Can photonics help in reducing the power consumption in Radio Access Networks?

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Abstract: we discuss the challenges of future radio access networks in meeting the growth of traffic without a parallel explosion of energy consumption. The opportunities offered by integrated photonics technologies are analyzed.

1. Introduction

Extreme weather is an evident signal of the current climate change, showing no sign of turnaround. Communications industry's contribute to carbon footprint with only 1.4% of global greenhouse gases [1] and, more important, can enable 15% reduction of emissions in other sectors [2]. Nevertheless, staying with the current design practices, the energy consumption would follow the exponential growth of the data traffic, becoming unsustainable in the long term. Most of the research on optical communication systems has the goal of improving their performance, for example increasing the bit rate or decreasing the latency, but it does not put a similar emphasis on the energy efficiency: joule/bit is not considered as important as bit/second to measure the fitness of a network. Actually, improving the energy efficiency is not only important for sustainability purposes but it is also necessary to keep the total cost of ownership low enough to ensure a return of investment. Reducing the environmental impact of next generation networks requires a holistic approach, encompassing new hardware and software design paradigms and innovations in network planning algorithms and operation practices. In this paper we will focus on recent advances of optical transceivers technology and their use in new generation sustainable radio access networks (RAN). Section 2 will introduce co-packaged optics (CPO) transceivers as a key enabling technology to meet the exponential traffic growth in future 6G RAN, avoiding a parallel increase of power consumption. The differences with CPO technology under development for datacom applications will be discussed. Section 3 will illustrate instead what changes are required to optical coherent transceivers to move from their traditional domain (long-haul and metro optical transport) to RAN, putting emphasis on energy efficiency aspects. Conclusions are drawn in Section 3.

2. Co-packaged optical transceivers for energy efficient radio access networks

CPO transceivers can provide optical interconnections with a bandwidth density of the order of Terabit/s per square millimeter. Moving to 200 Gbit/s interconnection speed, traditional copper interconnects would need power consuming digital signal processing (DSP) and signal regenerators (also referred as re-timers) even only to cover the short distance from Application Specific Integrated Circuit (ASIC)-to-ASIC in the same hardware board. CPO integrates optics and silicon on the same substrate (Figure 1) to solve this issue: compared to copper lanes, optical fibers or waveguides have negligible loss and are immune to electromagnetic interference. In addition, placing the optical chip close to the ASIC minimizes the loss and the impedance discontinuity of the electrical interface between the two devices, leading to further significant power savings. First introduced for data centers, to connect ultra-high-capacity switches and improve energy efficiency and footprint compared to front-panel pluggable optics, CPO will have an important role also in 6G RAN, to meet the demand for high capacity at low energy consumption [3]. Figure 1 compares the CPO approach with the traditional optical interconnect approach based on pluggable optical modules.

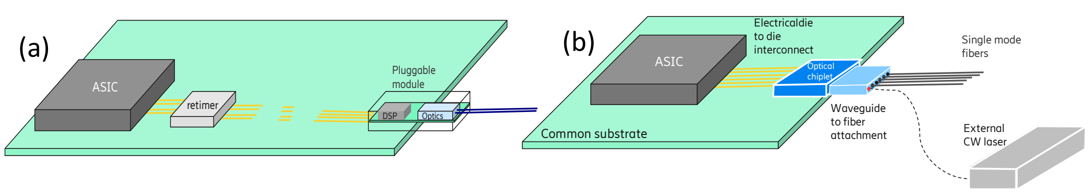

Figure 1: Comparison scheme for the interconnect based on pluggable optics (A) and CPO with disaggregated laser.

There are good reasons to keep the power consumption low in RAN. Cooling systems can take about 25% of the whole energy consumption of a radio base station [7] and have a negative impact on the equipment reliability (typical required lifetime in RAN is 10-15 years, compared to 3-5 years for data centers [3]). For example, the fan power is a cubic function of the fan speed [4]. This explains why, whenever possible, radio equipment is passively cooled. However, passive cooling requires heavy and big heatsinks, which complicate the installation practices and increase the related operational costs. Radio transmission at high frequencies (from centimetric to Sub-THz wave) is even more problematic: due to the reduced antenna unit size, power consuming devices such as digital ASICs and radio frequency front ends, interconnected by high-speed lanes (up to several Terabit/s), are all squeezed in a small area, creating high temperature hotspots. Avoiding the need for re-timers, optical interconnections are an effective, though partial, answer to this problem. Silicon photonics is well known to withstand with the high temperatures, >100°C, that may occur in hardware-dense radio boards. However, this is not the case with the laser, which needs to be disaggregated from the transmitter (Figure 1) and placed in a milder environment. This solution, referred as External Laser Source (ELS), is already used in data centers [5] but RAN pose the additional challenge of requiring the use of Single Standard Mode Fiber (SSMF) rather than Polarization Maintaining Fiber (PMF) for connecting laser and modulator [3]. One reason is multi-fiber optical connectors are cheaper with SSMF. Moreover, SSMF is more suitable for outdoor installations and the longer fiber lengths that may occur in RAN (in a typical scenario, the ELS could be co-located together with the power supply units at the feet of the antenna mast and the modulator would be at the radio unit at the top of the pole). In [3], three use cases are identified for CPO in RAN: site connectivity, intra-site connectivity and on-board connectivity, having energy consumption targets of approximately 10, 6 and 3 picojoule/bit, respectively. These challenging numbers are hard to achieve using a digital electrical interface between ASIC and CPO, like one of the Common Electrical I/O (CEI) interfaces standardized by the Optical Internetworking Forum (OIF). To further improve the energy efficiency, the OIF started the specification of an analog (also referred as linear) CEI interface at 112 Gbit/s. With a linear amplified interface, the electrical re-timer function in the CPO transceiver is removed to reduce its power consumption. This requires a linear modulator driver at the transmitter and a linear transimpedance amplifier at the receiver, not to distort the 4-levels Pulse Amplitude Modulation (PAM-4) signal, commonly used for high-speed interconnects. Based on a survey involving several CPO producers, the use of a linear interface would lead to about 50% power savings in the optical transceiver. However, since with this approach the distortions in the electrical and optical links concurrently contribute to impair the signal quality, the power saving decreases to about 30% when considering the whole system, including the ASIC. This is due to the more performing (and energy consuming) equalizers needed at the ASIC to compensate for the combined impairments. As a practical example, a long reach (LR) equalizer, like the one specified for the OIF CEI-112G-LR interface, might be needed even for extra short reach (XSR) distances, e.g., 50 millimeters, as for CEI-112G-XSR. An alternative approach that is gaining momentum avoids the use of Serializers/Deserializers (SERDES) using many low-speed parallel linear links. An example is the Universal Chiplet Interconnection express (UCIe) interface [6]. In both cases, a fully standardized solution, encompassing SERDES architecture and settings, as well as electrical and optical interfaces parameters, would be necessary to enable multi-vendor interoperable solutions. This is a current challenge that engages all relevant industries.

3. Energy efficient coherent optical transceivers for cloud RAN

Following the progress of silicon photonics and semiconductor manufacturing processes, the cost of coherent optical transceivers is expected to decrease in the next years, enabling their use in cost sensitive network segments such as mobile fronthaul, aggregation, and access. The long transmission distance made possible by the use of coherent optical transceivers leads to remarkable benefits on the energy efficiency of the whole network because it allows the centralization and virtualization of baseband processing functions in a single data center, skipping smaller intermediate sites. This is a concept commonly referred as Cloud RAN (C-RAN). But there is no free lunch: coherent optical transceivers require Digital-to-Analog Conversion (DAC) at the transmitter in addition to Analog-to-Digital Conversion (ADC) and Digital Signal Processing (DSP) at the receiver, which notoriously are power hungry functions. The power consumption of coherent optical modules decreased from 1800 to 200 pjoule/bit from 2013 to 2020 but this trend is reaching a plateau [8], calling for more radical innovations in the transceiver architecture. For example, DAC and ADC might be made more energy efficient by means of adaptive methods for the control of their resolution (the lower the signal-to-noise ratio, the higher the effective number of bits). A similar approach can be considered for the DSP. The DSP is usually designed to always run at the best performance but, when the link conditions allow, some functions could be down-scaled or even shut-down. Examples are reported in [9], concerning sub-band equalization of the chromatic dispersion, use of Soft-Decision Forward Error Correction (SD-FEC) codes with adjustable number of iterations, shortened Multi-Input Multi-Output (MIMO) equalizers for short reach application and clock gating to disable unused functional blocks. More advanced energy saving strategies might be envisaged in future by jointly controlling DSP, DAC/ADC and signal modulation and coding. Similar concepts underly the optimization of the modulation format in a multi-dimensional space [10] for which, however, the right compromise with the increased resolution (and power consumption) required to the DAC is still an open point. Looking far ahead, moving functions, such as the DAC [11], from the electrical to the optical domain may dramatically cut down the power consumption, but technology is still at an early maturity stage.

4. Conclusions

A new generation of energy-efficient optical transceivers emerged recently thanks to the latest advances in the Complementary Metal Oxide Semiconductor (CMOS) fabrication processes adopted for both digital electronic circuits and silicon photonics circuits, though with a very different integration scale. Terabit/s-per-square-millimeter capable CPO transceivers are today available for performing quasi pjoule/bit optical interconnections, which is an essential requirement in future RAN. However, this needs new standardized designs for ELS and electrical interfaces, which are still under investigation. In parallel, high speed (coherent optical transceivers up to 400 Gbit/s today, 800 Gbit/s targeted in the next years) became available in a pluggable form factor, which was simply inconceivable a couple of years ago. Despite this progress, energy efficiency remains a current challenge, no longer affordable only relying on smaller integrated circuits process nodes. Novel multi-disciplinary design approaches will be required for the joint optimization of DSP, DAC/ADC and signal modulation, asking for new competences to industry and academia.

5. References

[1] Heather Johnson, “How information tech can address challenges in climate change and education,” www.weforum.org, 12 Sep 2022.
[2] J. Malmodin and P. Bergmark. "Exploring the effect of ICT solutions on GHG emissions in 2030." EnviroInfo and ICT for Sustainability 2015. Atlantis Press, 2015.
[3] A. Tartaglia et al. "Perspectives for Co-Packaged Optics in Radio Access Networks." 2023 23rd International Conference on Transparent Optical Networks (ICTON). IEEE, 2023.
[4] M. Dayarathna, Y. Wen and R. Fan, "Data Center Energy Consumption Modeling: A Survey," in IEEE Communications Surveys & Tutorials, vol. 18, no. 1, pp. 732-794, Firstquarter 2016, doi: 10.1109/COMST.2015.2481183.
[5] OIF Implementation Agreement “External Laser Small Form Factor Pluggable (ELSFP)”, August 2023.
[6] D. Das Sharma et al.: Universal chiplet interconnect express (UCIe): An open industry standard for innovations with chiplets at package level, IEEE Trans. On Components, vol. 12, no. 9, Sep. 2022.
[7] S. N. Roy, "Energy logic: A road map to reducing energy consumption in telecom communications networks," INTELEC 2008 - 2008 IEEE 30th International Telecommunications Energy Conference, San Diego, CA, USA, 2008, pp. 1-9, doi: 10.1109/INTLEC.2008.4664025.
[8] https://www.infinera.com/blog/five-considerations-for-comparing-optical-power-consumption/tag/optical/
[9] M. Kuschnerov, T. Bex and P. Kainzmaier, "Energy efficient digital signal processing," OFC 2014, San Francisco, CA, USA, 2014, pp. 1-3, doi: 10.1364/OFC.2014.Th3E.7.
[10] E. Agrell and M. Karlsson, "Power-Efficient Modulation Formats in Coherent Transmission Systems," in Journal of Lightwave Technology, vol. 27, no. 22, pp. 5115-5126, Nov.15, 2009, doi: 10.1109/JLT.2009.2029064
[11] Y. Sobu *et al*., "Highly power-efficient (2 pJ/bit), 128Gbps 16QAM signal generation of coherent optical DAC transmitter using 28-nm CMOS driver and all-silicon segmented modulator," *2022 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2022, pp. 1-3.