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Enabling Technologies for OTDM Networks at 160 Gbit/s and Beyond

Jorge Seoane, Anders T. Clausen, Leif K.Oxenløwe, Michael Galili, Torger Tokle and Palle Jeppesen
Research Center COM, Technical University of Denmark, Building 345V, Oersteds Plads, Kgs. Lyngby, DK-2800 Denmark
jsg@com.dtu.dk

***Abstract*-State-of-the-art OTDM systems are revised. The feasibility of signal processing at ultra high bit rates is outlined.**

I. Introduction

Means to upgrade existing transmission systems will have to be considered shortly as the reported demand for bandwidth increases consistently. High-speed per channel systems have the potential of offering highly compact optical systems with a minimised footprint and a maximised cost-per-bit efficiency. To-date state-of-the-art electronics can only operate at bit rates up to 80 Gbit/s [1]. Optical time division multiplexed (OTDM) systems, in which a high-speed aggregated optical signal is obtained by time interleaving low-speed channels, have the capability of providing ultra high-speed operation circumventing the existing electronic bottleneck.

II. High-Speed Systems

A large effort has been devoted in recent years to the development of ultra high-speed OTDM systems based on novel modulation formats that alleviate a number of transmission impairments, e.g. dispersion, polarisation-mode dispersion (PMD) and nonlinearities. Simultaneously, the advantages offered by polarisation multiplexing have been thoroughly exploited to increase either capacity or spectral efficiency.

The single-wavelength capacity record is currently held by the traditional return-to-zero (RZ) modulation format using polarisation multiplexing, for which 1.28 Tbit/s transmission has been reported [2]. OTDM has been successfully combined with wavelength division multiplexing (WDM) as in e.g. [3], where a 10 x 320 Gbit/s transmission system over standard single-mode fibre (SMF) has been demonstrated.

Differential phase shift keying (DPSK) has gained considerable attention in the last years. Data are encoded using the phase difference between consecutive bits and therefore, decoding is feasible as long as the carrier phase remains stable over a duration of two bits. Additionally, direct detection can be employed with the implementation of a one-bit-delay interferometer, which results in a cost-effective enhanced receiver sensitivity if a balanced receiver is used. Using DPSK, generation and detection of a 160 Gbit/s signal [4], and 640 Gbit/s transmission [5] have been demonstrated.

Multi-level modulation formats are highly desirable as the resulting transmission bandwidth is reduced proportionally to $\log_2(N)$, where N represents the number of levels. Four-level phase modulation or differential quadrature phase-shift keying (DQPSK) has been intensively researched for optical communication systems with great success [6].

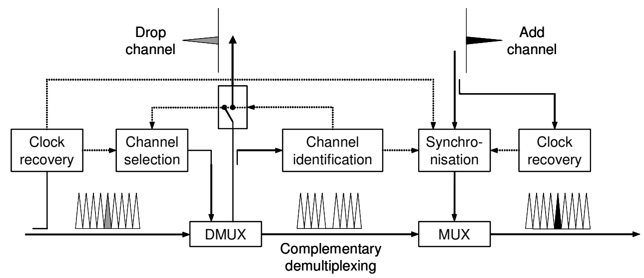

Fig. 1 Typical add-drop node structure for a high-speed OTDM signal

Following a similar concept to multi-level modulation, orthogonal phase and amplitude modulation, combining for example DPSK and amplitude shift keying (ASK), can be employed to generate an optical signal with double bit rate of the current state-of-the-art electronic equipment [7]. This orthogonal modulation scheme has very recently shown promising results when used in conjunction with OTDM techniques [8].

Despite the advances in novel modulation formats, OTDM technology currently appears as the most promising technique for 160 Gbit/s and beyond optical systems [9].

III. Signal Processing

The focus in optical systems has shifted from high-capacity long-haul transmission to more flexible network concepts. Fig. 1 illustrates the expected structure of an optical add-drop multiplexer (OADM) in an OTDM system. OTDM-based systems are characterised by access to individual bits in the data stream, which makes them highly granular and perfectly suited for operation within a networking scenario. However, immense technical challenges remain.

Clock recovery blocks are essential to OTDM systems as signal processing requires a clock reference due to the temporal nature of the OTDM channels. Furthermore, clock extraction becomes increasingly difficult as the bit rate increases since a perfect OTDM signal only contains frequency harmonics at integer multiples of the aggregate bit rate. Demultiplexing requires clock extraction at the base rate, which has been reported from 160 Gbit/s using electro-absorption (EA) modulators, see e.g. [10], and semiconductor optical amplifiers (SOAs), see e.g. [11]. SOAs are particularly interesting for their versatility, potential for integration and record speeds up to 400 Gbit/s [12]. A different approach was described in [13], where an optical clock at the base rate is co-propagated with the data signal and used directly at the receiver without O/E conversion for demultiplexing. All-optical techniques have the potential for ultra-high speed operation and have been reported to achieve clock extraction at an aggregate bit rate of 160 Gbit/s [14], which can be subsequently used for 3R regeneration.

Additionally, the extraction of a time reference has to be associated to a means of channel identification since dropping a specific channel is achieved by changing the phase of the recovered clock. The channel identification block provides feedback to the channel selection, so that the position of the targeted channel within the aggregated OTDM signal is known at all times. Several schemes have been proposed for unambiguously identifying the temporal position of each channel, e.g. using polarisation flag[15], amplitude modulation [16] or pilot tone modulation [17].

The keystone of an OADM is the (de)multiplexing stage (DMUX/MUX in Fig. 1). All-optical techniques require the generation of an appropriately narrow switching window in order to fully exploit the granularity of ultra high-speed OTDM systems. To-date, recovery of a 10 Gbit/s base channel from a single polarisation 640 Gbit/s signal relies on the Kerr-effect in optical fibres, either in the form of a nonlinear optical loop mirror (NOLM) [18] or a recently proposed fibre Kerr-switch [19]. Highly nonlinear fibre (HNLF) or photonic crystal fibre (PCF) with very large nonlinear coefficients can be used as nonlinear medium. However, they are bulky and far from compact integration. Semiconductor devices appear as a more promising option, but still cannot compete with fibre based demultiplexers speed-wise [20].

A novel concept of networks, mainly based on optical packet switched networks (OPSN), has obtained large recognition in the past years. In these networks, the data structure is divided into the label or header, which contains the destination and the supervision data, and the payload, which carries the information. By optically processing the headers, the packages can be directly routed in the optical layer in an OADM without O/E conversion. This concept is developed in [21] aiming at achieving full transparency in the optical node.

Simultaneous with the improvement of these advanced node functionalities, a great effort has been devoted to the investigation of optical techniques that can extend the transmission limits of these high-speed systems while preserving an adequate quality of service. Raman amplification has proved an invaluable instrument as it helps preserve optical signal-to-noise ratio. Moreover, Raman-assisted wavelength conversion of a 160 Gbit/s signal, with clear potential for regeneration, has been reported [22].

CONCLUSION

Despite some technical issues such as optical buffering are still pending, strong foundations for a bit rate upgrade have been laid in recent years. The migration to ultra high-speed systems and networks seems technically feasible.

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