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An alternative for the implementation of 40-km reach Ethernet at 400 Gb/s using an 8×50 Gb/s PHY at 1310 nm with SOA pre-amplification

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ABSTRACT

The proposal and technical feasibility of a wavelength-division multiplexed system consisting of eight optical channels, each transporting data at 50 Gb/s in NRZ modulation format, are presented. It is numerically demonstrated that, aided by a semiconductor optical pre-amplifier with 23 dB of gain and setting the laser output power of an electro-absorption-based transmitter to +7.9 dBm, a propagation distance of 40 km over conventional single-mode optical fiber can be achieved with a BER $< 1\times 10^{-13}$. Despite its high sensitivity, dispersion power penalty is minimized by setting a 400 GHz channel plan in O-band whose center is slightly red-shifted from the zero-dispersion wavelength of the fiber. Moreover, non-zero dispersion is found to be useful in reducing the deleterious amplifier nonlinear gain modulation at mid-range distances, whereas four-wave mixing is found to play a practically inconsequential role. In agreement with previous results derived for 25 Gb/s multi-channel links, optical signal-to-noise ratio degradation becomes the prominent corrupting factor at long fiber span lengths. The proposed architecture thus represents an alternative for the implementation of the physical layer of next-generation Ethernet or similar metropolitan data networks.

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1. Introduction

Since its conception more than 40 years ago, Ethernet has been continually evolving, expanding and adapting to the needs of a dynamic networking world. By fulfilling the requirements of operators and end users, Ethernet is now the most widely deployed networking technology [1]. Although originally designed for computer interconnection in local area networks (LANs), its reach has recently been extended to also embrace metropolitan area networks (MANs). In particular, the most recent update to the IEEE standard, considering a maximum operational data rate of 100 Gb/s, defines a physical medium dependent (PMD) sublayer designed to reach up to 40 km over single-mode fiber (SMF) [2]. It is termed 100GBaseER4, where ER stands for “extended-reach”. The next generation of the standard, running at 400 Gb/s, is currently under development by the IEEE 802.3bs Task Force (400 GbE TF) [3]. Four interfaces are being defined: 100 m reach over multimode fiber (MMF), 500 m reach over SMF, 2 km reach over SMF and 10 km reach over SMF. While the first three interfaces are meant for interconnection of equipment within data centers, the 10-km objective is intended for data interconnection across campus and intra-city infrastructure. Clearly, the latter fiber length is insufficient for extended-reach applications aimed for MANs and inter-city interconnection. Unfortunately, the 400 GbE TF members opted for not setting a 40 km SMF PMD, even though the early market applications for 400 GbE are expected to be similar to those considered for the 100 GbE optical interconnects [4]. For instance, China Unicom predicts that at least 10% of its MAN to backbone transport connections will require a 400 GbE 40-km interface [4]. As a response to this unfulfilled need, in this contribution we propose and numerically demonstrate the technical feasibility of a 40 km reach optical interface over SMF that is based on an 8×50 Gb/s WDM configuration. Although 4-level pulse-amplitude modulation (PAM-4) has been practically adopted for the 10 km PMD [5], such a modulation format is not expected to be easily adapted to reach a distance of 40 km without the use of FEC [6]. We have thus decided to use non-return to zero (NRZ) format in our proposal. Besides, NRZ is considered to be a simpler and lower power alternative to PAM-4 [7–9]. The proposed architecture is also based on the use of a semiconductor optical pre-amplifier (SOA) to avoid the use of forward error correction (FEC) and to maintain the BER below 1×10^{-13}, which is the BER

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threshold set in the 400 GbE TF objectives [10].

An alternative worth to be investigated, especially now that cost-effective, compact and high power semiconductor-based quantum-dot laser diodes emitting at around 1240 nm are available [11], is the use of distributed Raman amplification, which has been successfully demonstrated to extend the reach of passive optical networks [11] and to enable a 10 × 40 Gb/s WDM link 55-km long in the 1310-nm wavelength domain [12]. In contrast to SOAs, distributed Raman amplifiers (DRAs) exhibit a higher output saturation power of about 20 dBm and an improved noise figure of approximately 4 dB that lead to a considerable enhancement in receiver sensitivity [12]. Thanks to these characteristics, a DRA that exhibits 18 dB of gain would suffice to meet the power budget requirements of the link analyzed in this work. However, this comes at the cost of a narrower amplification bandwidth of about 10 nm and the need for a pump laser delivering at least 800 mW [13]. The first consequence can be dealt with reducing the system channel spacing, but the high power required to operate the pump laser adds on electrical power consumption and associated operation costs. A more important drawback presented by DRAs is, nonetheless, that by its own nature, DRAs require a minimum fiber length (of several km) to transfer power from the pump to the signal. In contrast, an SOA-amplified system operates correctly irrespective of fiber length (from 0 to 40 km in our case). Moreover, further research to integrate the pump laser into a high port density CDFP form-factor pluggable transceiver would be necessary before the 400 GbE TF would be in the position of recommending DRAs as part of the Ethernet standard.

Our proposal builds upon previous analyses carried out at lower speed per optical lane and higher channel count (wider optical bandwidth) [14–17]. A low number of optical lanes is desirable because it favors transceiver module downsizing and power consumption reduction. It also presents a narrower transmission bandwidth that fits well within the available SOA bandwidth, which is about 40 nm [17], thus leading to wavelength-independent (flat) gain for all optical channels. Still, the use of a higher bit rate per optical lane presents its own inconveniences. On one hand, it might intensify the impact of self- and cross-gain modulation in the SOA due to the finite recovery time of this highly nonlinear element, especially at short fiber lengths (high input powers). On the other hand, it increases the power penalty produced by group velocity dispersion in the optical fiber. Therefore, the advantage of using a low channel count can be compromised when the design parameters of the proposed system do not properly compensate the extra power penalties caused by the use of a high bit rate, while preserving a BER $<1\times10^{-13}$. For instance, reference [18] suggests that good performance in terms of fiber dispersion of a 50 Gb/s per channel transmission system over conventional SMF can be achieved provided that the system optical bandwidth is constrained to 20 nm (as we did in our simulations) and the channel plan is positioned around the zero-dispersion wavelength. The latter is a relevant design factor when operating at 50 Gb/s because, as demonstrated below, a slight wavelength shift in the overall channel plan can produce abrupt differences in system performance. This does not necessarily occur in a link running at 25 Gb/s [16]. Special attention has to be paid as well to the selected SOA characteristics, otherwise unacceptably high BER values can be produced. For example, a BER of about 2×10^{-5} is reported in reference [18] for a low-gain device when employed within an 8 × 54 Gb/s architecture using a channel spacing of 250 GHz. This is far above the BER value suggested for the 400 GbE standard. Our contribution therefore provides, for all utilized devices, design parameter values that guarantee the correct operation of the system at a data rate of 50 Gb/s per optical channel. Although the focus of the work is on system design, an analysis of the weight of the main deleterious effects, such as SOA nonlinear effects and signal degradation due to optical signal-to-noise ratio (OSNR) reduction, is also presented. The article is divided into four parts. In the following section, the setup used to carry out the simulations is detailed. Then, the technical feasibility of the system along with an analysis of the nonlinearities induced in the SOA are presented. Section 4 summarizes our conclusions.

2. Simulation setup

A schematic diagram of the proposed extended-reach architecture to set up the 400 Gb/s Ethernet link is shown in Fig. 1. It is based on optically multiplexing eight channels onto a conventional SMF 0–40-km long. Each optical lane is externally modulated at 51.5625 Gb/s in NRZ format. The 3.125% extra data rate per channel accounts for the header introduced at the physical coding sublayer (PCS), assuming that the coding scheme used in 100 GbE will be preserved. The receiver comprises of a SOA that amplifies all eight optical channels simultaneously before these are demultiplexed and received by individual optical front-ends (OFEs), each connected to an electrical receiver (Rx). The analysis is carried out for fiber lengths between 0 and 40 km because so far the IEEE 802.3 standard has not specified a minimum link length for the system, and then it is common practice among operators to deploy the same type of transceiver for interconnects of various lengths. The SMF is assumed to follow the ITU-T G.652 recommendation [19] since it is the most installed fiber nowadays. Its characteristics are summarized in Table 1. Note that an additional loss of 1 dB has been assumed. It accounts for fiber connectors and splices.

Each of the eight externally modulated lasers (EMLs) consists of a distributed feedback laser (DFB) and an electro-absorption modulator (EAM) driven by an electrical transmitter (Tx) [20–22]. The optical signal exhibits an extinction ratio (ER) of 8 dB, an OSNR of 38 dB and an amplified spontaneous emission (ASE) spectrum 5 THz wide that is centered at the signal wavelength. In the receiver end, each OFE is composed of a photodiode with an opto-electronic bandwidth of 50 GHz and responsivity of 0.7 A/W [23], and a transimpedance amplifier (TIA) that has a conversion gain of 1400 Ω with an input current noise density of 18 pA/sqrt(Hz) [24,25]. The electrical receivers have fifth-order RC filter characteristics with 50 GHz bandwidth and noise variance of 2.86 mV_{rms}. For multiplexer (MUX) and demultiplexer (DEMUX), arrayed waveguide gratings exhibiting an optical bandwidth (FWHM) of 175 GHz and an insertion loss of 3 dB were selected. The sensitivity, measured just before the OFE under back-to-back conditions at BER $=1\times10^{-13}$ for the single-channel 51.5625 Gb/s signal, resulted in −11.25 dBm.

The numerical analysis has been carried out using a well-tested optical transmission system simulator implemented in the graphic programming language LabVIEW™ [26], where the fiber and SOA models do not consider the vectorial nature of the electromagnetic field. Therefore, all channels can be implicitly assumed to be ideally co-polarized. Further model and implementation details can be found in [27]. Of particular interest is the SOA model. It is based

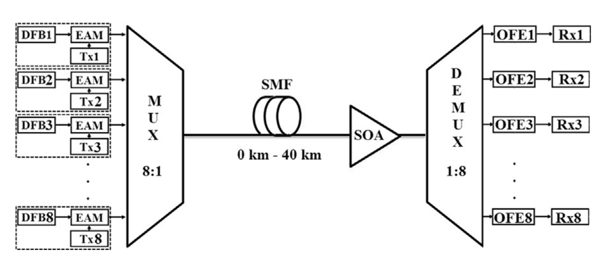

Fig. 1. Set up of the proposed 8 × 50 Gb/s optical link for Ethernet at 400 Gb/s.

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