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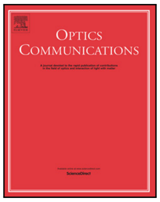

Invited paper

Digital pre-compensation techniques enabling high-capacity bandwidth variable transponders

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ABSTRACT

Digital pre-compensation techniques are among the enablers for cost-efficient high-capacity transponders. In this paper we describe various methods to mitigate the impairments introduced by state-of-the-art components within modern optical transceivers. Numerical and experimental results validate their performance and benefits.

1. Introduction

Over the last decade, we experienced a constant increase in bandwidth demand, which is now stabilizing around ~30% [1]. Fueled by the never-ending innovation of web-based services and fed by a continuously improved technology, optical communication infrastructures are being pushed to their physical limits. There exist numerous bandwidth hungry applications, that exploit highly geo-localized multi-media contents and services, leading to an enormous amount of data to be transported, over metro and core networks. In addition, the imminent deployment of 5G-networks and Internet of Everything, together with services such as 4k/8k HDTV, will define even more stringent requirements for the underlying optical networks. At the moment, operators and system vendors are seeking for alternatives to cope with these challenges and to simultaneously maximize their investments by evaluating solutions that allow to replace or install the minimum number of network elements. Among them, the elastic optical networks (EON) [2] paradigm is attractive, because it optimizes, and efficiently utilizes, existing optical infrastructures by replacing only the nodes and transponders, i.e., by means of bandwidth variable transponders (BVTs) [3,4]. A BVT can dynamically adapt the symbol rate and modulation format to the instantaneous needs, such as, for example, link and network requirements. This adaptability comes at the cost of a penalty due to the unavailability of opto-electronic components with sufficient performance. For example, when varying the symbol rate, we require devices with a significantly wide bandwidth. Similarly, when we increase the modulation formats order, we need highly linear devices so that the more complex constellations are not distorted.

Recently, the application of digital pre-compensation (DPC), to various modules within the transmitter, has been proposed in optics. DPC techniques are fundamental for optical transceivers because they (I) reduce the penalty introduced by the components, present already in optical back-to-back (ob2b); (II) relax the specifications of the

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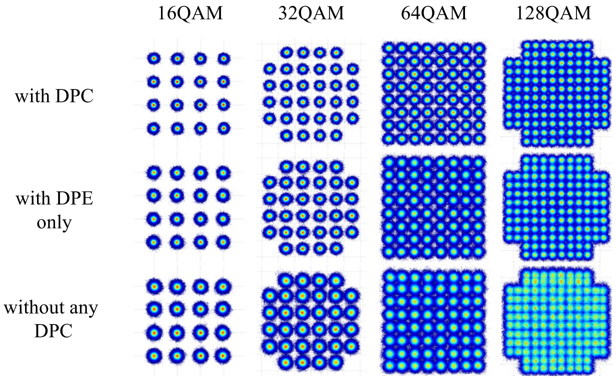

Fig. 1. Exemplary of measured high-order modulation format constellations at the receiver when applying different DPC techniques. From left to right: dual polarization (DP)–16 quadrature amplitude modulation (QAM), DP-32QAM, DP-64QAM, and DP-128QAM.
Source: Figure reproduced from [23].

transmitter main modules, thus lowering the overall costs; (III) enable the transmission of high-order modulation formats, thus increasing the spectral efficiency; (IV) allow transmitting different and higher symbol rates, which let employing different forward error correction overhead (FEC-OHs), so that transmission can be adapted to the parameters of the current link [5–7]. Last, DPC paves the way for high data-rate single-carrier transmission that simplifies the transponder design and reduces the engineering costs [8].

DPC is applied at the transmitter and/or receiver as part of the digital signal processing (DSP) unit. Numerous methods have been reported with different level of complexity and performance. In [9–15] have been proposed solutions to mitigate, through feed-forward digital pre-emphasis (DPE),[2] the penalty caused by limited electrical bandwidth at the transmitter. Other DPC techniques reduce the impact of the in-phase and quadrature modulator (IQM) nonlinear characteristic by applying, for example, an arcsin function [16–18] or by implementing more complex and better performing methods such as the minimum mean-square based approach reported in [19,20]. In [22–24] comprehensive works that aim at compensating for the entire transponder, including IQ imbalance, have been presented. Fig. 1 graphically displays the improvement provided by DPC techniques when applied to different constellation size. The first row is with DPC, the second with DPE only, and the last without any DPC.

This article is structured as follows: Section 2 presents the general setup and motivates the work by describing the main impairments affecting a modern transponder. Sections 3–5 present different DPC techniques varying from linear DPE in Section 3 to full DPC of the complete transceiver in Section 5. Section 6 presents a comprehensive series of results ranging from numerical simulations to field trial experimental validation of the aforementioned methods. Section 7 draws with the conclusions.

2. System setup and main component limitations

2.1. Generic system setup

Fig. 2 illustrates the generic setup considered in this paper. The input signal $s(f)$ is filtered by a root-raised-cosine (RRC) filter $\sqrt{N(f)}$. We consider roll-off $\beta \in [0.1, 0.3]$. The DPC (in blue) precedes the blocks to be mitigated (in green) and it consists of two modules: (I) the DPD and/or DPE and (II) the cost-function calculation (CFC). The DPE applies a linear filter, while the digital pre-distortion (DPD) nonlinearly pre-distorts $z(f)$ (output of the RRC filter). Within the result Section 6, we will compare the case without any DPC, with only DPE, and with DPC. The CFC estimates the parameters necessary (e.g., the error) for varying the DPD and /or DPE in case of adaptive modules. The feedback signal to CFC can be taken at different stages of the transceiver. For example at the output of an analog-to-digital converter (ADC) or of a look-up table (LUT) as illustrated in Fig. 2. The main limiting components (the digital-to-analog converter (DAC), the driver amplifier (DA) and the IQM) follow the DPC. The channel is modeled by the transfer function $H(f)$ or as ob2b, i.e. $H(f) = 1$. At the receiver, the additive white Gaussian noise $n_{\text{load}}(f)$ performs the noise loading. The ADC presents similar characteristics to the DAC, and it is followed by a matched filter $\sqrt{N(f)}$. Finally, the DSP employs the algorithms described in [25] and the bit error rate (BER) is evaluated by Monte Carlo error counting.

2.2. Main component limitations

Electrical bandwidth limitations. The key-components at the transmitter are all limited in electrical bandwidth, commonly provided at −3dB (BW_{-3dB}). Their equivalent bandwidth is measured through the $\text{S}_{21}(f)$ and an exemplary is displayed in Fig. 3(**left**). In this example, we considered off-of-the-shelf devices, and we measured an equivalent $\text{BW}_{-3dB} < 10$ GHz and with $\text{BW}_{-6\text{ dB}} \sim 15$ GHz. Commercial BVTs already employ symbol rates ≥ 30 GBd and next generation BVTs will support up to 64 GBd. In this scenario the DPE of the bandwidth limitation, together with more high performing components, is a must to guarantee robust transmission.

DAC resolution. Besides the bandwidth limitation, DACs are also affected by low resolution. Devices currently on the market provide 8 nominal bits, which are reduced, due to sampling and jitter effects, to < 6 effective number of bits (ENOB), even at low frequency. The ENOB can be derived from the measurements of the signal-to-noise and distortion ratio (SNDR). A typical value for SNDR, at 0 Hz, is ∼ 35 dB. This parameter can be converted into ENOB (over the same frequency range) by applying Eq. (1) from [27]

$$\text{ENOB} = \frac{\text{SNDR} - 1.76}{6.02}. \tag{1}$$

Both SNDR and ENOB depend on the frequency [28]. A typical measured curve for ENOB versus frequency is displayed in Fig. 3(**right**).

Nonlinear behavior of driver amplifiers. DAs are characterized by a nonlinear response. Fig. 4 reports an exemplary of measured characteristic function of a DA as output versus input voltage. At low level input signals (< 0.2 V_{rms} for this example), the real measured DA (blue curve) operates in the linear region following the ideal DA (red curve). However, at higher input signals, we observe a nonlinear behavior in the amplifier performance, which leads to distorted outputs. The degradation can be quantified through the measurement of the amplifier gain (green curve). Clearly, the gain diminishes, when the DA operates in the nonlinear region. Other effects such as harmonic and intermodulation distortions also contribute to the DA nonlinear behavior. Besides nonlinearity, DAs are affected by memory effects, i.e. the DA output depends not only on the present value of the input, but also previous values [29].

Nonlinear behavior of an IQM. Optical IQMs present an intrinsic nonlinear sinusoidal characteristic, as displayed in Fig. 5. As it can be done for the DA, also the IQM can be operated within the linear region (red line in Fig. 5). Clearly, the smaller the operating region, the lower the output power. This condition becomes significantly severe in case of high order modulation formats, where the short Euclidean distance restricts the modulation to an even narrower linear region, which leads to a considerably low output optical power, that then requires the use of an additional optical amplifier.

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[2] Note: we indicate with DPE the linear DPC; with digital pre-distortion (DPD) the nonlinear DPC; and with DPC the joint usage of DPE and DPD.

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