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[invited]

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Terabit/s serial optical communications (invited)

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Abstract- **We report on an experimental demonstration of a 1.28 Tbit/s serial data generation and demultiplexing and discuss the prospects of upgrading other essential functionalities to 1.28 Tbit/s.**

I. Introduction

In year 2000, the first demonstration of reaching Tbit/s data rates on a single wavelength channel was achieved [1] using 640 Gbaud pol-MUX and simple OOK. Since then, only very few attempts have been made to approach this outstanding feat. Recently it has become apparent that Tbit/s bit rates for Ethernet applications will be needed very soon [2] and that the overall necessary capacity per fiber will reach several tens of Tbit/s [3], while the need for power reductions is getting more and more evident, where the Internet today emits more than 2% of the global CO_2 emission. This has spurred on a regained focus on increasing the bit rates, both with a single-channel perspective and with a spectral efficiency perspective using advanced modulation formats and latest advances in coherent receiver technology. A high single-channel bit rate has generally had the effect of cutting the overall systems cost, due to reduced network complexity, fewer components and hence lower power consumption per bit. A high spectral efficiency may also help in power per bit since the bandwidth is more efficiently used. Using OFDM has a high component count in the terminals, but on the other hand is very resilient to transmission impairments and hence needs less inline equipment for e.g. regeneration. So the optimum path to energy efficient high bandwidth communication systems is still open, and all routes must be explored to ensure future sustainability.

Recent highlights of the endeavors to boost the bit rates to the Tbit/s regime include the record breaking 2.56 Tbit/s using DQPSK and pol-MUX on a 640 Gbaud RZ pulse rate [4] and a recent upgrade to 8PSK on 640 Gbaud with pol-MUX resulted in below FEC-limit 3.56 Tbit/s using coherent reception and 2.38 Tbit/s using 16 QAM on 640 Gbaud without pol-MUX [5]. The combination of time division multiplexing and coherent receiver techniques has also been successfully studied by the Kikuchi group and recently led to a 1.28 Tbit/s based on 16 QAM on a 160 Gbaud pol-MUX OTDM pulse train [6]. Using coherent OFDM has also recently been demonstrated to reach 1 Tbit/s [7] and even 1.2 Tbit/s [8]. The simple OOK purely serial format has the advantage of being simple and having a low component count as well as being the only format with well-established suggestions for all-optical regeneration, which may also aid in driving the power consumption down. Drawbacks are the relatively low spectral efficiency and the severe challenges with respect to long-haul transmission. Until very recently, the baud rate had been limited to 640 Gbaud, but a new record of 1.28 Tbit/s was recently demonstrated [9] using only optical time division multiplexing (OTDM) from 10 Gbit/s and remaining in one single polarization.

In this paper we describe our recent progress on 1.28 Tbit/s data generation and demultiplexing and discuss opportunities and limitations of this technology. In addition we describe the demonstrated essential functionalities at 640 Gbit/s and discuss the prospect of upgrading these to 1.28 Tbit/s, and also what impact this could have on designing new network scenarios.

II. Experimental demonstrations

A schematic of the experimental set-up used for the demonstrations described here is shown in Figure 1. An erbium glass oscillator pulse generating laser (ERGO-PGL) supplies a 10 GHz optical pulse train at 1557 nm having a pulse width of 1.3 ps. A Mach-Zender modulator (MOD) is used to encode a data sequence (2^7-1 PRBS) on the pulse train. The 10 Gb/s modulated pulse train is compressed down to 350 fs in a highly
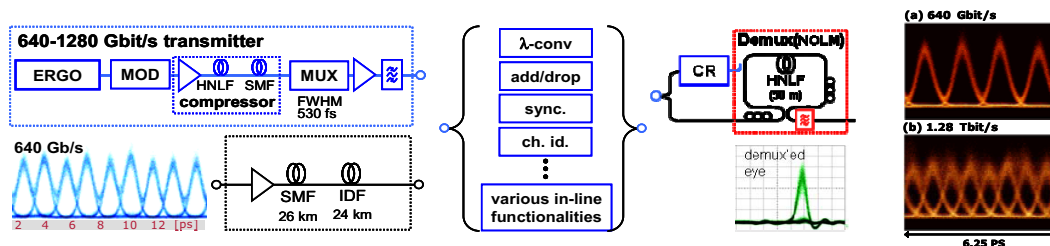

Figure 1. Schematic of the DTU OTDM test-bed for generating 640-1280 Gbit/s data. Insets: a) 640 Gbit/s eye diagram, b) 1.28 Tbit/s eye diagram.

non-linear fiber (HNLF) SPM-based chirp unit followed by linear dispersion, and subsequently multiplexed to 160-320-640-1280 Gbit/s in a passive fibre delay PRBS and polarization maintaining multiplexer (MUX). The multiplexed data is then subjected to various experiments.
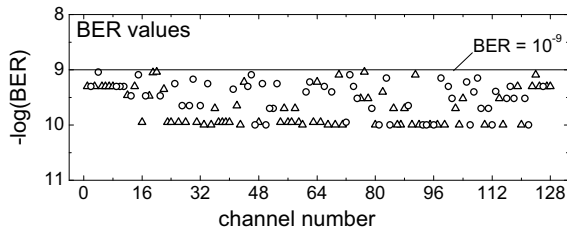

Figure 2. BER values for all 128 tributaries. All channels are error free (BER < 10^{-9}) corroborating the open eyes from figure 1. Taken from [9].

Figure 2 shows the BER results for all 128 demultiplexed OTDM tributaries of the 1.28 Tbit/s data signal. For this experiment a 15 m long HNLF ($\gamma \sim 10.5$ W^{-1}km^{-1}, zero dispersion at 1545 nm and a flat dispersion profile (slope: 0.015 ps/nm^{2}km)) was used in a NOLM for the demultiplexing. So, 1.28 Tbit/s serial data multiplexing and demultiplexing is possible as longs as the compressed pulses are of sufficient high quality and the walk-off is small in the NOLM.

Other interesting functionalities have already been demonstrated at 640 Gbit/s and show promise for higher bit rates. This goes for transmission and clock recovery, wavelength conversion and add/drop multiplexing, all of which has been demonstrated at 640 Gbit/s in our test-bed [10-15]. These functionalities are likely to be possible to perform at 1.28 Tbit/s, as the physical properties involved in the signal processing are fast enough. For the clock recovery scheme described in [10-11], a periodically poled Lithium Niobate (PPLN) device was used as an all-optical mixer, and it was fast enough to resolve the 640 Gbit/s data signal. In [16] is described how a similar PPLN device is used to compress an optical pulse to less than 100 fs, revealing the great speed potential of the $\chi^{(2)}$ process, which takes place on a fs timescale. So these devices have great potential for Tbit/s applications. The HNLF used for wavelength conversion and add/drop multiplexing in [12-15] are the same types as used for the 1.28 Tbit/s experiment, so they have already proven themselves able to operate at Tbit/s speeds. An alternative to HNLF is the very non-linear chalcogenide waveguides. In [17] we showed that such a device could be used to demultiplex a 640 Gbit/s data signal, and as with the HNLF and the PPLN, the active effect used for the optical signal processing is ultra-fast, and the only speed limitation lies in the design of the dispersion (this goes for all the devices). Recently, in [18], it was shown that these waveguides indeed have a THz response with a modulation bandwidth on the order of 2.5 THz. This means that this technology would also lend itself favorably to Tbit/s serial communication systems.

III. CONCLUSION

We have described a 1.28 Tbit/s experimental demonstration and shown that there are several technologies that can potentially deal with such high bit rates. This means that Tbit/s serial optical data may be a feasible path to accommodate for the future need for high-capacity communication systems.

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