High-Speed Short Reach Optical Communications: Technological Options and Challenges

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Abstract: We review the current trend in the research and development of short reach optical communications. Typical application scenarios with corresponding technological options are discussed, and an outlook on the challenges from different aspects are presented. © 2020 The Author(s)

1. Introduction

Short reach optical communications in the fiber-optics, as opposed of the long-haul communications, can be loosely defined as the optical communication links bridging two locations within a distance of ~100 km [1]. Currently, the short reach optical communications are being studied and analyzed intensively by both the academic and the industrial community. On the one hand, emerging applications and services are driving both the upgrade of existing network infrastructure and new deployment in telecom and datacom scenarios [2]. On the other hand, there is an increasing resistance in following the technological paths in upgrading the data rate while fulfilling the reach requirements, which imposes fundamental limits of devices, subsystems and systems.

In this study, we try to identify different technological options for several typical application scenarios. The state-of-the-art research and development efforts are reviewed, and their respective challenges are discussed. It is noted that we confine our discussions on the fiber-optic systems, and other short reach optical communication technologies within its broader definition, for instance the waveguided on-chip interconnects, or optical-wireless links connecting closely located devices, though very important to address, are not covered in this study.

2. Typical application scenarios for short reach optical communications

Figure 1 illustrates a few examples of the typical application scenarios where short reach optical communications are applied. Scenarios from both the telecom and datacom segments are shown, including the intra- and inter-data center (DC) connections and the access networks. Moreover, the 5G radio access network (RAN), which is a specific networking scenario in the access segments, is listed separately. In what follows we briefly discuss the characteristics and requirements for each scenario.

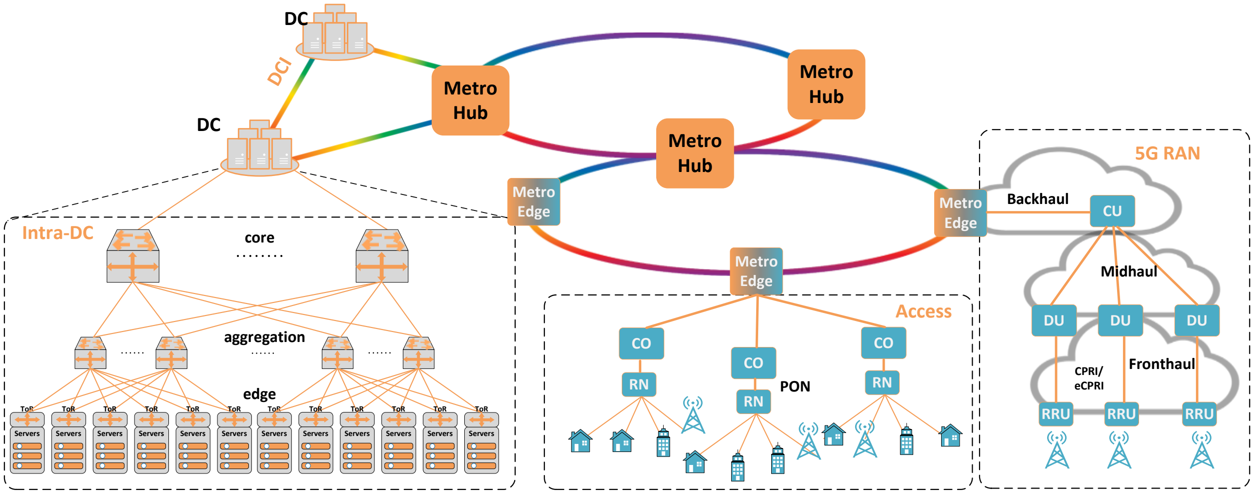

Fig. 1. Examples of application scenarios for short reach optical communications. DC: data center; DCI: data center interconnect, ToR: top-of-rack; CO: central office; RN: remote node; PON: passive optical network; RAN: radio access network; CU: central unit; DU: distributed unit; RRU: remote radio unit

2.1 Intra- and inter-data center network

The first demanding scenario is the modern data centers, where cloud storage for massive amount of data and large-scale high-performance computing (HPC) take place. Following the trend of data center networking evolution, one may expect a few potential transformations to occur gradually in the short- to mid-term inside the data centers. The first is the upgrade of data rate for interconnection towards 400G and above, which is already happening with some major data center providers. The second potential transformation is that the design of data center is moving towards a resource disaggregated pattern. In such a pattern the basic building element of the data center becomes resource blocks instead of the servers. Different resources are virtually connected with better utilization compared with the current design [3]. Last but not least, another possible transformation is the employment of active/passive optical/photonic switches to address the port density, speed and power consumption constraints when moving towards massive connectivity [4, 5]. Typical distances of the intra-DC connections are within 2 km, and traditionally the intensity modulation and direct detection (IM/DD) schemes are preferred in such a scenario.

Outside of the data centers, the interconnections between the data centers either within a campus or across the metro distance, are commonly referred to as data center interconnect (DCI). The typically DCI distances are between 10 km and 80 km. Dense wavelength division multiplexing (DWDM) links in the C-band can be used to support these connections. Currently, there is a transition to shift from the IM/DD to the digital coherent optical systems when upgrading the lane rate from 100G to 400G for the DCI links.

2.2 Access optical networks and 5G RAN

Short reach optical communications are used to support the access applications like broadband and cable services. Access optical networking infrastructure, including the passive optical networks (PON) is being deployed with the consideration of long-term upgradability and sustainability. Main standardization bodies including the IEEE and the ITU-T have been devoting efforts to the definition of beyond 10G PON standards, and the next targeted nominal line rate of up to 50 Gbps are considered [6]. Among various applications, the 5G X-haul (including fronthaul, midhaul and backhaul) supporting the radio access network (RAN) is a specific scenario where stringent system requirements, especially on the latency, should be met. The optical distribution network (ODN), which connects the optical line terminal (OLT) and the optical network units (ONUs) in the PON, is being considered to support both general applications and the 5G X-haul. Consequently, the main challenges to overcome in the access scenario include the coexistence with legacy PONs, high ODN loss budget (up to 33 dB), and low-latency transport [7].

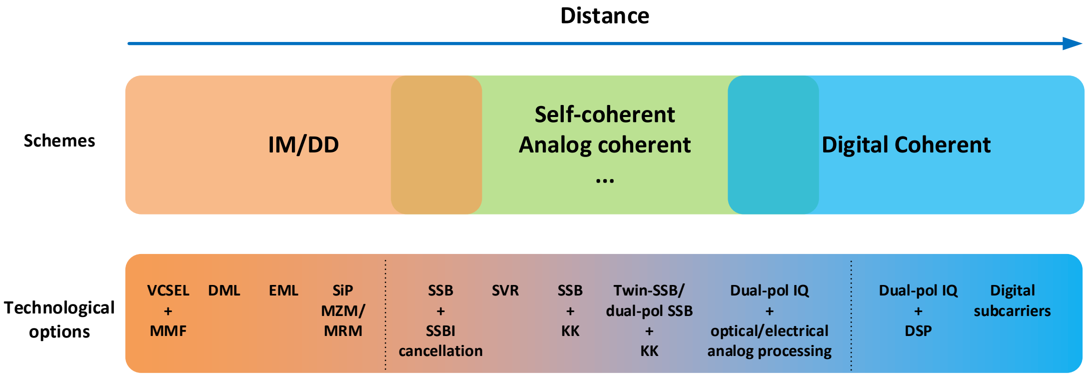

Fig. 2. A non-exhaustive summary of technological options for short reach optical communications.

3. Technological options, research and development status and challenges

Figure 2 non-exhaustively summarizes the technological options in the short reach optical communications with respect to the supporting distance. On the two sides of the spectrum are the IM/DD and the digital coherent schemes, which have been widely adopted in commercial 100G interfaces, and are being developed to continue supporting the upcoming 400G services. There are open discussions around the candidates for future upgrade to 800G and beyond.

For intra-DC applications within the distance of 2 km, the IM/DD schemes are preferred for 800G owing to its advantages in power consumption, size/footprint and cost. Though there are added complexities from the current adoption of the 4-level pulse amplitude modulation (PAM-4), digital signal processing (DSP) and forward error correction (FEC) in the 400G modules, the advancements in the electrical interfaces and the broadband optoelectronic components continue supporting higher lane rate and reducing the lane count. Lately reported achievements include high-speed digital/analog to analog/digital converters (DACs/ADCs), broadband optoelectronic components including the direct-/electro absorption-modulated lasers (DML/EML) and silicon photonics (SiP)-based modulators [8]. In the authors' opinion, it is possible to extend the current IM/DD approach to 800G for up to 10-km coverage, and even beyond 800G for the <2-km scenarios with the advanced components and DSP [9-11]. Similarly, IM/DD is expected for the 50G PON applications to stay within the latency and cost constraints. For DCI applications with distances above 40 km, the digital coherent scheme shows clear advantages. The upgrade from IM/DD-based 100G DWDM to digital coherent 400G DWDM is already ongoing [12], where the 400ZR modules are adopted [13]. The advantages of the digital coherent for applications in this range will be clearer for 800G and beyond.

The remaining segment of the spectrum, shown as the centered green block in Fig. 2, remains undetermined at the moment for 800G and beyond (100G and beyond for PON). The authors estimate that this part approximately spans between 2 km and 40 km. In this range, it is fundamentally challenging for IM/DD schemes to support the required lane rate and power budget simultaneously, whereas the digital coherent may not yet close the gap of its complexity, power consumption and cost. In this context, various technological options recently appear to fill in the gap between the IM/DD and the digital coherent, including the self-coherent and the analog coherent variants [14-17]. The main challenges for these technologies towards applications include the limited development time window, unclear market size and lack of development momentum, in the authors' opinion. Nevertheless, there can be potential scenarios where the unique advantages of these technologies are irreplaceable.

It is worth mentioning that there are many factors that may alter the picture. For example, the adoption of optical switches inside the data center and the advancement of low-complexity digital coherent transceivers may drive the digital coherent scheme into the intra-DC scenario [18]. Moreover, novel concepts from the industry, like the coherent digital subcarrier-based solution XR-Optics [19], may impact on the choices for the short reach scenarios.

4. Conclusions

The status of applications and research of short reach optical communications are summarized. The outlook on future technological evolution directions are discussed from the authors' perspective.

5. Acknowledgement

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6. References

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