Optical Fiber Technology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Regular Articles

Coherent optical WDM systems for 1.6 Tb/s Ethernet over 40 km of single-mode fiber

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ARTICLE INFO

Keywords:
Coherent optical communications
Phase shift keying
Quadrature amplitude modulation
IEEE 802.3 standard
Metropolitan area networks
Wavelength division multiplexing

ABSTRACT

Two 1.6 Tb/s coherent optical wavelength division multiplexed (WDM) systems targeting inter-data center links of up to 40-km reach over conventional single-mode fiber (CSMF) on C-band are proposed and numerically analyzed: a DP-QPSK-based 16 × 112 Gb/s system and a DP-16-QAM-based 8 × 224 Gb/s system. To satisfy the metro access space, noise and power transceiver characteristics are optimized, avoiding the use of any type of optical amplification or forward-error correction (FEC) scheme. Accordingly to the current Ethernet standard, feasibility of both 28 GBd architectures is hence numerically demonstrated at a very low bit-error-ratio (BER) threshold of 1×10^{-13}, uncovering power sensitivities of −26.0 and −13.5 dBm and optical signal-to-noise ratio (OSNR) sensitivities of 35 and 40 dB for the first and second architectures, respectively. Negligible transmission OSNR and power penalties with respect to the back-to-back (BtB) case are calculated, thus demonstrating the effectiveness of the utilized DSP algorithms. Our simulation work also confirms that the 16-QAM-based scheme is more demanding in terms of OSNR and transmission power specifications than the 16-channel one, requiring approximately 12 dB more power and 5 dB more OSNR level at the transmitter laser outputs, with similar requirements at the receiver end. It is also demonstrated that laser linewidths of at most 1 MHz should be specified in both architectures, that the transmitter laser characteristics play a more appreciable role than those of the receiver laser, and that the frequency offset between these two lasers should be kept below 3 GHz. Our research work leverages the use of optical coherent technology at metro network level and claims for a necessary technological upgrade to such schemes for a forthcoming 1.6 Tb/s Ethernet standard to be feasible.

1. Introduction

Due to the continuous emergence of new services and applications such as video-on-demand, server virtualization, cloud computing, grid computing and "the internet of things", bandwidth (BW) demand at the metropolitan and local network level will steadily continue growing at least for the next few years [1–3]. As a response to this claim, the main drivers in the telecommunications community have joined forces to develop or extend technology and standards to augment the transmission data rates of the corresponding optical fiber-based systems. Ethernet, for instance, increased in 2010 the operational speed of its PHY and MAC layers from 10 to 40 and 100 Gb/s, while 200 and 400 Gigabit Ethernet (GbE) standards are expected to come up in the very near future [4]. These ongoing standardization efforts, nonetheless, have been limited to short-reach links within the data center (intra-data center), whereas for the links between data centers (inter-data center) no standards are currently being developed [5]. This can be explained by noting that intra-data center traffic currently accounts for more than 70% of all data center-related traffic. However, it must be pointed out that inter-data center traffic is growing at over 30% a year [6]. In order to cope with this increasing bandwidth demand in the metro space, a technological leapfrog will soon be required. Recent technological achievements to increase the speed and reach of current architectures have focused on taking advantage of faster electronics to speed up the symbol or bit rate per wavelength channel, on increasing the optical channel count, or on employing more spectrally-efficient modulation formats [7]. Regarding the high-capacity alternatives for intra-data center links, most of them have been implemented within the framework of conventional intensity-modulation with direct detection (IM-DD) schemes using CSMF and operating in O-band to avoid the use of chromatic dispersion compensation modules. For instance, in previous work [8–11], we have demonstrated by means of numerical simulations the technical feasibility of non-return to zero (NRZ)-based systems able to transmit up to 400 Gb/s targeting a BER $\leq 1 \times 10^{-12}$ without using

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https://doi.org/10.1016/j.yofte.2018.01.021
Received 28 June 2017; Received in revised form 12 December 2017; Accepted 20 January 2018

FEC. A maximum reach of 40 km employing a semiconductor optical amplifier (SOA) at the receiver is achieved. In [12], the transmission of 640 Gb/s up to 25 km using one booster SOA and one SOA preamplifier, a dual polarization scheme, NRZ as modulation format and avoiding the use of FEC, was experimentally demonstrated for a BER target of 1×10^{-9}. Moreover, a 10-km reach increase achieved by replacing the booster SOA by a Raman amplifier in this system, was also demonstrated [13]. For these NRZ-based systems, a maximum overall data rate of 960 Gb/s to reach 40 km has been predicted [14]. Other IM-DD systems using more complex modulation formats such as 4-levels Pulse Amplitude Modulation (PAM-4), Carrierless Amplitude/Phase (CAP) modulation and Orthogonal Frequency Division Multiplexing/Discrete Multi-Tone (OFDM/DMT) have also been extensively investigated [1,15–20]. Although relatively uninvolved and cost-effective for intra-data center applications with a reach of less than 40 km and capacity requirements of up to 1 Tb/s, these IM-DD unrepeated transmission systems exhibit serious limitations in terms of transmission distance and data rate per wavelength channel (see Fig. 9 of [21]), that make them unsuitable for the implementation of inter-data center terabit metro networks, where the reach should cover distances between 10 and 80 km [1]. In contrast, coherent optical communication systems (COCSs) offer higher sensitivity and efficient use of the available spectrum. Moreover, they can deal with multi-level modulation formats (in power, phase and polarization), incorporate adaptive electronic equalization of transmission impairments (such as electronic dispersion compensation, enabling operation in C-band to reduce fiber losses), and they can even allow for compensation of imperfections of the transmitter and receiver front-ends [22,23]. It is therefore straightforward to envisage that, provided that the cost of key enabler components such as high-performance transceivers [24] sufficiently decreases (as normally happens), a down-scaling of COCS from the long-haul realm to the metro or even the access space, instead of an up-scaling from short-reach technology to inter-data center solutions, will eventually occur [5,6,25,26]. In fact, the Ethernet Alliance has already tentatively considered a bit rate of 1.6 Tb/s in its 2016 roadmap for a future Ethernet standard [27], which will most probably be based on the use of coherent transceivers assisted by digital signal processing, wavelength division multiplexing (WDM), and low cardinality advanced digital modulation formats, that is, QPSK and 16-QAM [28]. COCS have been proposed as an alternative to implement, next-generation, 400 Gb/s Ethernet over SMF [29]. Their use not only allows to extend the system's maximum reach from 10 to at least 40 km [30], serving inter-data centers, but also to halve the already agreed optical channel count [31]. The performance analysis of 100 Gb/s PM-QPSK and 200 Gb/s PM-16-QAM transceivers with respect to relevant transmission characteristics have been presented in [30,32] for metro access point-to-point links, and in [24] for a ROADM-based metro ring topology that relies on the use of optical amplifiers, FEC (i.e. BER $\leq 1 \times 10^{-3}$) and a tightly spaced 144-channel Nyquist WDM grid. Also, Demonstrator 2 of the Horizon 2020 EU DIMENSION ongoing project focuses on an amplified COCS targeting link lengths between 10 and 80 km and considers the development of a power-efficient tunable 200 Gb/s optical transmitter [1]. Still, further investigations are necessary to expand the already insufficient reported research in this topic.

Based on the aforementioned arguments, in this contribution we propose, compare and numerically demonstrate the technical feasibility of two COCS operating at 1.6 Tb/s that might be suitable as high-speed optical data center interconnects (DCI) at metro level. Having in mind the extended reach of a prospective physical medium dependent sub-layer of an imminent 1.6 Tb/s Ethernet standard, an objective reach of 40 km over conventional single-mode fiber (SMF) on C-band (for minimum fiber attenuation) with a maximum BER of 1×10^{-13} has been defined. Given the limited coverage of a metro access network, neither amplification nor FEC (to reduce latency, power consumption and frame overhead) have been considered for the link. Moreover, a wide channel spacing of 100 GHz has been set. This avoids the need for pulse shaping through (Nyquist) optical filtering at the transmitter that is normally used to increase the system spectral efficiency in long-haul systems. Also, the transceiver characteristics were chosen so as to satisfy the more cost-conscious metro space rather than just transfer components from the long-haul market. All these features set our systems apart from the frequently investigated COCS based on the use of advanced modulation formats. Therefore, our simulation analysis is not only different from more common approaches, but call for a high level of optimization (see Section 3) to meet the demanding objective of BER $\leq 1 \times 10^{-13}$. The first proposal consists of a dual-polarization (DP) 16 WDM channels scheme running at 100 Gb/s per wavelength, while the second proposal is based on a DP 8 × 200 Gb/s architecture. The former (latter) implementation relies on QPSK (16-QAM) for digital modulation, hence the raw data rate, signal bandwidth and symbol duration of all optical channels become the same. The remainder of this article is organized as follows. We begin presenting the setup and implementation details of the aforementioned architectures. Next, an optimization analysis, mainly focused on the transceivers' laser performance, is discussed. We follow demonstrating error-free transmission of both systems for up to 40 km reach. Finally, in Section 4, the main conclusions of this work are outlined.

2. Simulation setup

The performance of the proposed architectures was analyzed using the well-tested VPItransmissionMaker™ co-simulation suite. Care has been taken to select model parameters in accordance to specifications of commercial or close-to-market devices, thus guaranteeing reliable simulations. Among these devices we can mention the transmitter and receiver lasers, the IQ-modulators, the optical filters, the optical fiber, the hybrids, the balanced photodetectors (BPDs) and the analog-to-digital converters (ADC) that are detailed below, including the references that support our choice. A general diagram of the analyzed COCSs is shown in Fig. 1, where N is the number of WDM channels for a total raw data rate of 1.6 Tb/s, i.e., N = 16 (8) for the first (second) architecture. Since the total symbol rate per optical channel in both architectures is 28 GBd (25 GBd plus 12% of Ethernet overhead), the overall bit rate per optical channel becomes 112 Gb/s (224 Gb/s) for the first (second)

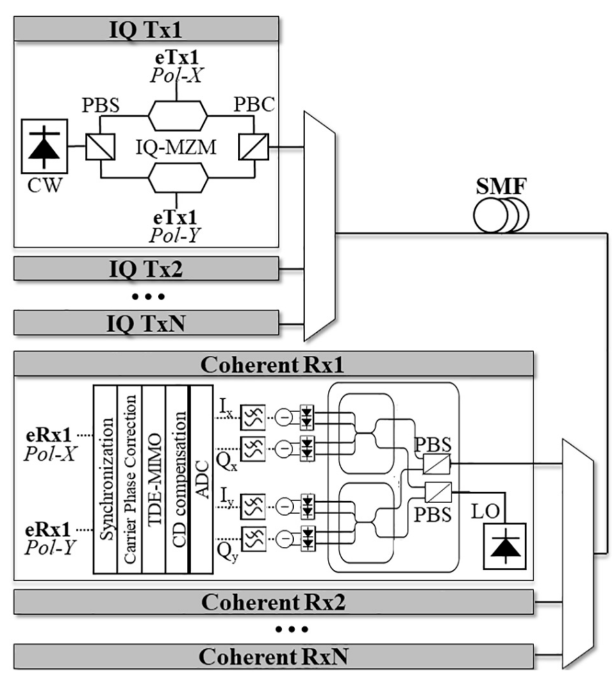

Fig. 1. System setup. N = 16 (8) when DP-QPSK (DP-16-QAM) is used as modulation format. PBC: Polarization beam combiner, PBS: Polarization beam splitter.