Short Reach Communication Technologies for Client-Side Optics Beyond 400 Gbps

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Abstract— Short reach optical communication technologies are increasingly demanded in several fast-evolving application scenarios in both telecom and datacom. Low-cost and low-complexity intensity modulation and direct detection (IM/DD) technologies are challenged to scale up the link rate beyond 400 Gbps by increasing the single-lane rate towards 200 Gbps, to maintain a low lane count in client-side optics. Limited by the bandwidth of both electronics and optoelectronics, and the more pronounced chromatic dispersion in the fiber, such high baud rate systems require the use of digital signal processing techniques with forward error correction (FEC) coding. Therefore, in this work, we first summarize a few potential alternative technologies to the IM/DD for future development and then focus on extending the IM/DD systems towards 200 Gbps lane rate. We study both their capability and their performance limits using numerical simulations and transmission experiments.

Index Terms— Intensity modulation, optical fiber communication, optical interconnections.

I. Introduction

SHORT reach communications in the fiber-optics can be loosely defined as the optical communication links bridging two locations within ~100 km [1]. Emerging applications are driving both the upgrade of existing network infrastructure and new deployments in short reach scenarios [2]. However, increasing resistance is anticipated to upgrade the client-side optics beyond 400 Gbps due to fundamental limits in current devices and systems. Therefore, new transmission technologies and networking paradigms for short-reach communications are being proposed and intensively studied.
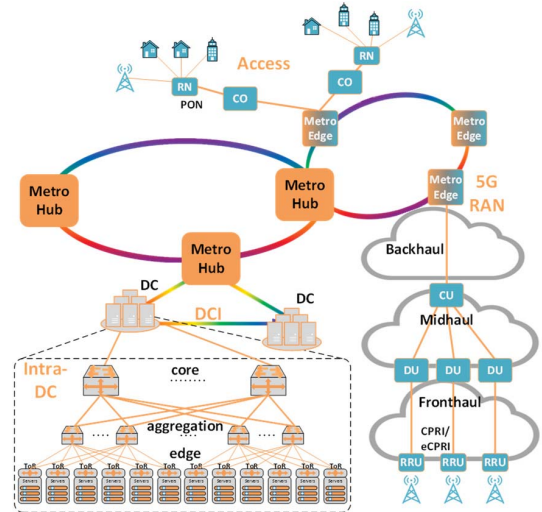
Fig. 1. Examples of application scenarios for short reach optical communications. DC: data center; DCI: data center interconnect; CO: central office; RN: remote node; PON: passive optical network; RAN: radio access network; CU: central unit; DU: distributed unit; RRU: remote radio unit.

Figure 1 shows some typical short reach communication scenarios. The first demanding scenario is for the modern data centers (DCs), where Big Data storage and large-scale high-performance computing (HPC) take place. A typical DC architecture is designed in a multi-layer data aggregation pattern, and data links inside the DCs are normally within 2-km distances. Therefore, low-cost intensity modulation and direct detection (IM/DD) schemes are preferred. Following the data center networking (DCN) evolution trend, some potential transformations inside the DCs can occur in the short- to mid-term: 1) link rate upgrade to 400 Gbps and beyond; 2) rearrangement of the DCN towards resource disaggregation for more efficient utilization, where the basic building elements become resource blocks instead of servers [3]; 3) adoption of passive/active optical/photonic switches to address the port density, speed, and power consumption issues [4]. These transformations will likely require higher link speed and/or higher loss budget. For data center interconnect (DCI) links between DCs with typical distances within ~100 km, C-band dense wavelength division multiplexing (DWDM) technologies are often used. The upgrade of the DCI lane rate from 100 Gbps to 400 Gbps is ongoing. For telecom, short-reach optical communications are used to deliver broadband and cable services to end users. As shown in Fig. 1, like in the DCN, similar data aggregation patterns are often employed in access networks. Among various applications, the 5G
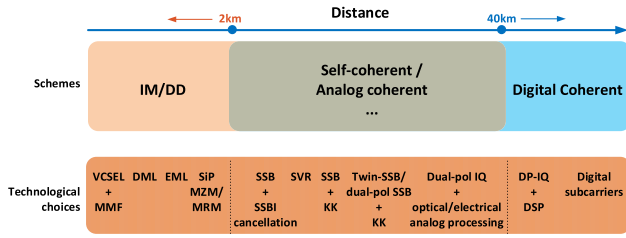
Fig. 2. A non-exhaustive summary of technological choices for 800 Gbps short reach applications. VCSEL: vertical cavity surface emitting laser; MMF: multimode fiber; MRM: micro-ring modulator; SSB: single sideband; SSBI: signal-signal beat interference; SVR: stokes vector receiver; KK: Kramers-Kronig receiver [14]–[19].

x-haul (fronthaul, midhaul and backhaul) in the radio access network (RAN) is a specific scenario where stringent system requirements should be met [5], [6].

In this letter, we extend our discussions presented in [7] and summarize technological choices for beyond 400 Gbps applications in typical scenarios. Then we focus on the IM/DD transmission technologies of 200 Gbps lane rate and evaluate the system performance in detail. System simulations are performed to study the choices of modulation formats and pulse shapes concerning system components bandwidth and fiber reach. We also show an experimental demonstration of a 200 Gbps IM/DD system with high end-to-end bandwidth and low signal processing complexity.

II. TECHNOLOGICAL CHOICES AND RESEARCH STATUS

We non-exhaustively summarize the technological choices for short-reach applications with respect to distance in Fig. 2. On the two sides, there are IM/DD and digital coherent schemes. They have been adopted for commercial 100 Gbps interfaces and developed for 400 Gbps. For 800 Gbps and beyond, there are open discussions around candidates.

For intra-DC applications within 2-km range, the IM/DD schemes are preferred for 800 Gbps owing to their advantages in power consumption, size/footprint, and cost. Despite the added complexity from the use of the 4-level pulse amplitude modulation (PAM4), digital signal processing (DSP), and forward error correction (FEC), a higher lane rate, and a lower lane count are expected with the advancements of electronics and optoelectronics. High-speed digital/analog to analog/digital converter (DAC/ADC) [8], and broadband optoelectronic components including the direct-/electro absorption-modulated lasers (DML/EML) and silicon photonics (SiP)-based modulators [9] are being reported. With advanced components and DSP, several IM/DD system demonstrations of beyond 200 Gbps lane rate have been reported [10]–[14].

For DCI applications over 40 km, the digital coherent shows clear advantages. The upgrade from IM/DD-based 100 Gbps DWDM to digital coherent 400 Gbps DWDM is ongoing with 400ZR modules [15], [16]. The advantages of the digital coherent for above 40 km will be clearer for 800G and beyond.

The remaining gray area in Fig. 2, estimated to be between 2 km and 40 km, is yet to be determined for 800 Gbps and beyond. In this range, it is fundamentally challenging for IM/DD schemes to support the required lane rate, distance, and power budget simultaneously. On the other hand,
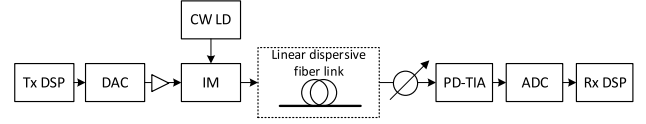

Fig. 3. Simulation setup. CW LD: continuous-wave laser diode; IM: intensity modulator; PD-TIA: photodetector with transimpedance amplifier.

the digital coherent may not yet close the gap of its complexity, energy consumption, and cost, concerning the requirements for complex hardware and DSP. Several technological choices are proposed recently to fill this gap, including the self-coherent and the analog coherent variants [17]–[20]. In our opinion, the main challenges to develop these technologies towards real application include the unclear development time window before digital coherent closes its gap, as well as the lack of development experience and momentum. Nevertheless, we believe it worth continuing to drive the research in these technologies, as there can be potential scenarios where the unique advantages of these technologies are irreplaceable.

Finally, it is worth mentioning that there are factors that may alter the current roadmap. For example, the adoption of optical switches may push the use of low-complexity digital coherent modules inside data centers [21]. Moreover, novel concepts from the industry, like the coherent digital subcarrier-based solutions [22], may impact the choices for the short reach scenarios owing to their unique advantages in supporting data aggregation architectures.

III. SIMULATION AND EXPERIMENTAL STUDIES OF 200 Gbps IM/DD TECHNOLOGIES

We perform numerical simulations to study the performance limit of IM/DD transmissions at 200 Gbps per lane. The simulation setup is shown in Fig. 3 and the detailed simulation configuration is specified in Table I. If we consider single-mode operations in the O-band with 4-λ CWDM or LAN-WDM channel assignments for 800 Gbps, fiber dispersion will impose limitations on the transmission distance, particularly for the short-wavelength channels with negative dispersions [23]. Therefore, we focus on the dispersion tolerance with two modulation formats, 224 Gbaud non-return-to-zero (NRZ) on-off-keying (OOK) and 112 Gbaud PAM4. For each modulation format, we perform two types of equalization at the receiver, namely, to equalize towards the full-response symbol levels, and to equalize towards the partial response duobinary (DB) symbol levels, respectively [13]. Hard-decision demodulations are performed for the corresponding signal formats after the equalization. As the modulator is driven in the linear region and the channel is modeled as a linear dispersive fiber link, we use 30-tap linear feed-forward equalizers (FFE) at the receiver for all test cases. For detailed performance analysis concerning the equalizer complexity, one can refer to [24]. For both modulation formats, we configure the system components' bandwidth into a half symbol-rate and a quarter symbol rate to compare the performances. Figures 4 and 5 show the simulation results of the required received optical power (ROP) at the bit error rate (BER) of 2×10^{-3} versus different dispersion values for the 224 Gbaud NRZ and 112 Gbaud PAM4, respectively. From the figure, one can see that the system performance is directly affected by the system bandwidth, pulse shape, and the equalization/demodulation targets.

TABLE I
SIMULATION CONFIGURATION

Components	Value
Transmitter	
Pulse shaping filter	Root-raised cosine filter
Pulse shaping roll-off	0.1/0.5/1
DAC ENOB	5.5
DAC filter model	5th order Bessel filter
DAC cut-off bandwidth	0.5/0.25*Baud rate
Modulator driving signal V_{pp}	$0.6*V_\pi$
Laser RIN	-145 dB/Hz
Tx output extinction ratio	5 dB
Tx output power	5 dBm
Transmission channel	
Channel	Linear dispersive fiber link
Receiver	
Photoreceiver	PIN-TIA
PD responsivity	0.5 A/W
Receiver noise current	18 pA/$\sqrt{Hz}$
PD filter model	4th order Butterworth filter
PD-TIA cut-off bandwidth	0.5/0.25*Baud rate
ADC ENOB	5.5
ADC filter model	5th order Bessel filter
ADC cut-off bandwidth	0.5/0.25*Baud rate
DSP	
Equalizer	30-tap symbol-spaced FFE
Demodulation	PAM/duobinary-PAM

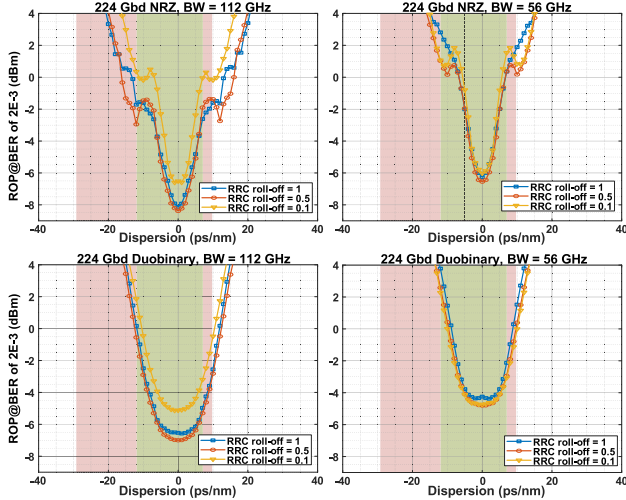ENOB: Effective number of bits; V_{pp}: peak-to-peak voltage; $V_\pi=2V$.

Fig. 4. Simulation results of required received optical power as a function of dispersion for 224 Gbaud NRZ (upper-row) and DB-NRZ (lower-row) with system components' bandwidth of half-symbol rate (left-column) and quarter-symbol rate (right column). The shadowed regions correspond to the dispersion ranges for CWDM 2-km FR4 (green) and LAN-WDM 10-km LR4 (red).

By comparing the duobinary signals with their corresponding full-response counterparts, we observe intrinsic penalties of around 1.5 dB for NRZ and about 2.5-3 dB for PAM4 at zero dispersion. On the other hand, the duobinary formats for both NRZ and PAM4 show higher tolerance of channel dispersion by showing a slower increase of power penalties. Therefore, we may consider using the full-response signals in DR4 or DR4+ applications with parallel single-mode (PSM) configuration to achieve better sensitivity. However, if we consider 4-λ CWDM for 2-km FR applications (dispersion
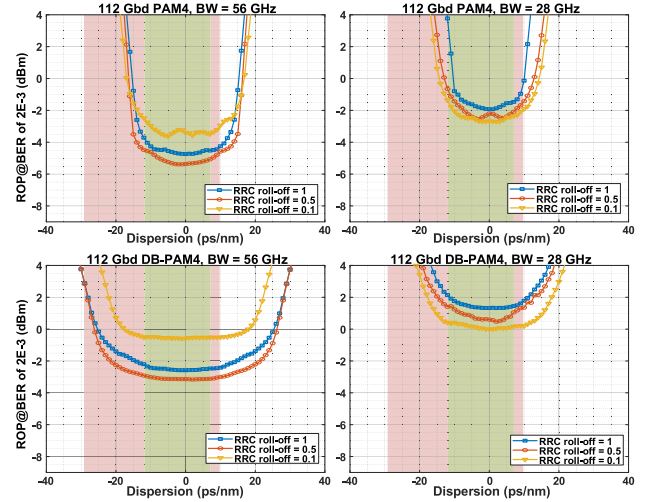

Fig. 5. Simulation results of required received optical power as a function of dispersion for 112 Gbaud PAM4 (upper-row) and DB-PAM4 (lower-row) with system components' bandwidth of half-symbol rate (left-column) and quarter-symbol rate (right column). The shadowed regions correspond to the dispersion ranges for CWDM 2-km FR4 (green) and LAN-WDM 10-km LR4 (red).
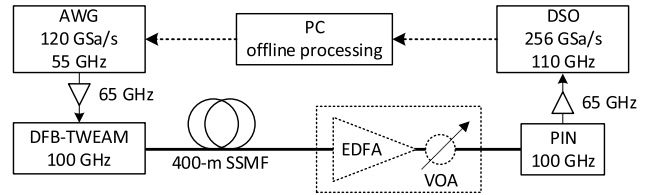

Fig. 6. Experimental setup.

range: -11.9 ps/nm $-$ $+6.7$ ps/nm) or 4-λ LAN-WDM for 10-km LR applications (dispersion range: -28.4 ps/nm $-$ $+9.5$ ps/nm) [23], we may choose the partial-response duobinary signaling with a chirped modulator to increase dispersion tolerance at the cost of power penalty [25]. Moreover, one can observe that it is challenging to meet power budget requirements for 200 Gbps/λ applications with the conventional configurations. Along with the development of devices with better noise characteristics, approaches such as higher-power optical sources, more powerful DSP and FEC, and/or optical amplification may be adopted at the cost of their respective shortcomings. We expect more dedicated studies focusing on this aspect to be carried out.

We experimentally studied 100 Gbaud PAM4 transmissions operated in the C-band, with the purpose to demonstrate the achievable system performance with high-performance devices and state-of-the-art testing equipment. Figure 6 shows the experimental setup. A 120 GSa/s arbitrary waveform generator with 55 GHz analog bandwidth (AWG, Keysight M8194A) was used to generate the signal and perform a frequency domain pre-equalization. A C-band distributed feedback laser-traveling wave electro-absorption modulator (DFB-TWEAM) was used for optical modulation [26]. After 400-m single-mode fiber (SMF), an optical preamplifier (EDFA) and a variable optical attenuator (VOA) were used to adjust the power before a PIN photodetector (PD) of 100 GHz 3-dB bandwidth. The signal was captured by a digital storage oscilloscope of 256 GSa/s and 110 GHz bandwidth (DSO, Keysight UXR1102A).
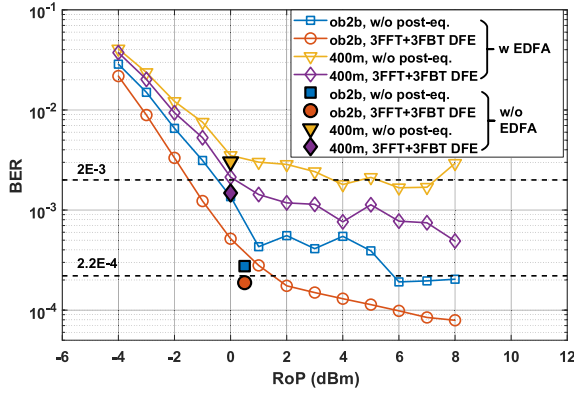
Fig. 7. Experimental results.

The BER performances are shown in Fig. 7. With a broad end-to-end system bandwidth and effective pre-equalization at the transmitter, we may skip the post-equalizer to achieve BER performance below 2×10^{-3} at 0 dBm ROP for the optical back-to-back (ob2b), and at 4 dBm after the 400-m SMF. When we apply a simple decision feedback equalizer (DFE) with 3 feedforward taps and 3 feedback taps, the receiver sensitivity at BER of 2×10^{-3} can be improved to 0 dBm after the 400 m SMF. Further increasing the DFE tap number can improve the BER to go below the 2.2×10^{-4} KP4-FEC limit, which has a shorter FEC overhead and lower latency [27]. We may also skip the EDFA in the setup, however, the insertion loss of the VOA is no longer affordable. Therefore, for ob2b and 400-m SMF, we only measured one power value for each case. The solid markers in Fig. 7 show the BER performances of those cases. We can observe the improved performance without adding the amplified spontaneous emission (ASE) noise from the EDFA. As the PIN PD is not the bandwidth bottleneck of the link, the sensitivity of our system could be further improved if we use a PD of a smaller bandwidth integrated with a trans-impedance amplifier (TIA), which should offer better responsivity and a narrower noise bandwidth. If we consider O-band operation, in our experiments demonstrated dispersion tolerance corresponds to approximately 2.2 km for the worst dispersion channel in a LAN-WDM4 configuration.

IV. Conclusion

The status of applications and research of short-reach optical communications are summarized. We also provide our opinions on the observation of the research status towards future technological choices. Simulation and experimental studies of IM/DD transmission indicate the possible use of client-side optics with 200 Gbps lane rate to support 800 Gbps short-reach applications, provided that the limitations on power, bandwidth, and noise performance from both optics and electronics will be resolved with the research and development effort in the years to come. The advantages of digital coherent optical solutions over IM/DD on the client side are expected to become clearer beyond 800 Gbps.

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