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# FDM and DMT performance comparison in high capacity point-to-point fibre links for intra/inter-datacentre connections

A. Gatto, P. Parolari*, P. Boffi*

*Politecnico di Milano, Dipartimento Elettronica Informazione e Bioingegneria, P.zza Leonardo da Vinci 32, 20133 Milano, Italy*

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ABSTRACT

Frequency division multiplexing (FDM) is attractive to achieve high capacities in multiple access networks characterized by direct modulation and direct detection. In this paper we take into account point-to-point intra- and inter-datacenter connections to understand the performance of FDM operation compared with the ones achievable with standard multiple carrier modulation approach based on discrete multitone (DMT). DMT and FDM allow to match the non-uniform and bandwidth-limited response of the system under test, associated with the employment of low-cost directly-modulated sources, such as VCSELs with high-frequency chirp, and with fibre-propagation in presence of chromatic dispersion. While for very short distances typical of intra-datacentre communications, the huge number of DMT subcarriers permits to increase the transported capacity with respect to the FDM employment, in case of few tens-km reaches typical of inter-datacentre connections, the capabilities of FDM are more evident, providing system performance similar to the case of DMT application.

## 1. Introduction

Nowadays, cost-effective, energy-efficient and reduced-complexity optical solutions are being sought for applications such as short/medium reach fibre links (e.g. intra- and inter-datacentres connections, respectively), where higher and higher transported capacity transmission is required in order to face the huge increasing data traffic. In these network contests, the exploitation of a standard approach based on single optical carrier modulation, widely used for long-haul transmission, appears not so effective, since it is very sensitive to the signal-to-noise ratio (SNR) and to the bandwidth of the devices and components employed in the network [1]. Besides the choice to use a superchannel approach provided only a limited improvement in hardware density and power efficiency [1].

In order to be able to exploit cost-effective solutions from the point of view of optical transmitters/receivers, the exploitation of the multicarrier approach combined with direct modulation (DM) of the optical source seems very promising to guarantee high-bit rate transmissions. Orthogonal frequency division multiplexing (OFDM) [2,3], discrete multitone (DMT) modulation [4] and frequency division multiplexing (FDM) [5] are the most eligible candidates as they exploit narrower modulation bandwidths with respect to multiple pulse-amplitude modulation (M-PAM) and on-off keying (OOK) modulation, avoiding chromatic dispersion compensation, wide-band drivers and photo-receiver circuits. DMT and OFDM assure the highest spectral efficiency by means of the partial subcarrier overlapping; moreover, both OFDM and DMT modulation formats allow the exploitation of bit and power loading, which can minimize the penalty due to signal-to-signal beating interference (SSBI), sometimes referred to the intermodulation distortion introduced by direct detection (DD) [6]. DMT is particularly used for very high-bit rate transmission (also targeting single-wavelength 100 Gb/s) in data communications, supported by multimode fibre links and low-cost vertical-cavity surface-emitting laser (VCSEL) sources [7,8]. However, they show the disadvantage of very high peak-to-average power ratio (PAPR) due to the coherent superposition of many subcarriers in the time domain, inducing significant signal distortion in case of nonlinear response of the system components employed in the network and of nonlinear fibre impairments [9]. In the last decades, different approaches have been proposed to deal with the PAPR issue, such as signal amplitude clipping or signal coding, but these techniques achieve PAPR reduction at the expense of transmit signal power increase, signal distortion, bit error rate (BER) increase, data rate loss and computational complexity increase [10].

On the other hand, FDM [11] is a multicarrier alternative modulation interesting for its intrinsic flexibility: the allocation, modulation format and baud rate of each subcarrier can be adapted to the system characteristics, including the non-linear and bandwidth-limited behaviour of the employed devices, the channel crosstalk and/or the application requirements. A suitable FDM signal spectrum design can be provided to shrink the bandwidth and relax the electrical bandwidth

* Corresponding author.
*E-mail addresses:* alberto.gatto@polimi.it (A. Gatto), paola.parolari@polimi.it (P. Parolari), pierpaolo.boffi@polimi.it (P. Boffi).

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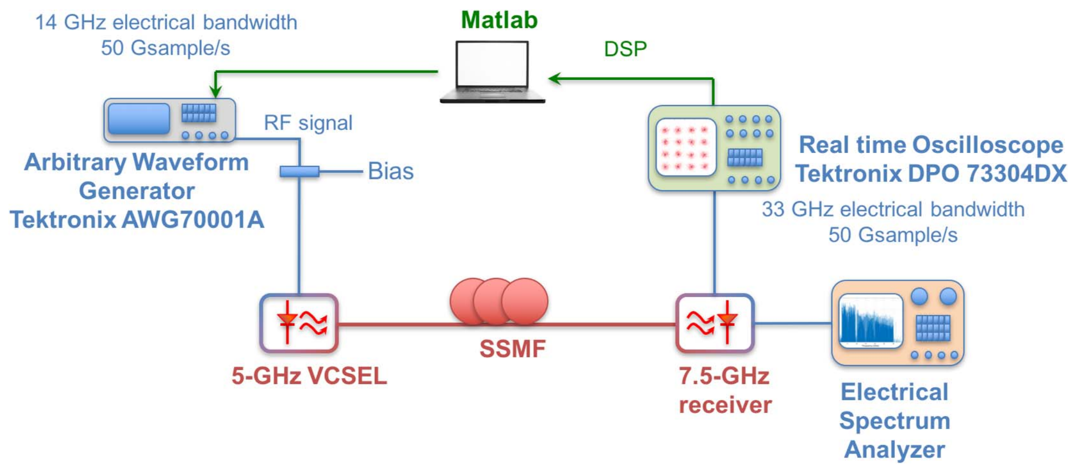


**Fig. 1.** Experimental set up.

requirements both of the transmitter (e.g. the laser driver) and of the receiver. In case of DD, to reduce the penalties due to the signal-to-signal beating interference, an optimized spectral allocation of the subcarriers with a tailored spectral guard-band can be implemented. However, for multiple access applications, FDM appears particularly interesting because it does not require complex synchronization among the simultaneous access units and the whole FDM signal can be constituted combining one subcarrier or a subset of subcarriers per each individual user in an independent way. Compared with OFDM and DMT, FDM modulation exploits just a limited number of subcarriers, relaxing the complexity of the transmission system and nonlinear signal distortions due to a reduced PAPR; moreover, it permits the exploitation of non-uniform subcarriers in terms of spectral widths, modulation formats and signal shaping, leading to an intrinsic flexibility. However, in order to achieve the same high spectral efficiency of OFDM/DMT modulation without subcarrier overlapping, a suitable subcarrier spectrum shaping (as Nyquist shaping with null roll-off factor) is required. Furthermore, in case of FDM modulation the exploitation of bit- and power-loading-like techniques is not so straightforward as in OFDM/DMT-based transmitters. With respect to single carrier systems, both OFDM/DMT and FDM modulations suffer from an intrinsic drawback. Since the former exploits a sinc-like subcarrier spectrum to achieve channel orthogonality while the latter employs filters at transmitters/receivers to create a rectangular spectral profile, there is a long oscillating tail in the frequency or time domain, respectively, resulting in disadvantages such as vulnerability to intercarrier interference (ICI) in OFDM/DMT-based systems or a long memory length for pulse shaping in FDM-based transmission [12].

While OFDM and DMT are widely discussed in literature, FDM modulation has been mainly considered for point-to-multipoint multiple access contests and, therefore, it deserves to be analysed and discussed in case of point-to-point applications. In particular, it is interesting to better understand if in these network applications FDM exploitation can achieve operation performance close to the DMT one. In this paper, we considered a data communications scenario, based on a short-reach point-to-point optical connection, where the reduced complexity of the employed optical solutions is mandatory and where the exploitation of multicarrier modulation appears very promising. A point-to-point data interconnection, characterized by DM at the transmitter side and DD at the receiver was studied with propagation over uncompensated single-mode fibre (SMF) reaches covering a few hundreds of meters, such as in case of intra-datacentre communications, or up to tens of kms, for inter-datacentre networks. In this contest, we compared the performance achieved by DMT and FDM targeting the maximum transported capacity by facing the limited bandwidth of the optical directly modulated VCSEL and of the receiver and the non-uniform frequency response of the whole system. The DMT and FDM performance in terms of capacity is shown in case of 100-m, 10-km and 20-km SMF propagation, discussing the pros and cons of the two multicarrier modulation solutions.

## 2. Bandwidth-limited system set up for high-capacity data interconnections

In our analysis, we designed a data communication system based on DM and DD, taking into account its mandatory requirements in terms of sensitivity to the cost, footprint and power consumption, also when its reach target is about few tens of kms with very high transmitted capacity, such as for example in case of inter-datacentre connections. With respect to the exploitation of single-carrier OOK or M-PAM, multicarrier modulations have been exploited to achieve high capacity in a reduced signal bandwidth, also in presence of a limited and non-uniform system transfer function, owing to the employment of low-cost devices, such as directly-modulated sources characterized by frequency chirp and to propagation over uncompensated links without any kind of chromatic dispersion (CD) compensation.

The experimental set up was based on the employment as laser sources of low-cost directly-modulated bandwidth-limited VCSELs, as usually utilized in data communications links. In particular, targeting propagation reaches up to few tens of kms a long-wavelength VCSEL [13] has to be used. Owing to DM, the VCSEL emission is naturally affected by frequency chirp; moreover, DM generates a double-sideband signal spectrum. In presence of DD, the frequency chirp, combined with the cumulated chromatic dispersion and the double-sideband spectrum, impacts on the frequency response of the system, inducing frequency dips whose position depends on the propagation distance over the uncompensated SMF, moving towards lower frequencies for higher dispersion. This non-uniform limited-frequency response of the system was suitably matched in our experimentation by a proper loading of the signal subcarriers achieved automatically (i.e. by Chow's bit- and power-loading algorithm [6]) for DMT modulation or manually in case of FDM exploitation.

In Fig. 1 the experimental set up, employed for the performance evaluation of both FDM and DMT systems, is shown. The low-cost 1580-nm single-mode VCSEL [14] employed in our experimentation showed a 8-MHz linewidth and 3-dB bandwidth of 5 GHz, with a frequency chirp with linewidth enhancement factor $\alpha \approx 5.5$ and an adiabatic component of about 1 GHz/mA, correspondent to a laser-specific adiabatic constant $\kappa \approx 10^{13}$ (with 0.5-mW emitted output power). The FDM/DMT signal is calculated by Matlab® and the RF signal is generated by a Tektronix 50-GS/s arbitrary-waveform-generator with 14-GHz electrical bandwidth, which drives the VCSEL current via a bias-Tee, that also combines a 9.5-mA DC current to bias the device. The directly modulated signal is transmitted over different lengths (100 m,