments for loss budget and flexible use as Blueprint 7.3.4.

8.2.5. 2 km intraoffice CRAN hub site intraoffice backhaul Blueprint

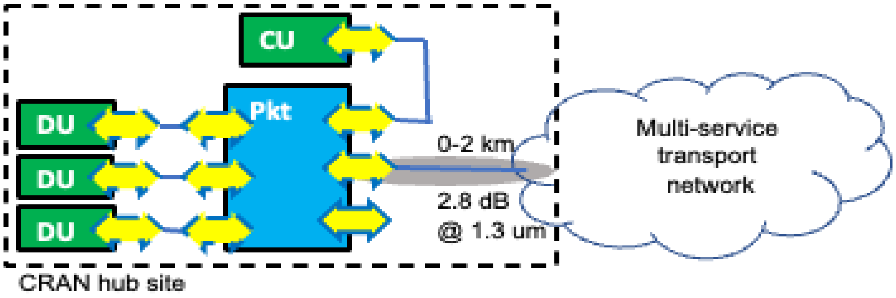

Figure 23: 2 km CRAN hub site intraoffice backhaul direct parallel fiber Blueprint. The link specified has a gray background. In cases where the CU is located at another location, HLS is illustrated. The pluggables at the CRAN hub site may be C-temp as indicated by dashed borders for the intraoffice ones.

2 km intraoffice CRAN hub site intraoffice backhaul Blueprint			
Typical UC	CRAN hub site packet node to leased line service, e.g., AAV, with local (i.e., box at cell site) demarcation node, providing the transport to the metro transport network.		
Distance	Typ Min 0 km; Typ. Max: 2 km		
Channel IL	2.8 dB O-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm		
Temp. Range/Class	I-temp (preferred) or C-temp (see section 5.1)		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	100 Gb/s
Form factor	SFP+	SFP28	QSFP28
FEC, Mod. format	No, NRZ	Yes, NRZ	Yes, PAM4 or NRZ for 4WDM
Power Class	PC2 (1.5 W)	PC2 (1.5 W)	PC4 (3.5 W)
Pluggables codes	10G-2 km-O-G-1-2-SFP+	25G-2 km-O-G-1-2-SFP28	100G-2 km-O-G-1-2-QSFP28, or 100G-2 km-O-C-4-2-QSFP28
Key technologies	-	Low-cost 25G DFB	Low-cost integrated 4x25G WDM or single lambda 100G Tx and Rx.
Standards	IEEE 802.3 Cl 52 See Appendix A Table 1	IEEE 802.3 Cl 114 See Appendix A Table 1	IEEE 802.3 Cl 140 or CWDM4 MSA See Appendix A Table 4
Market status and outlook	Mature and relatively common case.	Emerging, few cases.	Few cases. Port capacities beyond 100G, ie 400G, may be needed in the mid-term, for example with form factors QSFP, QSFP-DD or OSFP or port aggregation".

Table 20: 2 km CRAN hub site intraoffice backhaul Blueprint.

8.2.6. 10 km CRAN backhaul, direct parallel fibers, dual and BiDi fiber Blueprint

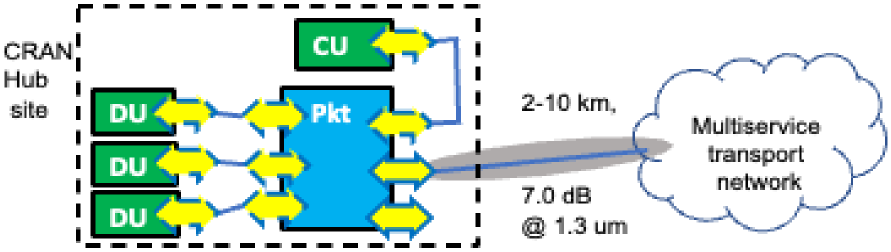

Figure 24: 10 km CRAN backhaul Blueprint (direct P2P, no WDM). The link specified has a gray background. In cases where the CU is located at another location, HLS is illustrated. The pluggables at the CRAN hub site may be C-temp as indicated by dashed borders for the intraoffice ones.

10 km CRAN hub site backhaul direct parallel fiber Blueprint			
Typical UC	CRAN hub site Pkt node to Multiservice transport network at another site.		
Distance	Typ Min 2 km; Typ. Max: 10 km		
Channel IL	7.0 dB O-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: O-band 1310 nm. BiDi O-band 1270nm/1330 nm.		
Temp. Range/Class	I-temp (preferred) or C-temp (see Section 5.1).		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	100 Gb/s
Form factor	SFP+	SFP28	QSFP28
FEC, Mod. format	No, NRZ	Yes, NRZ	Yes, PAM4 or NRZ for 4WDM
Power Class	PC2 (1.5 W)	PC2 (1.5 W)	PC4 (3.5 W)
Pluggables codes	10G-10 km-O-G-1-2-SFP+ 10G-10 km-O-B2-2-1-SFP+	25G-10 km-O-G-1-2-SFP28 25G-10 km-O-B2-2-1-SFP28	100G-10 km-O-G-1-2-QSFP28, or 100G-10 km-O-C/L-4-2-QSFP28 100G-10 km-O-B2-2-1-QSFP28
Key technologies	-	Low-cost 25G DFB	Low-cost integrated 4x25G WDM or single lambda 100G Tx and Rx. BiDi: 1270 nm/1330 nm BOSA with single lambda 100G.
Standards	IEEE 802.3 Cl 52 & 158 G.9806 (Amend 2) See Appendix A Tables 5,6,7	IEEE 802.3 Cl 114 & 159 G.9806 (Amend 2) See Appendix A Tables 5,6,7	IEEE 802.3 Cl 140 & 88, ITU-T G.9806 (Amend 3) See Appendix A Table 8.
Market status and outlook (*)	Mature and relatively common case	Emerging, complement to 10G	Few cases but emerging.

Table 21: 10 km CRAN backhaul direct parallel fiber Blueprint. (*) The fiber abundant 10 km case is common for CRAN backhaul.

8.2.7. 40 km CRAN backhaul, direct parallel fibers, dual and BiDi fiber Blueprint

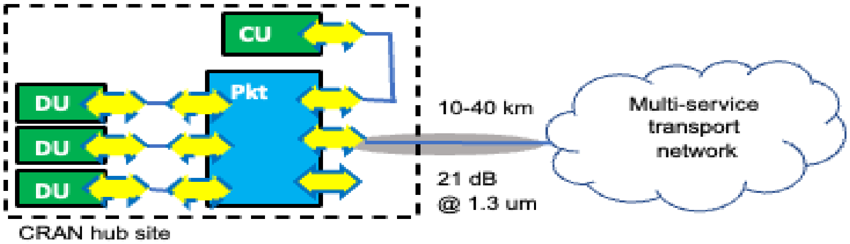

Figure 25: 40 km CRAN hub site backhaul direct parallel fiber Blueprint. The link specified has a gray background. In cases where the CU is located at another location, HLS is illustrated. The pluggables at the CRAN hub site may be C-temp as indicated by dashed borders for the intraoffice ones.

40 km CRAN hub site backhaul direct parallel fiber Blueprint			
Typical UC	CRAN hub site Pkt node to Multiservice transport network at another site.		
Distance	Typ Min 10 km; Typ. Max: 40 km (*)		
Channel IL	20.0 dB O-band, 15.0 dB C-band (For typ. max distance)		
Mode, Nr ch., WL	Dual fiber: For 10G: C-band 1.55 um. For 25G and 100G O-band 1.3 um. BiDi O-band 1270nm/1330 nm.		
Temp. Range/Class	I-temp (preferred) or C-temp (see Section 5.1).		
Lifespan	15 years		
Data rates	10 Gb/s	25 Gb/s	100 Gb/s
Form factor	SFP+	SFP28	QSFP28
FEC, Mod. format	No, NRZ	Yes, NRZ	Yes, PAM4 or NRZ for 4WDM
Power Class	PC4 (2.5 W)	PC4 (2.5 W)	PC4 (3.5 W)
Pluggables codes	10G-40 km-C-G-1-2-SFP+ 10G-40 km-O-B2-2-1-SFP+	25G-40 km-O-G-1-2-SFP28 25G-40 km-O-B2-2-1-SFP28	100G-40 km-O-G-1-2-QSFP28, 100G-40 km-O-L-4-2-QSFP28 100G-40 km-O-B2-2-1-QSFP28
Key technologies	-	Low-cost 25G EML.	Low-cost integrated 4x25G WDM or single lambda 100G Tx and Rx. BiDi: 1270 nm/1330 nm BOSA with single lambda 100G.
Standards	IEEE 802.3, Cl 52 & 158 See Appendix A Tables 14,15	IEEE 802.3 Cl 114 & 159 See Appendix A Tables 14,15	100G Lambda MSA, IEEE 803.3 Cl 88 ITU-T G.9806 (Amd 3). See App A Tables 14,15
Market status and outlook (**)	Mature and relatively common case.	Emerging, few cases.	Few cases.

Table 22: 40 km CRAN backhaul direct parallel fiber Blueprint. (*) 40 km is challenging for 25G and 100G. (**) The fiber abundant 40 km case is less common than 10 km for CRAN backhaul.

8.2.8. 15 km CRAN backhaul, passive DWDM over a single trunk fiber Blueprint

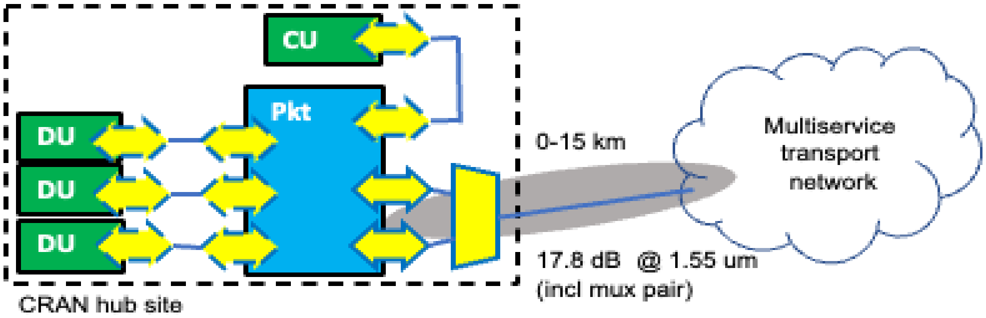

Figure 26: 15 km CRAN backhaul, DWDM passive wavelength multiplexed Blueprint. In cases where the CU is located at another location, HLS is illustrated.

15 km CRAN hub site backhaul DWDM Blueprint		
Typical UC	CRAN hub site Pkt node to Multiservice transport network at another site. Up to 15 km DWDM P2P links with up to 24 SFP+ pairs using the same single trunk fiber.	
Distance	Typ Min 0 km; Typ. Max: 15 km	
Channel IL	6.8 dB C-band for the fiber (For typ. max distance), 5.5 dB per WDM mux: Total 17.8 dB	
Chromatic Dispersion	270 ps/nm	
Mode, Nr ch., WL	Dual fiber pluggables, single fiber trunk: 48 wavelengths @ 0.8nm/100GHz spacing	
Temp. Range/Class	I-temp (preferred) or C-temp (see Section 5.1)	
Lifespan	15 years	
Data rates	10 Gb/s	25 Gb/s
Form factor	SFP+	SFP28
FEC, Mod. format	No, NRZ	Yes, NRZ
Power Class	PC4 (2.5 W)	PC4 (2.5 W)
Pluggables codes	10G-15km-C-D-48-2-SFP+	25G-15km-C-D-48-2-SFP28
Key technologies	Low-cost EML DWDM, without wavelength lockers. Athermal AWG and TFF filters.	
Standards	ITU-T G.698.1, Table 8.3. See Appendix A Table 13	-
Market status and outlook (*, See Note for 7.3.2)	Mature. Few cases	Few cases

Table 23: 10 km CRAN hub site backhaul DWDM Blueprint. (*) Intra-office, direct fiber cases are more common.

8.2.9. 20 km DRAN Backhaul and HLS with TDM-PON, Separate ONU box Blueprint

A PON system consists of OLT and multiple subtended ONUs. The ONU functionality at the cell site can be provided as a separate ONU box as shown in this Blueprint.

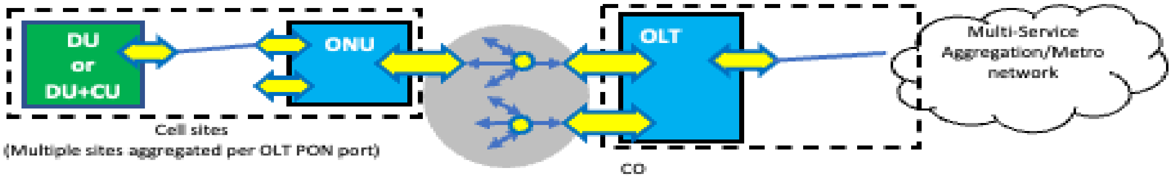

Figure 27: Up to 20 km Backhaul and HLS with TDM-PON using separate ONU box. HLS is depicted in cases where the CU is centralized. Backhaul is depicted in cases where the CU is located at the cell site.

20 km DRAN Backhaul and HLS with TDM-PON, Separate ONU box Blueprint			
Typical UC	Transport from small/medium cell site with DU and optionally CU to the multiservice transport network at another site. The separate ONU box can act as a demarcation point, and as an aggregating point at the cell site when having multiple interfaces. For cases where there is available space for an external transport box at the cell site.		
Distance	Typ. Max: 20 km		
Transmission mode	Single fiber (BiDi)		
Temp. Range/Class	I-temp		
Lifespan	15 years		
Data rate Down/Up	GPON: 2.5 / 1.25 Gb/s	XGS-PON, 10G EPON: 10 / 10 Gb/s	25GS-PON, 25G EPON: 25/10 (or 25) Gb/s
Channel IL	B+ (28 dB), C+ (32 dB), C++ (34 dB). Highest Class: D (35 dB).	N1 (29 dB) and N2 (31 dB). Higher classes: E1 (33 dB), E2 (35 dB).	Starting at N1 (29 dB). Higher classes (N2, E1,E2) for longer term.
Wavelength bands	1300-1320 nm Up 1480-1500 nm Down	1260-1280 nm Up 1575-1580 nm Down	Multiple options in the O-band depending on coexistence requirements.
Form factor	SFP, SFP-DD for dual OLT module	SFP+	SFP28
FEC	Yes	Yes	Yes
Power Class	Dual OLT module: PC4 (2.5 W) Single OLT module: PC2 (1.5 W) ONU module: PC2 (1.5 W)	OLT module: PC4 (2.5 W) ONU module: PC3 (2 W)	OLT module: PC4 (2.5 W) ONU module: PC4 (2.5 W), evolution to PC3 (2 W) is desired.
Pluggables codes	GPON-20 km-OS-B3-1-SFP-OLT GPON-20 km-OS-B3-1-SFP-ONU	XGS-PON-20 km-OL-B3-1-SFP+-OLT XGS-PON-20 km-OL-B3-1-SFP+-ONU	25GS-PON-20 km-O-B3-1-SFP28-OLT 25GS-PON-20 km-O-B3-1-SFP28-ONU
Key technologies	BOSA with DML and PIN or APD.	BOSA with EML and APD.	BOSA with EML and APD.
Standards (Phy & MAC)	ITU-T G.984.x See Appendix A Table 16	IEEE 802.3 Cl. 75. ITU-T G.9807.x See Appendix A Table 16	IEEE 802.3 Cl 141. 25GS-PON MSA See Appendix A Table 16
Market status and outlook	Mature, mass deployments for FTTx, volume deployments for 4G	Mature, volume deployments for FTTx, 5G small cell deployments	Emerging technology under validation, future deployments

Table 24: 20 km DRAN Backhaul and HLS with TDM-PON, Separate ONU box Blueprint. (Note: There are also SFP family-based OLT modules combining both XGS-PON and GPON in a single fiber.)

8.2.10. 20 km DRAN Backhaul and HLS with TDM-PON, Pluggable ONU

Instead of an external box, the cell site ONU functionality can be integrated into the pluggable optic (*Pluggable ONU*, also known as *ONU on a stick* or *Integrated ONU* (iONU)).

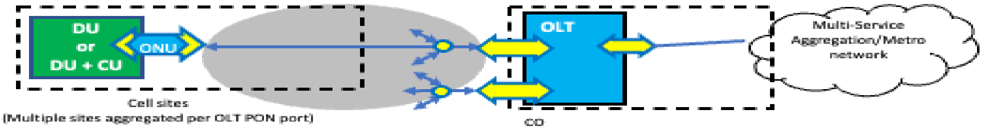

Figure 28: Up to 20 km backhaul and HLS with TDM-PON using pluggable ONU. HLS is depicted in cases where the CU is centralized. Backhaul is depicted in cases where the CU is located at cell site.

20 km DRAN Backhaul and HLS with TDM-PON, Pluggable ONU Blueprint			
Typical UC	Transport from small or medium cell site with DU and optionally CU functionality to multiservice transport network at another site. Preferred solution if there is no space for external transport box at cell site.		
Distance	Typ. Max: 20 km		
Transmission mode	Single fiber (BiDi)		
Temp. Range/Class	I-temp		
Lifespan	15 years		
Data rate Down / Up	GPON: 2.5 / 1.25 Gb/s	XGS-PON, 10G EPON: 10 / 10 Gb/s	25GS-PON, 25G EPON: 25 / 10 (or 25) Gb/s
Channel IL	B+ (28 dB), C+ (32 dB), C++ (34 dB). Highest Class D (35 dB)	N1 (29 dB) and N2 (31 dB). High classes E1 (33 dB) and E2 (35 dB)	Starting at N1 (29 dB). Higher classes (N2, E1, E2) for longer term.
Wavelength bands	1300-1320 nm Up 1480-1500 nm Down	1260-1280 nm Up 1575-1580 nm Down	Multiple waveband options in the O-band depending on coexistence requirements.
Form factor	SFP, SFP-DD for dual OLT module	SFP+	SFP28
FEC	Yes	Yes	Yes
Power Class	Dual OLT module: PC4 (2.5 W) Single OLT module: PC2 (1.5 W) integrated ONU module: PC3 (2 W)	OLT module: PC4 (2.5 W) Integrated ONU module: PC4 (2.5 W), evolution to PC3 (2 W) is desired	OLT module: PC4 (2.5 W) Integrated ONU module: TBD.
Pluggables codes	GPON-20 km-OS-B3-1-SFP-OLT GPON-20 km-OS-B3-1-SFP-iONU	XGS-PON-20 km-OL-B3-1-SFP+-OLT XGS-PON-20 km-OL-B3-1-SFP+-iONU	25GS-PON-20 km-O-B3-1-SFP28-OLT 25GS-PON-20 km-O-B3-1-SFP28-iONU
Key technologies	BOSA w. DML and PIN or APD. Pluggable also contains SoC for ONU PON MAC.	BOSA with EML and APD. Pluggable also contains SoC for ONU PON MAC.	BOSA with EML and APD. Pluggable also contains SoC for ONU PON MAC.
Standards (Phy & MAC)	ITU-T G.984.x See Appendix A Table 16	IEEE 802.3 Cl. 75, ITU-T G.9807.x See Appendix A Table 16	IEEE 802.3 Cl 141, 25GS-PON MSA See Appendix Table 16
Market status and outlook	Mature, mass deployments for FTTx, volume deployments for 4G	Mature, volume deployments for FTTx, 5G small cell deployments	Emerging technology under validation, future deployments

Table 25: 20 km DRAN Backhaul and HLS with TDM-PON, Pluggable ONU Blueprint. (Note: There are also SFP family-based OLT modules combining both XGS-PON and GPON in a single fiber.)

9. Cloud RAN optical solutions

This paper is intentionally focused on the optical solutions of mobile networks and not the particular implementations of the RAN functions. However, there are at least two distinct ways to implement baseband (DU with or without CU) equipment: integrated or cloud RAN, where the latter is much less understood from an optical perspective.

Cloud RAN [CloudRAN] is defined as using compute server [server] hardware for DU and/or CU functions, sometimes called vDU and vCU, see the figure below for an example with a vDU. The compute server is equipped with one or more pluggable NICs (Networks Interface Card, [NIC]), typically using either PCIe or OCP interfaces to the server. The NICs host one or multiple optical pluggables. As an example, NIC may have four ports of SFPx / QSFPx..

As can be seen from the figure below, there are several connectivity solutions between the vDU and the RUs, already outlined in previous chapters: parallel dual or bidi gray fibers, packet aggregation and WDM aggregation.

One example of optical performance monitoring is by using ethtool [ethtool], which is a generic tool for linux kernels. The -m command will provide all the content of the SFP EEPROM, including (if supported) the SFP temperature, TX and RX optical powers, etc. Also, the DMFT NC-SI specifications [NC-SI] describe how this info can be obtained, while the specification focuses on module temperature.

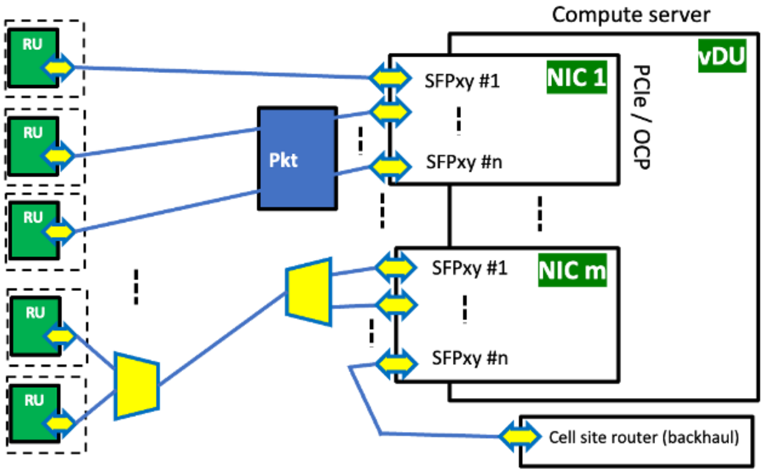

Figure 29: Cloud RAN optical solution. Several connectivity solutions between vDU and RU are shown (from top to bottom) parallel dual or bidi gray fibers, packet aggregation and DWDM aggregation.

During June-August 2024, the MOPA Operator Advisory Board were asked about their plans and inputs on Cloud RAN with emphasis on the optical solutions. Their inputs are summarized below:

Timelines: Some operators are already using Cloud RAN while most are currently performing lab evaluations with planned introduction 2026+. Some operators raise concerns that Cloud RAN does not have feature parity with integrated RAN.

Packet and WDM switching: Some operators plan/investigate to use packet switching between RUs and vDU, while others prefer passive WDM. Some operators also plan/investigate optical switching for dynamic path reconfiguration.

Vendor mixing. All operators indicated that they plan to use vendor mixing, either already from the start or in later stages.

MOPA blueprints. The preferred operator Blueprints are indicated in Figure 29:

- 6.2.1 (DRAN) and 7.3.2 (CRAN) gray parallel fibers.
- 7.3.4 and 7.3.3 passive DWDM and CWDM CRAN.
- 7.3.8 packet switching for CRAN.

Data rates and form factors: Operators commonly indicate using SFP28 ports for LLS connections, while some will also use SFP+ and look to SFP56 for the future. QSFP28 may also be used for aggregation (packet and port) and for future higher data rates.

Requirements for optical pluggables: All operators agree that the same optical requirements needed for integrated RAN (see chapter 6) are also necessary for Cloud RAN. Related statements mention that power consumption, heat as well as Interoperability are critical for successful deployments.

As a continuation of the above, the MOPA Operator Advisory Board was asked in February 2025 about their views on packet aggregation solutions for Cloud RAN. While MOPA's scope does not directly involve packet aggregation aspects, the types of boxes and their locations play a key role in the types of optics needed. Figure 30 illustrates some possible packet aggregation/switching solutions for Cloud RAN.

The operator's views are summarized below:

Are both FH switches and ToR needed at the central office side? Having both these boxes seems to be redundant so only one of them is required, i.e. either ToR or FH switch depending on operator preference.

Is it beneficial to have a FH switch at the cell site? Operators have expressed interest in a packet switching stage at the cell site if it can be used as a bandwidth-lowering aggregation stage at the same location as other equipment, namely the cell site cabinet. Assuming eCPRI, a FH switch at the cell site aggregates traffic and saves on fiber resources.

Is soft-switching in the compute servers sufficient? The operators seem to agree that there are some benefits to soft switching, which may mean that other solutions in the FH networks to reduce the number of fibers are not needed (i.e. packet switch as discussed above, WDM aggregation, etc).

Based on these discussions, the operators are favorable to add Cloud RAN to the list of Blueprints.

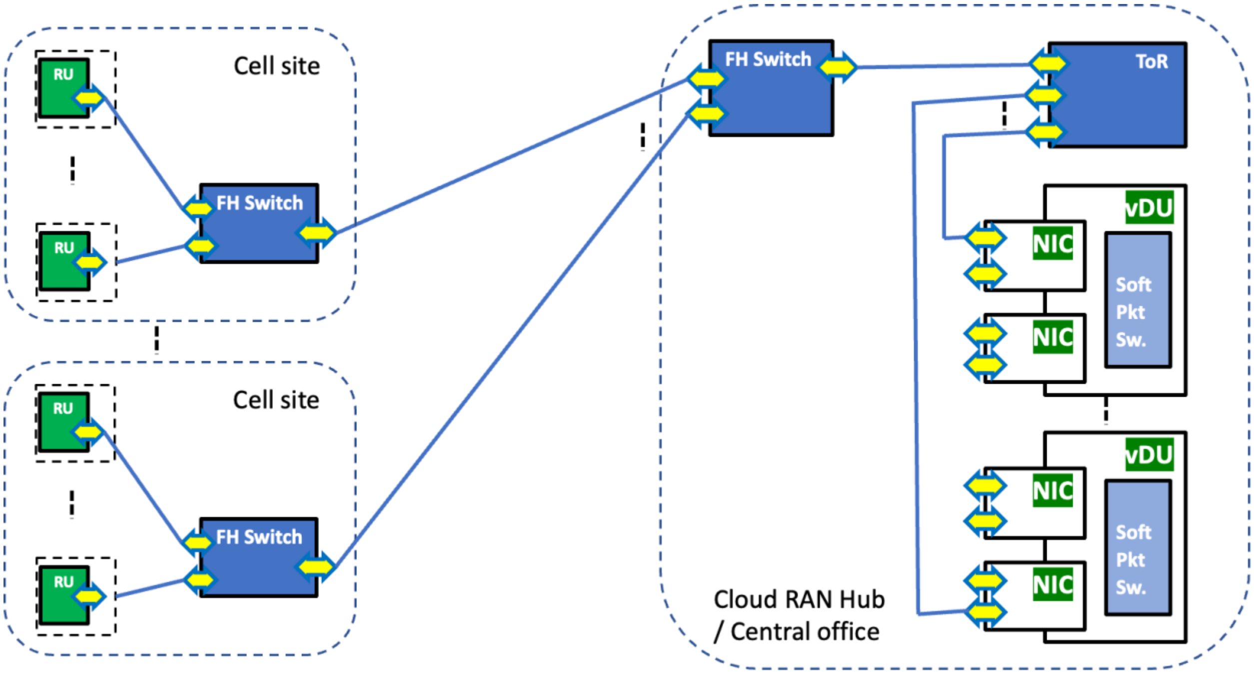

Figure 30: Different packet aggregation solutions for Cloud RAN. Packet aggregation and switching may be done as soft-switching inside the compote servers, with ToR (Top of Rack) switches, and FH (Fronthaul) switches at the central office and cell sites. This is a superset illustration while in practice a subset of these packet aggregation solutions will be used as discussed in this section.

Regarding NIC card evolution, it has been observed that NIC cards with QSFPx ports may be more common, and available earlier in the cycle, than NICs with many SFPx ports. Thus, it is interesting to compare the use of 4 SFPs with that of a QSFP28 PSM4 (Figure 31) (4 parallel single mode fibers, see e.g. [PSM4]). Primarily LR and FR distances are considered at this point. Survey responses from MOPA members comparing the various options is summarized as follows:

Footprint / Size: QSFP has an advantage with 2-3x smaller footprint and thus higher NIC port density.

Power Consumption: Four SFPs have about the same power consumption as one QSFP. There may be a slight advantage for QSFP, assuming that key component technologies (lasers and ICs) are common. There might be a difference at high temp due to the difference in thermal dissipation, which depends on design. Power dissipation density is likely higher for the QSFP form factor owing to the fact that the function of four SFPs are contained in one QSFP, which, as mentioned above, is about 2-3x smaller.

Reliability: 4x SFP has an advantage since a port failure on the NIC cord only impacts one RU (in this scenario).

Flexibility: 4x SFP has an advantage since each RU link may be upgraded independently of others.

Interop: 4x SFP has an advantage since the same implementation can be bookended and used on both sides of the link.

Cost: The options here come out about the same, or a slight advantage for QSFP, but this of course heavily depends on volume of the components used.

Latency: Same, assuming that the technologies of key components are common.

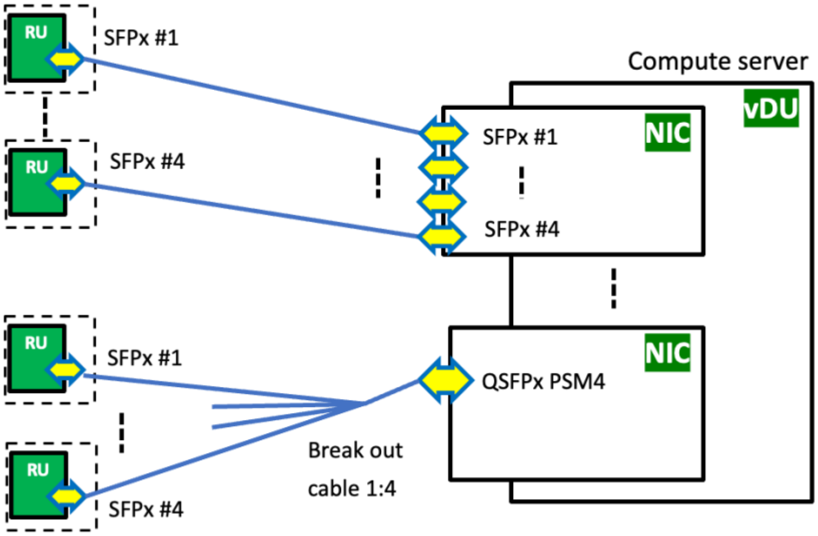

Figure 31: Illustrations of 4 times SFPx (top) and one QSFPx PSM4 (bottom) to connect four RU SPFx with p2p fibers.

10. Summary of Optical Pluggables vs. Blueprint

The tables below summarize the pluggable variants used by the different Blueprints described in the paper. It should be noted that the tables in this section include all the pluggables used in the Blueprint illustrations, not only the ones highlighted and covered by the individual Blueprint tables

for example, dual fiber 10G and 25G pluggables used to connect equipment within the same site. The following codes are used for the 2nd row in the tables below:

- x: a pluggable that is the same at both ends.
- y: a pluggable that is only at the network side (closer to mobile core network)
- z: a pluggable that is only at the access side (closer to the RU)

If the module type is the same at both ends, it gets an x in the table. If there are two module types, one for each end, there is both a y and a z in the table entry.

Pluggables vs Blueprints	**10G-2 km-O-G-1-2-SFP+**	**10G-10 km-O-G-1-2-SFP+**	**10G-15 km-O-G-1-2-SFP+**	**10G-40 km-C-G-1-2-SFP+**	**25G-2 km-O-G-1-2-SFP28**	**25G-10 km-O-G-1-2-SFP28**	**25G-15 km-O-G-1-2-SFP28**	**25G-40 km-O-G-1-2-SFP28**	**50G-2 km-O-G-1-2-SFP56**	**50G-10 km-O-G-1-2-SFP56**	**50G-15 km-O-G-1-2-SFP56**	**100G-2 km-O-G-1-2-QSFP28 ***	**100G-10km-O-G-1-2-QSFP28 ***	**100G-15km-O-G-1-2-QSFP28 ***	**100G-40km-O-G-1-2-QSFP28 ***
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
7.2.1	o				o				o						
7.2.2		o				o				o					
8.3.1			o				o				o				
8.3.7					o							o			
8.3.8							o							o	
9.2.1	o				o							o			
9.2.2		o				o							o		
9.2.3				o				o							o
9.2.5	o				o							o			
9.2.6		o				o							o		
9.2.7				o				o							o

Table 26: Summary of dual fiber client (only one pluggable pair using each fiber) pluggables needed for each Blueprint. (The 100G dual fiber pluggables may also be 4x25G, e.g., 100G-40km-O-L-4-2-QSFP28)*

Pluggables vs Blueprints	10G-10 km-O-B2-2-1-SFP+	10G-15 km-O-B2-2-1-SFP+	10G-40 km-O-B2-2-1-SFP+	25G-10 km-O-B2-2-1-SFP28	25G-15 km-O-B2-2-1-SFP28	25G-40 km-O-B2-2-1-SFP28	50G-10 km-O-B2-2-1-SFP56	50G-15 km-O-B2-2-1-SFP56	100G-10 km-O-B2-2-1-QSFP28	100G-15 km-O-B2-2-1-QSFP28	100G-40 km-O-B2-2-1-QSFP28
	yz	yz	yz	yz	yz	yz	yz	yz	yz	yz	yz
7.2.2	o			o			o				
8.3.1		o			o			o			
8.3.6											
8.3.7					o					o	
9.2.2	o			o					o		
9.2.3			o			o					o
9.2.4											
9.2.6	o			o					o		
9.2.7			o			o					o

Table 27: Summary of bidi client (only one pluggable pair using each fiber) pluggables needed for each Blueprint. (The 100G dual fiber pluggables may also be 4x25G, e.g., 100G-40km-O-L-4-2-QSFP28).*

Pluggables vs. Blueprints	10G-10 km-*-C-6-2-SFP+	25G-10 km-*-C-6-2-SFP28	10G-15km-O-L-12.2-SFP+	25G-15km-O-L-12-2-SFP28	10G-15 km-C-D-48-2-SFP+	25G-15 km-C-D-48-2-SFP28
	x	x	x	x	x	x
8.3.2	o	o				
8.3.3			o	o		
8.3.4					o	o
8.3.5					o	o
8.3.6					o	o
9.2.4					o	o
9.2.8					o	o

Table 28: Summary of line (multiple pluggable pairs sharing each fiber using WDM) pluggables needed for each Blueprint.

Pluggables vs. Blueprints	GPON-20 km-OS-B3-1-SFP - OLT	GPON-20 km-OS-B3-1-SFP-ONU	GPON-20 km-OS-B3-1-SFP-iONU	XGSPON-20 km-OL-B3-1-SFP+-OLT	XGSPON-20 km-OL-B3-1-SFP+-ONU	XGSPON-20 km-OL-B3-1-SFP+-iONU	25GSPON-20 km-O-B3-1-SFP28-OLT	25GSPON-20 km-O-B3-1-SFP28-ONU	25GSPON-20 km-O-B3-1-SFP28-iONU
	y	z	z	y	z	z	y	z	z
9.2.9	o	o		o	o		o	o	
9.2.10	o		o	o		o	o		o

Table 29: Summary of TDM-PON pluggables needed for each Blueprint.

11. 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. Driven by the acceleration of 5G deployments and consumer adoption, MOPA proposes a common view and understanding of the optical solutions needed for 5G transport (fronthaul and backhaul). The aim is to solve the current challenges faced by operators, system vendors and optical pluggable suppliers—specifically ambiguity and complexity—and enable them to choose the right technology and focus on the most relevant needs of the industry. MOPA benefits the entire ecosystem by ensuring timely, cost-efficient, and optimized architectures.

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Appendix A: Referenced Physical Layer Standards Exceptions for MOPA Blueprints

Existing standards and implementation agreements produced by Standards Development Organizations (SDOs), Industry Fora and multi-source agreements (MSAs), where the Blueprints cover the different technical aspects, can help form a broad description of optical solutions useful and important for mobile transport networks. MOPA is working actively to contribute to SDOs such as ITU-T and IEEE to provide requirements and perspective from mobile optics and in general to align the industry. Related to such requirements are form factors for next generation speed upgrades: In Sections 6 and 7 and the blueprints dealing with direct parallel fiber LLS links, 100 Gb/s is not yet included for p2p links and for blueprints dealing with packet multiplexing, so far only QSFP28 form factor has been listed. However, due to tight requirements on footprint and power consumption (due to stringent thermal requirements) the serial SFP format is favored for radio units. Thus, SFP112 form factor has been added to the LLS p2p blueprints in the next paper revisions.

The tables in this Appendix show the various MOPA Blueprints described in Chapters 6, 7 and 8 along with an industry specification(s) that is closely aligned *or nearly aligned (with exceptions)*. The table rows below “Parameters” list parameters where there are significant differences and where the MOPA Blueprint requirements are not fulfilled. In the case where there are such parameter exceptions, the intent is that they are relatively minor and will allow optics suppliers to leverage existing high-volume transceiver solutions. These tables are informative guidelines.

2 km, 10/25/50G, dual-fiber	**10 Gb/s**		**25 Gb/s**		**50 Gb/s**	
	10G-2km-O-G-1-2-SFP+		**25G-2km-O-G-1-2-SFP28**		**50G-2km-O-G-1-2-SFP56**	
Parameter	*IEEE 802.3 Cl. 52 (10GBASE-L)**	*MOPA Blueprint*	*IEEE 802.3 Cl. 114 (25GBASE-LR)**	*MOPA Blueprint*	*IEEE802.3 Cl. 139 (50GBASE-LR)**	*MOPA Blueprint*
		No exceptions		*No exceptions*		*No exceptions*

*Table APA.1: 2 km, dual-fiber, Blueprints. Insertion loss (IL) budget = 2.8 dB in O-band. *The insertion loss budgets for these IEEE specifications (IL = 6.3 dB, for up to 10 km) may be viewed as overengineered and not be cost optimized for the corresponding MOPA Blueprint.*

2 km, 100G, dual-fiber	**100 Gb/s (Dual-Fiber)**	
	100G-2km-O-G-1-2-QSFP28 or 100G-2km-O-C/L-4-2-QSFP28	
Parameter	*IEEE 802.3 Cl. 140 (100GBASE-FR1) or 100G CWDM4 MSA*	*MOPA Blueprint*
		No exceptions

Table APA.2: 2 km, 100 Gb/s, dual-fiber IL budget = 2.8 dB in O-band.

10 km, 10/25/50G, dual-fiber	**10 Gb/s**		**25 Gb/s**		**50 Gb/s**	
	10G-10 km-O-G-1-2-SFP+		**25G-10km-O-G-1-2-SFP28**		**50G-10km-O-G-1-2-SFP56**	
Parameter	*IEEE 802.3 Cl. 52 (10GBASE-LR)*	*MOPA Blueprint*	*IEEE 802.3 Cl. 114 (25GBASE-LR)*	*MOPA Blueprint*	*IEEE802.3 Cl. 139 (50GBASE-LR)*	*MOPA Blueprint*
Wavelength	1260–1355 nm	1260–1355 nm	1295–1325 nm	1295–1325 nm	1304.5 - 1317.5 nm	1304.5–1317.5 nm
Launch power (min) in OMA minus TDP	-6.2 dBm	-5.4 dBm	-5.0 dBm	-4.3 dBm	-2.9 dBm	-2.2 dBm
Optical Modulation Amplitude (min)	-5.2 dBm	-4.4 dBm	-4.0 dBm	-3.3 dBm	-1.5 dBm	-0.8 dBm

Table APA.3: 10 km, dual-fiber, Blueprint. IL budget = 7 dB in O-band. Since the MOPA IL budget is higher than the one used by IEEE, the MOPA blueprint would use the IEEE specification with a slightly increased launch power and optical modulation amplitude. Also, the wavelength range is tightened compared to the full O-band.

10 km, 10/25/50G, BiDi	**10 Gb/s**		**25 Gb/s**		**50 Gb/s**	
	10G-10km-O-B2-2-1-SFP+		**25G-10km-O-B2-2-1-SFP28**		**50G-10km-O-B2-2-1-SFP56**	
Parameter	*IEEE 802.3 Cl. 158 (10GBASE-BR10)*	*MOPA Blueprint*	*IEEE 802.3 Cl. 159 (25GBASE-BR10)*	*MOPA Blueprint*	*IEEE 802.3 Cl. 160 (50GBASE-BR10)*	*MOPA Blueprint*
Wavelength	1270/1330 nm (±10 nm)	1270/1330 nm (±10 nm)	1270/1330 nm (±10 nm)	1270/1330 nm (±10 nm)	1270/1330 nm (±10 nm)	1270/1330 nm (±10 nm)
Launch power (min) in OMA minus TDP	-6.2 dBm	-5.4 dBm	-5.0 dBm	-4.3 dBm	-2.9 dBm	-2.2 dBm
Optical Modulation Amplitude (min)	-5.2 dBm	-4.4 dBm	-4.0 dBm	-3.3 dBm	-1.5 dBm	-0.8 dBm

Table APA.4: 10 km, BiDi, Blueprint. IL budget = 7 dB in O-band. Since the MOPA IL budget is higher than the one used by IEEE, the MOPA blueprint would use the IEEE specification with a slightly increased launch power and optical modulation amplitude.

10 km, 10/25/50G, BiDi	**10 Gb/s**		**25 Gb/s**		**50 Gb/s**	
	10G-10km-O-B2-2-1-SFP+		**25G-10km-O-B2-2-1-SFP28**		**50G-10km-O-B2-2-1-SFP56**	
Parameter	ITU-T G.9806 Amend. 2* (Tables 7-1, 7-2)	*MOPA Blueprint*	ITU-T G.9806 Amend. 2* (Tables 7-1, 7-2)	*MOPA Blueprint*	ITU-T G.9806 Amend. 2* (Tables 7-1, 7-2)	*MOPA Blueprint*
Wavelength	1270/1330nm (±10nm)	1270/1330nm (±10nm)	1289/1314nm (±8nm)	*Recommend IEEE wavelength range*	1289/1314nm (±8nm)	*Recommend IEEE wavelength range*
		No other exceptions		*No other exceptions*		*No other exceptions*

*Table APA.5: Alternative referenced standards for 10 km, BiDi, Blueprint. IL budget = 7 dB in O-band. *The link budgets for these ITU specifications (S class, IL = 15 dB) may be viewed as overengineered and not be cost optimized for the corresponding MOPA Blueprint.*

10 km, 100G, Dual-fiber, BiDi	**100 Gb/s (Dual-Fiber)**		**100 Gb/s (BiDi)**	
	100G-10km-O-C/L-4-2-QSFP28 or 100G-10km-O-G-1-2-QSFP28		**100G-10km-O-B2-2-1-QSFP28**	
Parameter	IEEE 802.3 Clause 88 (100GBASE-LR4) or Clause 140 (100GBASE-LR1)	*MOPA Blueprint*	*IEEE 802.3dk or ITU-T G.9806 (Amend. 3)*	*MOPA Blueprint*
Wavelength	1294.53 to 1310.19 nm (LAN WDM) or 1304.5 to 1317.5 nm	1294.53 to 1310.19 nm (LAN WDM) or 1304.5 to 1317.5 nm	-	TBD
Launch power (min) in OMA minus TDECQ	-2.3 dBm or -1.5 dBm	-1.6 dBm or -0.8 dBm	-	TBD
Optical Modulation Amplitude (min)	-1.3 dBm or -0.1 dBm	-0.6 dBm or +0.6 dBm	-	TBD

Table APA.6: 10 km, 100 Gb/s, dual-fiber and BiDi Blueprints. IL budget = 7.0 dB in O-band. For dual-fiber: Since the MOPA IL budget is higher than the one used by IEEE, the MOPA blueprint would use the IEEE specification with a slightly increased launch power and optical modulation amplitude.

15 km, 10/25/50G, Dual-fiber	10 Gb/s		25 Gb/s		50 Gb/s	
	10G-15km-O-G-1-2-SFP+		**25G-15km-O-G-1-2-SFP28**		**50G-15km-O-G-1-2-SFP56**	
Parameter	_IEEE 802.3 Cl. 158 (10GBASE-BR20)*_	_MOPA Blueprint_	_IEEE 802.3 Cl. 159 (25GBASE-BR20)*_	_MOPA Blueprint_	_IEEE 802.3 Cl. 160 (50GBASE-BR20)*_	_MOPA Blueprint_
Wavelength	1270/1330nm (±10nm)	1260 – 1340nm	1289/1314nm (±8nm)	1281-1322nm	1289/1314nm (±8nm)	1281-1322nm

Table APA.7: 15 km, dual-fiber, Blueprint. IL budget = 9 dB in O-band. *The BR20 specification (IL budget = 15 dB) is used as a starting point, but the higher loss budget may be viewed as overengineered and therefore not cost-optimized when applied to this MOPA blueprint. However, here the system would not use the diplexer.

15 km, 10/25/50G BiDi	10 Gb/s		25 Gb/s		50 Gb/s	
	10G-15km-O-B2-2-1-SFP+		**25G-15km-O-B2-2-1-SFP28**		**50G-15km-O-B2-2-1-SFP56**	
Parameter	_IEEE 802.3 Cl. 158 (10GBASE-BR20)*_	_MOPA Blueprint_	_IEEE 802.3 Cl. 159 (25GBASE-BR20)*_	_MOPA Blueprint_	_IEEE 802.3 Cl. 160 (50GBASE-BR20)*_	_MOPA Blueprint_
Wavelength		_No exceptions_	1289/1314nm (±8nm)	1289/1314nm (±8nm)	1289/1314nm (±8nm)	1289/1314nm (±8nm)

Table APA.8: 15 km, BiDi, Blueprint. IL budget = 9 dB in O-band. *The BR20 link budget = 15 dB may be viewed as overengineered and not be cost optimized for the corresponding MOPA Blueprint.

15 km, 100G Dual-fiber, BiDi	100 Gb/s (Dual-Fiber)		100 Gb/s (BiDi)	
	100G-15km-O-C/L-4-2-QSFP28 or 100G-15km-O-G-1-2-QSFP28		**100G-15km-O-B2-2-1-QSFP28**	
Parameter	_100G 4WDM-20† or 100G Lambda MSA (100G-LR1-20)††_	_MOPA Blueprint_	_IEEE 802.3dk or ITU-T G.9806 (Amend. 3)_	_MOPA Blueprint_
		No exceptions		TBD

Table APA.9: 15 km, 100 Gb/s, dual-fiber and BiDi Blueprints. IL budget = 9 dB in O-band. †The link budget for this specification (IL = 10.2 dB) may not be cost optimized for the corresponding MOPA Blueprint. ††The link budget for this specification (IL = 9.8 dB) may not be cost optimized for the corresponding MOPA Blueprint.

15 km, 10/25G CWDM	10 Gb/s		25 Gb/s	
	10G-10km-*-C-6-2-SFP+			
Parameter	*ITU-T G.695 (07/2018)*	*MOPA Blueprint*	*ITU-T G.698.5, Application codes D12-8-10B-9-D1 (10 km, IL = 10.7 dB) and D12-8-20B-9-D1 (20 km, IL = 15.9 dB) †*	*MOPA Blueprint*
		Use Table 8-15 as starting point for a 6-wavelength interface		*Use these ITU-T application codes as starting points.*

Table APA.10: 10 km, CWDM Blueprint. IL loss budget = 11.5 dB. †In progress

15 km, 10/25G DWDM	10 Gb/s		25 Gb/s	
	10G-15km-C-D-48-2-SFP+		25G-15km-C-D-48-2-SFP28	
Parameter	*ITU-T G.698.1 (11/2009) Table 8-3*	*MOPA Blueprint*	*ITU-T G.698.1 (06/2023) Table 8-6*	*MOPA Blueprint*
		*No exceptions**		No exceptions**

*Table APA.11: 15 km, DWDM Blueprint. IL budget = 17.8 dB in C-band. *ITU-T specification supports 1000 ps/nm of chromatic dispersion which is more than the 270 ps/nm assumed for 15 km of standard G.652 SMF. **The referenced ITU-T specification applies to a chromatic dispersion tolerance of 200ps/nm which corresponds to 10km of standard G.652 SMF.*

40 km, 10/25/100G Dual-fiber	**10 Gb/s**		**25 Gb/s**		**100 Gb/s**	
	10G-40 km-C-G-1-2-SFP+		**25G-40 km-O-G-1-2-SFP28**		**100G-40 km-O-L-4-2-QSFP28 or 100G-40 km-O-G-1-2-QSFP28**	
Parameter	*IEEE 802.3 Cl 52 (10GBASE-ER)*	*MOPA Blueprint*	*IEEE 802.3 Cl 114 (25GBASE-ER)*	*MOPA Blueprint*	*IEEE 802.3 Cl. 88 (100GBASE-ER4)* *Or* *100G Lambda MSA (100G-ER1-40)*	*MOPA Blueprint*
Wavelength	1530 to 1565 nm	-	1295 to 1310 nm	-	1294.53 to 1310.19 nm or 1308.09-1310.19 nm	-
Launch power (min) in OMA minus TDP	-2.1 dBm	+1.0 dBm*	-1.0 dBm	+1.0 dBm*	+0.1 dBm or +3.3 dBm	+2.1 dBm* Or +5.3 dBm*
Optical Modulation Amplitude (min)	-1.7 dBm	+1.4 dBm*	0.0 dBm	+2.0 dBm*	NA or +4.7 dBm	NA or +6.7 dBm*

*Table APA.12: 40 km, dual-fiber, Blueprint. IL budget = 20 dB in O-band or 15 dB in C-band. Since the MOPA IL budget is higher than the one used by IEEE, the MOPA blueprint would use the IEEE specification with an increased launch power and optical modulation amplitude. *Such high optical modulation amplitude may not be achievable with available cost-effective technology.*

40 km, 10/25/100G BiDi	**10 Gb/s**		**25 Gb/s**		**100 Gb/s**	
	10G-40 km-O-B2-2-1-SFP+		**25G-40 km-O-B2-2-1-SFP28**		**100G-40 km-O-B2-2-1-QSFP28**	
Parameter	*IEEE 802.3 Cl. 158 (10GBASE-BR40)*	*MOPA Blueprint*	*IEEE 802.3 Cl. 159 (25GBASE-BR40)*	*MOPA Blueprint*	*IEEE 802.3dk* *or* *ITU-T G.9806 (Amend. 3)*	*MOPA Blueprint*
Wavelength		*No exceptions*	1314/1289nm	1314/1289nm		*TBD*
Launch power (min) in OMA minus TDP	-1.0 dBm	+1.0 dBm*	-1.0 dBm	+1.0dBm*		*TBD*
Optical Modulation Amplitude (min)	0.0 dBm	+2.0 dBm*	0.0 dBm	+2.0 dBm*		*TBD*

*Table APA.13: 40 km, BiDi, Blueprint. Insertion loss budget = 20dB in O-band. Since the MOPA IL budget is higher than the one used by IEEE, the MOPA blueprint would use the IEEE specification with an increased launch power and optical modulation amplitude. *Such high optical modulation amplitude may not be achievable with available cost-effective technology.*

TDM-PON	**2.5/1.25 Gb/s**		**10/10 Gb/s**		**25 / 10 Gb/s or 25 Gb/s**	
	GPON-20 km-OS-B3-1-SFP-OLT GPON-20 km-OS-B3-1-SFP-ONU		**XGS-PON-20 km-OL-B3-1-SFP+-OLT XGS-PON-20 km-OL-B3-1-SFP+-ONU**		**25GS-PON-20 km-O-B3-1-SFP28-OLT 25GS-PON-20 km-O-B3-1-SFP28-ONU**	
Parameter	*ITU-T G.984.2*	*MOPA Blueprint*	*IEEE 802.3 Clause 75 (10GBASE–PR–D/U3) or ITU-T G.9807.1(Amend 2) (Annex B)*	*MOPA Blueprint*	*IEEE 802.3 Clause 141 (25/10-PQ30X) (25/25-PQ30X) or 25GS-PON MSA V2.0*	*MOPA Blueprint*
IL Budget	28dB	*No exceptions*	33 dB or up to 35 dB	*No exceptions*	29 dB or 31 dB	*No exceptions*

Table APA.14: 20 km TDM-PON Blueprint. Multiple insertion loss classes from 28 dB to 35dB depending on configuration and data-rate.