Maximizing the Capacity of Installed Optical Fiber Infrastructure Via Wideband Transmission

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Abstract: Optical wideband communication systems aim at transmitting over several, if not all, of the low-loss windows of single-mode fibre, i.e. the O-, E-, S-, C-, and L-band. Recently, there has been a clear trend in the industry to support additional bands beyond C-band. While C+L-band solutions are close to commercialization and first products are emerging, the research focus is shifting to supporting also the S-band and, finally, the whole O- to L-band (resulting in a total transmission bandwidth of 365 nm). This contribution highlights the perspectives of wideband communication systems for optical networks, providing a realistic roadmap for their deployment. Particular emphasis is paid on a first analysis to estimate the maximum transmittable capacity over these systems.

1. Introduction

Network operators face a continuous strong growth of traffic in their optical networks. For the time frame 2016-2021, the estimated compound annual growth rate (CAGR) of total IP traffic is $\sim$24% according to [1]. This leads to a continuously shrinking reserve of dark fibres until the point where links will reach the limit of their capacity in the C-band. With increased maturity of commercial L-band equipments, network operators have now the option to further scale the capacity of their deployed fibre infrastructures by increasing the total available optical bandwidth from 35 nm (C-band) to 95 nm (C+L-band). In principle, modern standard single-mode fibres (SSMF) without waterpeak absorption, such as ITU-T G.652D fibres, might support operation in the spectral window of 1260 nm - 1625 nm, i.e. in a total bandwidth of 365 nm from O- to L-band. This translates into $\sim$10$\times$ increased bandwidth with respect to existing C-band systems. Clearly, unlocking this potential poses several challenges. There has been research on components such as transceivers [2] and amplifiers leading to new record transmitted capacity of 115 Tb/s in S-, C- and L-band [3]. Another challenge is the diverse set of channel characteristics within the different bands such as the dispersion D ranging, in case of SSMF, from -5 ps/nm/km to $\geq$ 20 ps/nm/km, in the O- and L-band respectively, and the fibre losses α varying between 0.4 dB/km and 0.18 dB/km in O- and C-band respectively. To achieve a full optimization and exploitation of this enormous spectrum, adaptation to the channel characteristics on a per channel basis is required. For example, some initial experimental works on optical wideband transmission assumed quadrature phase-shift keying (QPSK) modulation in O- and E-band and 16-ary quadrature amplitude modulation (QAM) in S-, C- and L-band [4]. By using probabilistic shaping and / or rate-adaptive forward error correction (FEC) a finer granularity was achieved allowing a more efficient adaptation to the channel [3].

In this contribution, we discuss a theoretical framework based on the Gaussian noise (GN) [5] model to estimate the achievable capacity for optical wideband systems operating from O- to L-band. The framework is then used to compare the achievable capacities of legacy SSMF with waterpeak leading to high fibre losses in the E-band versus ITU-T G.652D fibre (w/o waterpeak). The channel optimization is carried out by applying the LOGO strategy to each band [6]. The remainder of the paper is structured as follows. Section 2 provides an overview on the evolution and a possible roadmap of optical networks into multi-band (MB) networks. Section 3 describes the considered system scenarios and assumptions for the capacity evaluation, while section 4 presents the theoretical framework and results.

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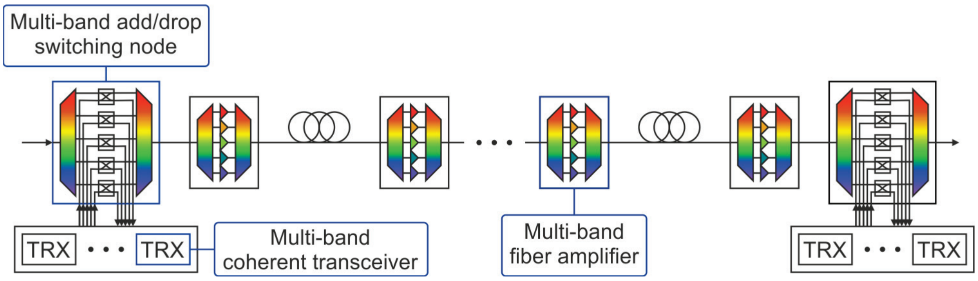
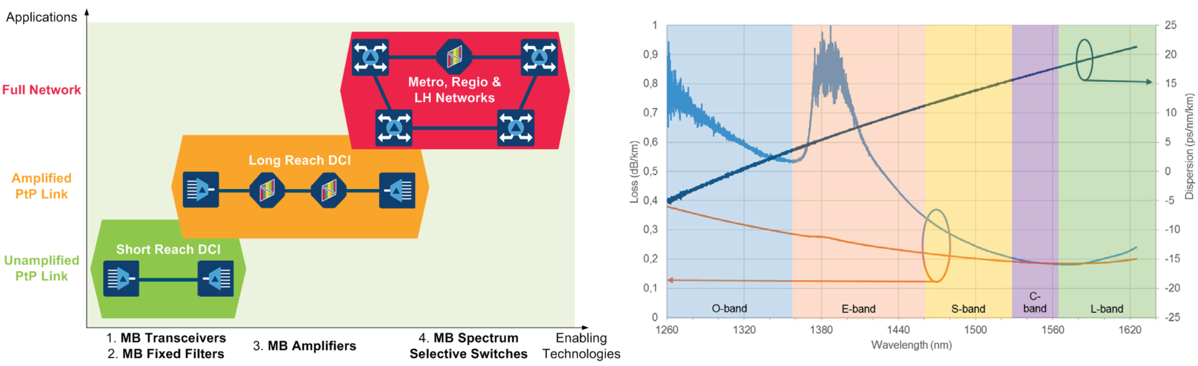


Fig. 1: Simplified block diagram of an optical MB system and its main components.

2. The multiband evolution of optical networks

One of the most limiting factors when upgrading any optical network, and particularly for metro and data-center interconnect (DCI) applications, is the cost per transmitted bit [7]. Exploiting the wideband characteristic of currently deployed optical fiber infrastructure is one of the most cost-effective approaches to increase the capacity of optical networks [8]. This advantage places MB transmission in a leading position with respect to alternatives such as using state-of-the-art multi-core/-mode optical fibers or additional optical fiber pairs (which may need to be deployed/leased). Moreover, MB transmission can be designed to support modular upgrades. Thus, the enabling of additional transmission bands can follow a pay-as-you-grow approach, i.e., specific hardware required to enable particular transmission bands can be deployed when the respective bands are required. In this case, for example, the optical amplifiers would be optimized for each band. A simplified block diagram of an optical MB system and the main required components (MB coherent transceiver, MB add/drop switching node, MB fiber amplifier) is depicted in Fig. 1, while Fig. 2a illustrates the key enablers of MB transmission. DCI and metropolitan ring networks (point-to-point (PtP) transmission) are the scenarios where wideband transmission has the highest potential in the short term. In this case, only MB transceivers and fixed-filters are a prerequisite. MB amplifiers may also be needed for the longer links, which leads to an increase of the capital expenditure. However, due to the possibility to implement a pay-as-you-grow characteristic of MB transmission, the investment in MB amplifiers may be partially postponed. Finally, MB reconfigurable optical add/drop multiplexers (ROADM) are highly desirable in multi-degree nodes. Fig. 2 of [9] shows a possible implementation of such a device. The proposed concept is similar to the one currently used for C-band only transmission. In this case, the optical fiber sub-bands are firstly divided and amplified by optical pre-amplifiers specifically designed for each sub-band. Next, the resulting signals in each band are dropped/added. Finally, the resulting bands are amplified (by booster amplifiers designed for operation in each band) and multiplexed in a single wideband signal by a MB multiplexer.



(a) (b)

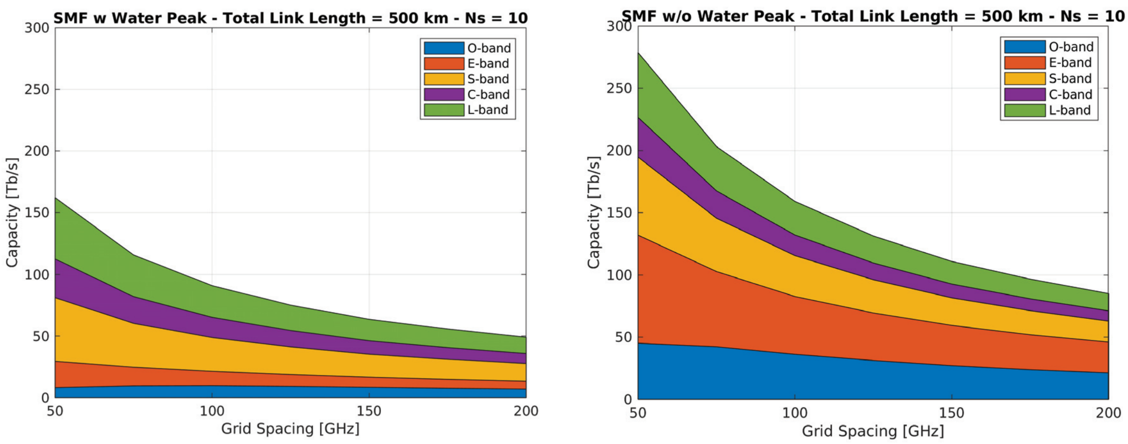
Fig. 2: (a) Key enabling technologies for MB systems for different network segments. (b) Measured dispersion (dark blue) and fiber loss. Light blue, legacy field-deployed fiber with waterpeak in E-band (ITU-T G.652A) and orange all waves fiber (ITU-T G.652D) within (1260 - 1625) nm (O- to L-band).

3. Considered transmission scenarios

In order to estimate the capacity increase gained by lighting up the additional low-loss bands of SSMF, a typical regional-reach scenario of 10×50 km SMF spans is considered. Since there are still remaining deployed legacy fibers with waterpeak, a MB upgrade scenario based on waterpeak fibers is compared to ITU-T G.652D fiber without waterpeak. In this work, the measured loss and dispersion values of the two fiber types, as shown in Fig. 2b, are used. Lumped amplification is performed after each span. The assumed noise figures of the optical amplifiers are: 7 dB in O-band (Praseodymium doped fibre amplifier), 6.4 dB in E-band (Neodymium doped fibre amplifier) [10], 7 dB in S-band (Thulium doped fibre amplifier), 5 dB in C-band (Erbium doped fibre amplifier), and 6 dB in L-band (Erbium doped fibre amplifier). A guard band of 2 nm is assumed between each band. As a simplifying assumption, flexible coherent transponders which are able to achieve Shannon capacity for any given optical signal-to-noise ratio (OSNR) and can, thus, seamlessly adapt to the channel, are assumed. The transponders operate at a gross symbol rate of 32 GBd.

4. Capacity evaluation

Based on the assumptions of Sec. 3, we report a first analysis on the maximum achievable capacity in Tb/s for a MB system operating from O- to L-band. We target a simple yet reliable estimation of the maximum capacity a SSMF fiber may convey in the low-loss windows. Considering state-of-the-art transmission techniques, based on depolarized signals and Nyquist-WDM spectral occupation, it has been extensively shown that the most limiting transmission phenomena are the accumulation of the amplified spontaneous emission (ASE) noise introduced by amplifiers and the nonlinear interference disturbance (NLI) generated by the fiber propagation. NLI generation does not present apparent bandwidth limitation and grows log-like with the bandwidth extension [11,12]. Among several models for prediction of NLI intensity, the GN-model, and in particular its analytic approximation (Eq. 41 in [5]), has extensively demonstrated its accuracy, also in multi-vendor commercial systems [13]. In this numerical analysis, the transmission on the O- to L-band with different WDM grids, starting from 50 GHz to 200 GHz, is analyzed. For the O-band, the no transmission (NoTx) band around the zero-dispersion wavelength is varied from 0 to 80 nm in order to evaluate the optimal trade-off between NLI generation and available bandwidth. Several approximations are done to provide a general assessment on the capacity improvement enabled by MB transmission: i) The wideband effects of NLI generation are neglected by assuming the absence of crosstalk between different optical bands. This assumption may be justified by the guard band introduced to separate the optical bands; ii) The SRS effect is not considered (this will be a topic of future research); iii) Within the GN model, the maximum value of α and the minimum of D for loss and chromatic dispersion, respectively, are assumed for each band. This approximation leads to a conservative assessment of performance; iv) In the case of transmission with waterpeak fiber (ITU-T G.652A), the transmission in the waterpeak region is not allowed, which corresponds to neglecting the spectrum between 1360 and 1420 nm. These approximations enable applying the local optimization for a global optimization (LOGO) approach separately on each band to estimate the



(a) (b)

Fig. 3: Estimated capacity versus channel grid spacing: (a) legacy fibre w/ waterpeak absorption (typically ITU-T G.652A); (b) ITU-T G.652D fibre w/o waterpeak absorption.

optimal power per channel per band [6]. Then, the GN-model (Eq. 41 in [5]) is computed to derive the generalized SNR and the consequent transmission capacity. The results reporting the estimated maximum transmission capacity are shown in Fig. 3, where the maximum capacity attainable in each band is identified by a different color. While SSMF with waterpeak presents a still limited capacity extension, only supporting up to $\sim$160 Tb/s over a 50 GHz grid, the SSMF without waterpeak (ITU-T G.652D) would add further $>$110 Tb/s of capacity. Fortunately, most of the currently deployed optical fiber, particularly in Europe, is of type ITU-T G.652D. Such value could lead to a capacity per node well above a Pb/s. For instance, assuming 12$\times$ITU-T G.652D fibers per node, this would lead to a capacity of 3.3 Pb/s per node. A comparison with the maximum capacity per node achievable using C-band only transmission ($\sim$300 Tb/s in the same conditions), shows the potential of MB transmission. As only transponders operating at 32 GBd are considered in this work, the most interesting channel spacing is 50 GHz. However, transponders operating at 64 GBd and above would make the 100 GHz grid an also interesting transmission solution, enabling to approximately halve the number of required interfaces for similar total capacity.

5. Conclusions

A first analysis on the achievable capacity when considering MB transmission using currently deployed optical fiber infrastructure is presented. We evaluate the cases with legacy SSMF (with waterpeak) and with newer ITU-T G.652D fibers (without waterpeak). The lighting up of the new optical bands has the potential to increase the total capacity by a factor 6$\times$ and 11$\times$ for the cases with and without waterpeak, respectively. This analysis shows that MB upgrades can significantly extend the lifetime of existing network infrastructures, avoiding heavy investments in deploying new fibers. Moreover, the pay-as-you-grow approach of MB transmission enables to further postpone investments by additing up new transmission bands only when needed.

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