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Co-packaged optics opportunities in radio-access networks

Charting the future of innovation

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Co-packaged optics is an emerging technology with the potential to play a key role in 6G radio-access networks, due to its ability to enable high capacity at low energy consumption. Creating a version of the technology that is suitable for radio applications will, however, require some dedicated development to address network characteristics.

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It is becoming increasingly difficult for communication service providers to use traditional copper interconnects to achieve sufficient bandwidth and distance in 5G radio-access networks (RANs) in an energy-efficient manner. The massive traffic growth expected with the introduction of 6G – estimated to be as much as 360 exabytes per month by 2027 [1] – will create an even greater need for high interconnect bandwidth with minimal energy consumption in 6G RANs.

The ability to enable high capacity with low energy consumption in RANs requires radical innovation in areas including integrated circuits (IC) architecture, digital signal processing, optical communications and packaging. Originally developed for use in data centers, co-packaged optics (CPO) technology makes it possible to improve both capacity and energy efficiency by integrating optics and silicon into a single packaged component. Widely recognized as a key enabler of future-proof cloud infrastructure, CPO also has great potential for use in 6G RANs. Much of the work around CPO that has been done for data centers can be reused, but some key aspects of the RAN require dedicated developments, including site cabling and the ability to operate outdoors in extreme temperatures.

Optics definitions and standards

Figure 1 provides a comparison between CPO and three other approaches to optical integration: on-board optics (OBO), near-packaged optics (NPO) and small form-factor pluggable (SFP) optics.

In CPO, at the top, an optical transceiver (TRX) is integrated into the same package as the IC. In this arrangement, the integrated optical TRX – also referred to as a chiplet – is placed directly onto the IC substrate and all electrical high-speed signals occur within the package substrate. Fiber attachment must be done from the package, which places high requirements on tolerances, manufacturability and compatibility with surface-mount technology. Fiber or waveguide alignments can be done from the reverse side of the package or with a fiber attachment on top of it.

In OBO – also known as board-mounted optics – an optical TRX module is placed on the same printed circuit board (PCB) as the packaged IC. High-speed electrical signals from the IC package to the PCB and up to the optical TRX package are transmitted by solder balls.

In NPO, the same type of optical TRX module used in OBO is placed on an extra interposer or substrate together with the packaged IC. The two components can be tested and

Terms and abbreviations

AOC – Active Optical Cable | **ASIC** – Application-Specific Integrated Circuit | **BER** – Bit Error Rate | **BGA** – Ball Grid Array | **CPO** – Co-Packaged Optics | **CRAN** – Centralized Radio-Access Network | **DAC** – Direct Attach Copper | **DRAN** – Distributed Radio-Access Network | **DU** – Distributed Unit | **ELS** – External Laser Source | **ELSFP** – External Laser Small Form-Factor Pluggable | **FEC** – Forward Error Correction | **I-Temp** – Industrial Temperature Range | **IA** – Implementation Agreement | **IC** – Integrated Circuits | **MCM** – Multi-Chip Module | **ns** – nanosecond | **NPO** – Near-Packaged Optics | **OBO** – On-Board Optics | **OIF** – Optical Internetworking Forum | **PCB** – Printed Circuit Board | **PMF** – Polarization Maintaining Fiber | **pJ** – picojoule | **RAN** – Radio-Access Network | **RRU** – Remote Radio Unit | **SFP** – Small Form-factor Pluggable | **TRX** – Transceiver | **XSR** – Extra-Short Reach

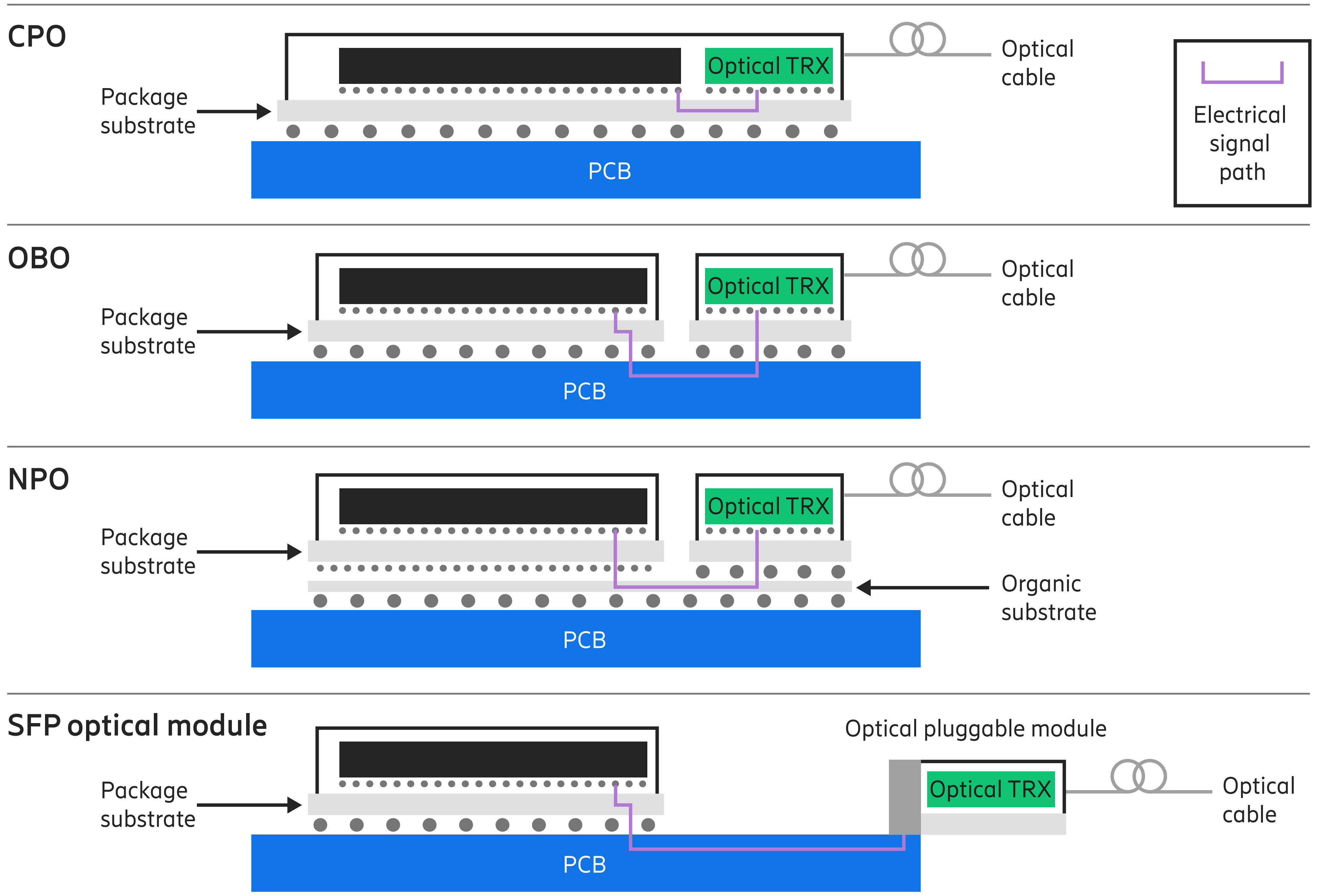

Figure 1: Four approaches to integrating optics

packaged separately. High-speed electrical signals are transmitted from the IC package to the common substrate using solder balls. As in CPO, fiber attachment must be done from the package.

SFP, which is also known as pluggable optics, refers to in-field optical TRX modules that can be plugged into a cage on the edge of the PCB, which is used to transmit high-speed electrical signals. Because SFPs can be easily added and removed, they make it easy to flexibly scale the capacity of the equipment and replace failed units. The downside of using SFPs is that they have a larger footprint than the other options in Figure 1, as well as consuming more power.

Of all the available options, CPO is the most beneficial in terms of minimizing both footprint and power consumption. It should be noted, however, that many of the considerations described in this article for CPO also apply to NPO and OBO – particularly those that pertain to the electrical interface and the external laser sources.

The optics requirements of RANs

The Optical Internetworking Forum (OIF) is developing Implementation Agreements (IAs) for the definition of the application space and the specifications of multi-vendor interoperable CPO modules [2]. The 3.2T Co-Packaged Optical Module IA defines interoperability requirements for a 3.2 terabit/s CPO module utilizing 100G electrical lanes. Both internal and external laser source (ELS) configurations are supported. The module is compatible with the IEEE (Institute of Electrical and Electronics Engineers) 802.3 Ethernet standards 400GBASE-DR4 and 400GBASE-FR4 to enable interoperation with pluggable optical modules, thus facilitating a broader market. The External Laser Small Form-Factor Pluggable (ELSFP) IA defines an ELS form factor for CPO modules. The ELSFP is a front panel pluggable module with a "blind mate" optical connector located at the rear of the module for eye-safety requirements.

> A key RAN requirement is for the optical TRXs to have long life spans that cover the full duration of the network service.

Although most of the specifications developed by the OIF for CPO in data centers also apply to RAN, there are some additional requirements to address. The table in **Figure 2** compares the high-level optics requirements for data centers, distributed RAN (DRAN) fronthaul, centralized RAN (CRAN) fronthaul and backhaul [3].

A key RAN requirement is for the optical TRXs to have long life spans that cover the full duration of the network service (typically 15 years) to avoid costly visits to remote sites and tower climbs to do repairs. This requirement is especially important for CPO, as there is no option to perform the kind of field replacements that are possible with SFP optical TRXs.

Another important RAN requirement is the ability for the optical TRXs to tolerate the broad range of environmental conditions at outdoor antenna locations. When antennas are located outdoors on high towers, using heavy heat sinks or other advanced heat dissipation mechanisms such as liquid cooling is problematic. These locations require low-power optical devices, including lasers at the transmitter that can operate at high temperatures that may reach close to 100°C in the most extreme conditions.

Co-packaged optics use cases in RANs

Figure 3 presents the three main use cases for CPO in the RAN: site connectivity, intra-site connectivity and on-board connectivity.

Use case #1: site connectivity

The site-connectivity use case covers the domain of today's pluggable optics – that is, optical cabling at radio sites. A link distance of 500m fits most DRAN scenarios, with the distributed unit (DU) placed in an enclosure close to the tower. In a CRAN, this use case applies to the site cabling between the remote radio units (RRUs) and the antenna site switch. The longer distances (15-20km) to the central office where the DUs are located will still be covered by pluggable optics hosted in the antenna site switch. As the CPO in the RRUs may have to interoperate with pluggable optics used in the switch, compliance with the applicable Ethernet optical standard is mandatory.

	Data center (intra-office)	Fronthaul (DRAN)	Fronthaul (CRAN)	Backhaul
Fiber distance	≤ 2km	≤ 2km (98% ≤ 500m)	≤ 15km (20km in extreme cases)	≤ 40km (80km in extreme cases)
Fiber supply	Abundant	Abundant	Scarce	Scarce
Data rates	100G, 400G	25G, 50G,100G+	25G, 50G, 100G+	25G, 100G
Sync	Not critical	Very critical	Very critical	Critical
Lifetime	3-5 years	15 years	15 years	10-15 years
Environment	Indoor, temperature controlled (commercial temperature range)	Outdoor, industrial temperature range (I-temp)	Outdoor, I-temp	Outdoor, I-temp
Service cost	Low	Very high	Very high	High
Deployment model	Greenfield	Brownfield	Brownfield	Brownfield

Figure 2: High-level optics requirements for data centers versus RANs

The targeted energy consumption of 10pJ/bit in Figure 3 is half that of the current best-of-breed generation of pluggable optics. It is quite challenging to achieve this with a retimed electrical interface, but it may be possible with a linear electrical interface. Depending on the loss budget and the equalizers in the application-specific integrated circuit (ASIC), the CPO attachment on the substrate will use a socket connector or ball grid array (BGA) soldering.

There is an ongoing debate in the CPO developer community about external versus internal laser sources. From the RAN perspective, ELS solutions are much better positioned, as the main driver we see for CPO adoption in radio units is removing optics from designs with critical thermal issues. Radio units are trending toward smaller sizes at feature parity, and the power consumption of several components is not reducing at the same pace as the unit volume. The power consumption of pluggable optics is actually increasing with the bit rate, due to the re-timers required to drive the long chip-to-module electrical channels. By making it possible to disaggregate the laser and ensure its reliability by putting it in a location with a milder environment, CPO modules can survive at junction temperatures similar to those of digital ASICs (105°C-110°C).

Use case #2: intra-site connectivity
The intra-site connectivity use case covers the domain of today's Direct Attach Copper (DAC) and Active Optical Cables (AOCs). DAC and AOCs are used for optical cabling between the units in a telecom rack or inside its radio outdoor equivalent (the rail mounting systems) where new 100G or 200G per-lane DAC generations cannot support the targeted distance of 3m shown in Figure 3. For this use case, compliance with the Ethernet optical standards is not strictly necessary, which opens up opportunities to further optimize energy consumption using novel technology approaches. The focus on energy efficiency in this case also requires the use of "linear" electrical interfaces between the ASIC and the CPO module.

Use case #3: on-board connectivity
The on-board connectivity use case covers the domain of today's high-speed copper interconnects such as PCB tracks and flyover cables. As the signaling speed goes up, it is becoming increasingly expensive to enforce signal integrity for high-speed copper interconnects, both in terms of high-frequency PCB materials and energy spent in the ASICs to compensate for impairments. The targeted distance of 2m in Figure 3 originates from the needs of massive MIMO (multiple-input, multiple-output) radio units with integrated antennas that can be large, particularly those in the sub-6GHz range. The nature of the interconnect is proprietary, and all the metrics need to be more like today's copper links than today's pluggable optics.

Implications of co-packaged optics on RAN site deployment

To minimize the potential disruptive impact of CPO introduction in the site-building process, some additional RAN-specific requirements must be addressed at macro mobile sites and street sites.

Using co-packaged optics at macro mobile sites
A macro site can be schematized as an antenna tower with radio units mounted on it and a ground-level cabinet to host traffic units plus all the necessary site-support functions including battery packs, power converters and site controllers. The cabinet can generally be regarded as an indoor environment. The traffic units inside the cabinet can be DUs (in DRAN deployments) or transport nodes such as antenna site switches (in CRAN deployments). The radio units on the antenna tower must be able to survive in the harsh outdoor environment of the mast. The short reach (up to 500m) optical connectivity between the traffic node and the radio units can be served by CPO.

The question of where to place the ELS feeding the radio units is important.

While the traffic unit could use an ELSP placed on the front panel of the indoor unit with a blind mate optical connector, the question of where to place the ELS feeding the radio units is important. The presence of a cabinet makes it possible to integrate an ELS into a dedicated box, placed within the enclosure and operating indoors. This solution allows the reuse of ELSFP defined for datacom use and avoids expensive tower climbs. The typical distance between the cabinet and the radio units is less than 500m,

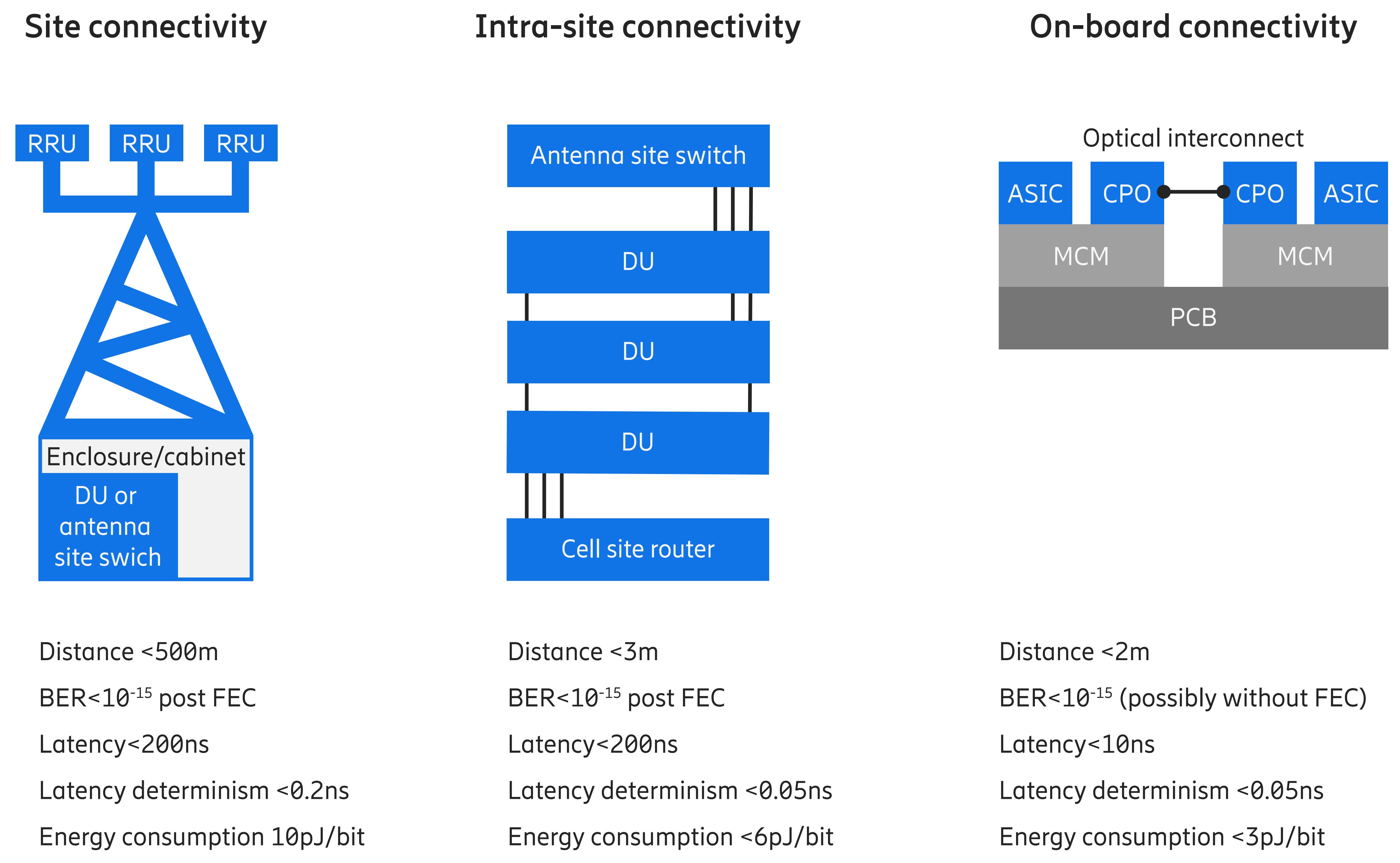

Figure 3: The three main use cases for CPO in the RAN

however, and such long strands of polarization-maintaining fiber (PMF) are expensive. Long strands of PMF also raise concerns regarding the attainable polarization extinction ratio at the modulator input. Further, the use of PMF makes it necessary to introduce new materials to current site deployment models.

The use of long strands of PMF can be avoided by placing the ELS that is feeding the radios in the enclosure of a macro site. Several approaches have been proposed for this and tested in experiments, with the "polarization-agnostic laser source" alternative [4] showing particular promise. Moving away from the blind-mate optical connector paradigm also requires careful consideration of eye-safety aspects: depending on the optical output power levels, additional circuitry may be needed in the ELSFP to detect fiber breaks and shut down the laser sources quickly enough to keep the hazard level below 1m, as defined in IEC (International Electrotechnical Commission) 60825-2. If ELSs serving the radios could be integrated directly onto the front panel of radio units with blind mate optical connectors, there would be no changes to the deployment model. However, the challenge would then shift to the ELSFP, which must operate at a high case temperature.

Using co-packaged optics at street sites

A street site is leaner than a macro site – in many cases there are no cabinets or supporting infrastructure at all. For example, a street site can be as simple as a lighting pole for which permission has been granted to mount networking equipment. The use case for CPO at a street site is when a traffic node – a DU for a DRAN or a small antenna switch for a CRAN – is deployed together with the radio units. In these cases, CPO could be used to deliver short reach optical connectivity between the traffic node and the radio units.

> ELSs improve system reliability by addressing issues of serviceability and thermal stress.

The absence of site-supporting functions removes the possibility of integrating the ELS into a dedicated box and operating in an indoor environment, but the ELS serving the radios could be integrated into dedicated ports of the traffic node with short additional PMF strands of just a few meters. Alternatively, the ELSs could be plugged into the front panel of radio units with blind mate optical connectors. It is, however, not possible to use ELSFPs designed for datacom in either case. Overcoming this challenge requires a careful redefinition of ELSFP output optical power and reliability figures in relation to the case operating temperature.

Enabling technologies

Two technologies are essential to enable CPO-based RAN deployments: ELSs that operate over standard optical fibers and energy-efficient electrical interfaces.

External laser sources

ELSs improve overall system reliability by addressing the issues of serviceability and thermal stress. This is especially beneficial in hardware-dense boards, where hot spots can easily reach temperatures higher than 100°C. ELSs make it possible to replace failed lasers an unlimited number of times. They also have a longer lifetime than internal laser sources, as they can be placed in a more favorable environment than the CPO module.

There are some restrictions on the use of ELSs, however, due to eye safety requirements that limit maximum power transmission and light polarization. In a system with a single ELS feeding eight CPO modules, for example, the output power of the laser is 21-23dBm with typical insertion loss figures on the optical transmit and receive paths, which is close to the eye safety limits defined by the IEC 60825-2 standard. Solutions can be mechanical (blind mate connectors) or software based (automatic power shutdown mechanisms). Alternatively, it is possible to consider solutions with multiple low-power sources. The example in **Figure 4** shows the case of eight ELSs: as the insertion loss is 8-11dB in this scenario, the required laser power for each ELS lowers to 11-13dBm.

The issue of the polarization arises from the strong polarization dependency of the modulators in the CPO

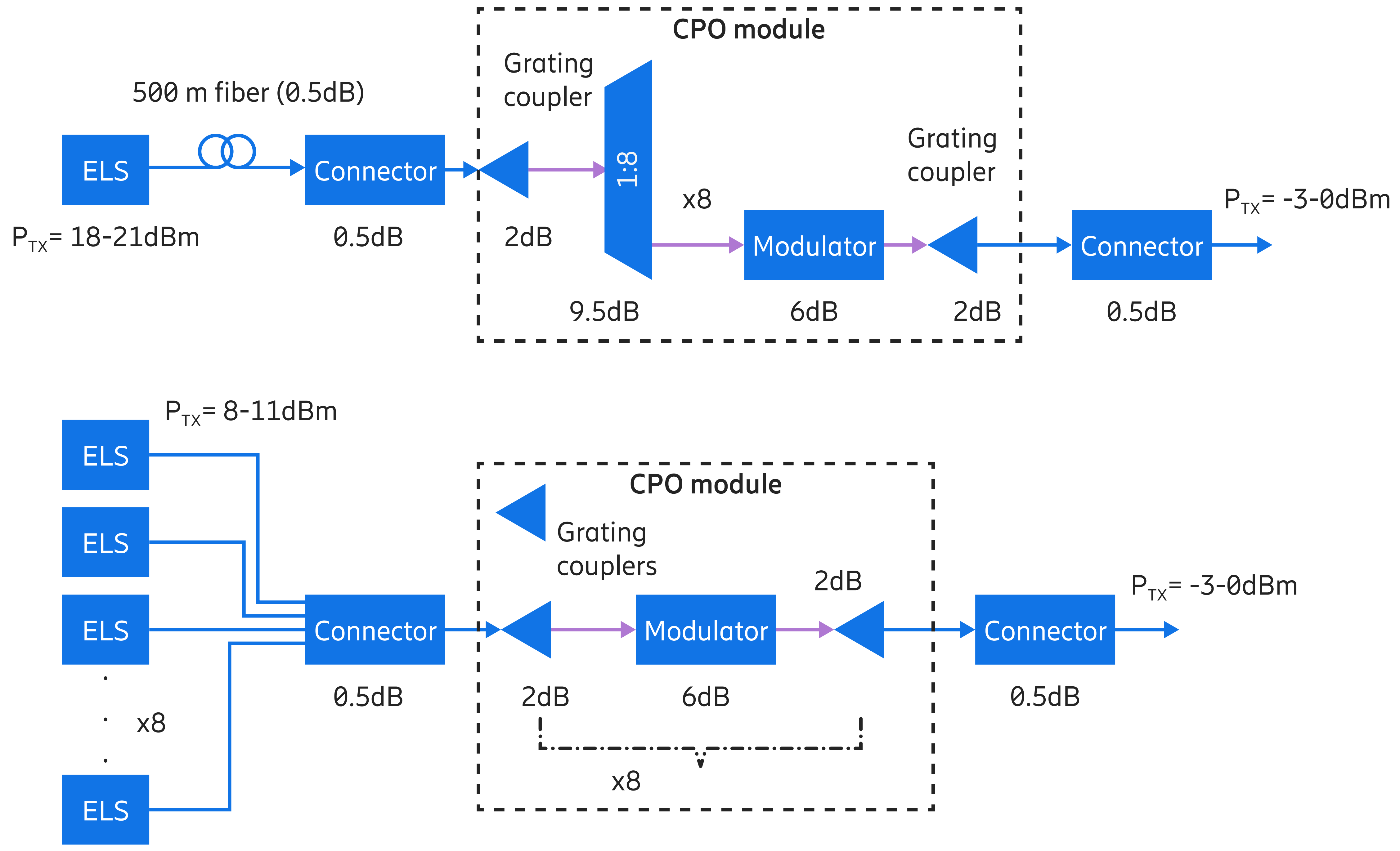

Figure 4: CPO example with eight ELSs

module. When the laser is separated from the module, the polarization may change along the fiber and lead to power fading. While current ELSs often use PMF to connect equipment located in the same site (in a lab, for example), it is less suitable for use over longer distances for cost and performance reasons.

For longer links, beyond 100m, alternative solutions such as polarization controllers and polarization-agnostic laser sources must be considered. Polarization controllers rotate the polarization based on feedback control and need an "endless algorithm" that avoids gaps in the control when the control variable reaches its practical bounds. Polarization-agnostic laser sources do not require complex feedback control; they deliver constant power output at the transmitter by assuring, on average, constant power on any polarization axis.

Experiments have demonstrated that it is possible to combine two laser sources at different wavelengths in such a way that their polarization is orthogonal and any rotation in the polarization that occurs along the fiber does not change the power available at each polarization axis [4]. More recently, novel approaches based on on-chip LEDs (light-emitting diodes) or quantum dot lasers have been proposed as thermally robust internal laser source alternatives to ELSs. However, while they do show promise, these technologies are at an early stage of development.

Energy-efficient electrical interfaces

CPO is expected to provide significant power savings compared with equivalent-capacity electrical interconnects because the placement of optical chiplets close to a digital ASIC minimizes the loss and the impedance discontinuity of the electrical interface between the two components. CPO may rely on several electrical interface standards such as those specified by the OIF or on parallel interfaces such as Advanced Interface Bus or Universal Chiplet Interconnect express. The OIF CPO IA [2] uses the CEI (Common Electrical Interface) 112G-XSR-PAM4 Extra Short-Reach (XSR) Interface, which is a digital retimed electrical interface.

Another electrical interface under consideration is a linear amplified interface, where the electrical re-timer function in the chiplet is removed to reduce the optical TRX power consumption. To avoid distorting the signal, this approach requires a linear modulator driver. However, with a linear interface, the ASIC equalizer must compensate for the propagation impairments introduced by both the electrical and the optical links, which are no longer decoupled by the re-timer. This results either in more complex equalizers, eroding the gain in energy efficiency, or in a shorter distance, keeping the same equalizer. Finding the best compromise between optical TRX power consumption and ASIC power consumption is a challenge for hardware designers.

Based on a survey we carried out among several CPO vendors, a linear interface results in power savings of about 50 percent in the CPO module and about 30 percent at system level, including the ASIC. Considering that the distance between the ASIC and the optical engine spans from about 50mm with XSR to 5mm with a direct drive interface [2], we estimate that there is enough distance to allow for disaggregation of ASIC and CPO, thereby alleviating the problem of hot spots.

Conclusion

Most of the technologies developed for co-packaged optics (CPO) in data centers have strong reuse potential in radio-access networks (RANs) because they are based on cost-effective silicon photonics, meet Ethernet standards and use external laser sources. This makes it possible to leverage on an already established ecosystem, with obvious benefits in terms of costs. However, in comparison to data centers, RANs have stricter requirements in terms of operating temperature, power consumption and site-building practices that make the use of polarization-insensitive ELSs and energy-efficient linear electrical interfaces mandatory. Moreover, most of the current CPO implementations are proprietary, creating a significant barrier to the large-scale deployment of CPO in RANs and making the definition of standardized CPO solutions for RANs an urgent need.

The authors

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References

1. Ericsson Mobility Report, June 2023
2. OIF, Co-Packaging Framework Document, February 3, 2022
3. Ericsson white paper, Optimized Optical Solutions – small form pluggable, March 2022
4. Electronics Letters, Experimental evaluation of silicon photonics transceiver operating at 120 °C for 5G antenna array systems, vol. 54, no. 24, pp. 1391–1393, Oct. 2018, Testa, F; Giorgi, L; Bigongiari, A and Bianchi, A

Further reading

- Ericsson, MOPA: Pluggable optics solutions to support 5G rollouts
- Ericsson, Photonic applications for radio systems and networks
- Ericsson blog, Photonic integration becomes a reality
- IEEE, Journal of Optical Communications and Networking, Optical transport for Industry 4.0 [Invited], vol. 12, no. 8, pp. 264-276
- International Conference on Transparent Optical Networks 2023 (Bucharest, Romania), Perspectives for Co-Packaged Optics in Radio Access Networks
- Ericsson, What is 6G?
- Ericsson, 5G RAN