Practical Consideration of Discrete Multi-Tone Transmission for Cost-Effective Access Networks

Radan Slavík, Zhixin Liu, and David J. Richardson(1)

(1) Optoelectronics Research Centre, University of Southampton, Southampton, U.K.
r.slavik@soton.ac.uk

Abstract: We review our recent work dealing with directly-modulated directly-detected transmission. In a repeater-less transmission through standard fibre, capacity of 35 Gbit/s and 22 Gbit/s is achieved for transmission distances of 50 and 125 km, respectively.

Introduction

The Discrete Multi-Tone (DMT) signal format is becoming increasingly attractive for short distance optical communications applications, such as inter-data centre interconnection and within optical access networks, due to its high spectral efficiency and capability of adapting to impairments (e.g. high-frequency roll-off in modulation response and fibre chromatic dispersion-induced frequency-dependent signal fading)[1]. Enabled by novel laser technologies and powerful digital signal processing (DSP), direct-modulation direct-detection (DM-DD) systems using the DMT format offer unprecedented capacities with minimum optical hardware[1,2] and it is consequently being actively developed by many vendors[1,3]. Despite the huge advantages of DMT it still requires a digital-to-analogue convertor (DAC), analogue-to-digital convertor (ADC), and DSP, which add cost and power consumption compared to systems based on simple formats such as OOK and PAM[4]. To make DMT competitive, the components' cost (related to their performance) and power consumption need to be minimized.

In the presentation, we will review our recent work in this filed. First, we will discuss electronic bandwidth required for low-loss (at 1550 nm) DM-DD DMT transmission over up to 150 km of dispersion-uncompensated SMF-28. We will show that due to dispersion-induced frequency fading, using a DAC with an RF bandwidth of more than 8 GHz (for 50 km) and more than 5 GHz (for 125 km) does not bring any significant benefit. Further, we will present the effect of digital pre-emphasis and show that its implementation brings negligible (~5%) improvement in capacity. Finally, we will show the impact of other parameters that affect system cost (by increasing complexity and power consumption), including DAC resolution and DAC sampling rate.

Experimental Setup

Fig. 1 shows the system we envisage – it uses a minimum of optical components: a directly modulated laser that might be integrated with a semiconductor optical amplifier (SOA) that can accommodate the modulation bandwidth used at the Tx (e.g., 2.5-8 GHz, as we discuss later) and an avalanche photodiode (APD) with a trans-impedance amplifier (TIA) at the Rx that can detect low-level signals (e.g., BER<10^{-12} at an input power of -26 dBm for 10 Gb/s OOK systems) to allow for long repeater-less transmission.

In our experiments, we aimed to characterize the system performance up to a bandwidth as high as possible and thus replaced some of the set-up components that we did not have available for those high bandwidths. Specifically, it was the SOA and APD that we replaced as follows. Instead of the Tx-integrated SOA (Fig. 1) we used an EDFA to boost the output power to 16 dBm. At the Rx side, instead of using an APD with a TIA, we used an EDFA with a bandpass filter followed by a standard photodiode operated in the photoconductive regime without any TIA at its output (it was coupled to 50 Ohms and amplified

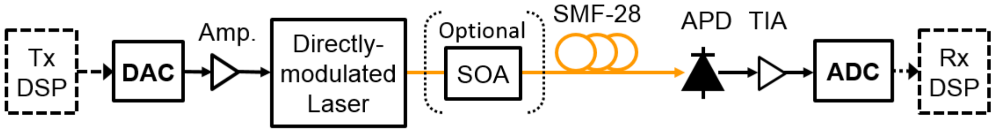

Fig. 1: Our envisaged system architecture: repeater-less, and filter-less transmission through SMF-28. DAC/ADC: Digital-to-analogue and analogue-to-digital converters; SOA: Semiconductor optical amplifier, DSP: Digital signal processing, APD: Avalanche photodiode; TIA: Transimpedance amplifier.

via a 23-dB gain voltage amplifier).

The DMT waveform samples were generated offline based on a PRBS of 2^{18}-1 length. An Inverse Discrete Fourier Transform (IDFT) size of 1024 was used for generating the DMT signal. The modulation format for each sub-carrier was assigned by the bit loading algorithm. A 1.6% cyclic prefix was placed both before and after each symbol. A clipping ratio of 10 dB was used.

DMT signals of different bandwidths were generated and digitally up-converted to create real-valued DMT samples. Two waveform generators (AWG) were used to generate electrical DMT signals: (1) a 10-bit (nominal) operating at 12/24 GS/s, 9.6 GHz bandwidth, and (2) 6-bit (nominal) operating at 34 GS/s with bandwidth of 17 GHz. The impact of the DAC resolution was studied by quantizing the DMT samples to a limited number of levels in the transmitter-side DSP software.

We used two directly modulated lasers. The first one was a 1549-nm pigtailed passive-feedback laser (PFL)[6] with 3-dB modulation bandwidth close to 30 GHz (drive signal of 2.5 V peak-to-peak). The other one was discrete mode laser (DML)[7] that is simple (fabrication process simpler than for DFB lasers) and thus also low-cost. Another advantage of this laser – as compared, e.g., to a DFB, is the smaller modulation chirp[8]. The DML was driven with 2.2 V peak-to-peak. Its package-limited 3-dB bandwidth was 8.6 GHz. The received signal was sampled by an 8-bit ADC at 50/80 GS/s and demodulated using offline DSP.

Bit loading was calculated using a QPSK-DMT probe with identical power on all sub-carriers. The bit loading for each subcarrier was coarsely determined by measuring the probe signal-to-noise ratio and fine adjustment was made using dynamic bit adaptation. Our modified bit-loading algorithm based on reference 9 maximized the total capacity at a BER target of 3.8×10^{-3}. The BER was calculated using error counting of the demodulated signal.

Transmission results

Different lengths of SMF-28 up to 150 km were used to study the performance of the repeater-less transmission, Fig. 2. The black diamonds show our result[5] employing 34-GS/s AWG. However, after 50 km, due to the dispersion-induced spectral fading (that influences mainly the high-frequency components), capacity obtained with much smaller bandwidth (8 GHz) was almost the same (worse by 5%) as compared to 17 GHz. Thus, lower-bandwidth AWG (9.6 GHz) only was used for investigating larger transmission distance performance[10]. Further, we found that DML outperforms PFL slightly at larger distances, which we attribute to smaller modulation chirp of the DML[10]. Thus, we show here (Fig. 2) only results with DML, using AWG bandwidth (limited in software) 2.5 (green-triangle), 5 (red-circle), and 8 (blue-square) GHz, respectively[10].

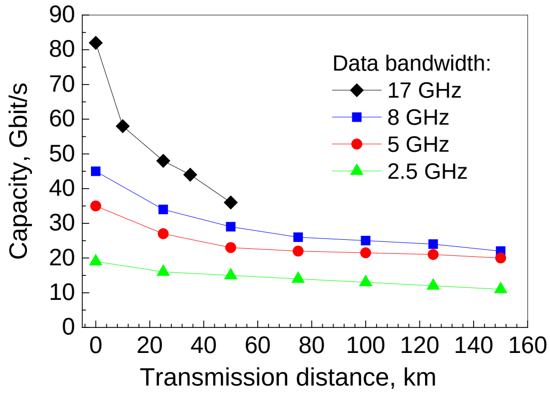

Fig. 2: Achieved capacity after transmission.

The key result is that even after 125 km of dispersive propagation, a capacity of 22 Gb/s was achieved with a signal bandwidth as small as 8 GHz (for the DML)[10]. This is a factor of 2 more than for competing technologies that use a more complex transmitter architecture, e.g., a chirp-managed laser that reaches 10 Gb/s (and this number is not improved if a smaller distance is to be covered)[10].

Summary

DM-DD repeater-less transmission in the low-loss 1550-nm window was studied with particular emphasis on the electronics components and computation power requirements[5,10]. The capacity benefit when using larger bandwidth RF signals in the transmitter is found to diminish as the transmission distance increase. For example, only 8 GHz bandwidth is needed for 50-km transmission through standard single-mode fibre. The effect of digital pre-emphasis is negligible (<5% in terms of capacity). At 125-km, 22 Gb/s repeater-less transmission is shown using a simple-structure low-cost semiconductor laser using an 8 GHz bandwidth signal. We also studied the impact of DAC resolution, signal bandwidth, and sampling rate, suggesting that a 6-bit DAC and a sampling rate of x1.5 the Nyquist rate are sufficient. Our results provide a general reference for practical considerations of the trade-offs between system performance and component parameters for previously-unexplored large-distance (>50 km) low-loss DMT DM-DD transmission.

Acknowledgements

This research has received funding from EPSRC Fellowship Grant Agreement No. EP/K003038/1 and EPSRC grant EP/I061196X (Photonic Hyperhighway).

References

[1] T. Tanaka, et. al., " Experimental investigation of 100-Gbps transmission over 80-km single mode fiber using discrete multi-tone modulation," Proc. SPIE 8646, doi:10.1117/12.2003735.

[2] L. Anet-Neto, et al., "Beyond 25 Gbit/s Directly Modulated, Directly Detected OFDM Using Channel Flattening by a Fabry-Perot Filter," Proc. OFC, M3J.5, Los Angeles (2015).

[3] Chongjing Xie et al., "Single-VCSEL 100-Gb/s Short-Reach System Using Discrete Multi-Tone Modulation and Direct Detection," Proc. OFC, Tu2H.2, Los Angeles (2015).

[4] L. Frejstrup Suhr, et al., "Direct modulation of 56 Gbps duobinary-4-PAM," Proc. OFC, Th1E.7, Los Angeles (2015).

[5] Z. Liu, et al., "Practical Considerations on Discrete Multi-tone Transmission for Cost-effective Access Networks," Proc. OFC, M3J.4, Los Angeles (2015).

[6] J. Kreissl, et al., "Up to 40-Gb/s Directly Modulated Laser Operating at Low Driving Current: Buried-Heterostructure Passive Feedback Laser (BH-PFL)," IEEE Photon. Tech. Lett., Vol. **24**, no. 5, p. 362 (2012).

[7] J. O'Carroll, et al., "Wide temperature range 0 < T < 85 °C narrow linewidth discrete mode laser diodes for coherent communications applications," Opt. Exp., Vol. **19**, no. 26, p. B90 (2011).

[8] P. M. Anandarajah, et al., "Generation of Coherent Multicarrier Signals by Gain Switching of Discrete Mode Lasers," IEEE Photon. J., vol. 3, no. 1, pp. 112 (2011).

[9] P. Chow, et al., "A Practical Discrete Multitone Transceiver Loading Algorithm for Data Transmission over Spectrally Shaped Channels," IEEE Trans. Commun., Vol. **43**, no. 2/3/4, p.773 (1995).

[10] Z. Liu, B. Kelly, J. O'Carroll, D. Richardson, and R. Slavík, "Direct-Modulation Direct Detection Discrete Multi-Tone for up to 150 km Transmission," *submitted to* ECOC 2015, Valencia, Spain (2015)