40-Gb/s Field Experiment over an 820-km Transmission Link Designed for 10 Gb/s, Using the APRZ Modulation Format

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Abstract

We present a 40-Gb/s transmission experiment on an installed link designed for DWDM transmission at 10 Gb/s, using the APRZ modulation format. The experiment confirms the superior non-linear tolerance of APRZ, even with typical DWDM filtering.

Introduction: Adding 40-Gb/s channels to existing 10-Gb/s dispersion-managed (DM) WDM systems is a cost-effective means to upgrade capacity, but poses challenges in terms of non-linear impairments [1], specifically, intra-channel cross-phase modulation (IXPM), causing timing jitter, and intra-channel four-wave mixing (IFWM), causing ghost pulses and amplitude jitter. IXPM can be
reduced by proper dispersion pre-compensation, while IFWM can be reduced with phase-modulation techniques [2–4]. One such technique is the alternate-phase return-to-zero (APRZ) modulation format [4], in which the optical phase between neighbouring bits differs by a value $\Delta \phi$. APRZ’s non-linear tolerance has been studied theoretically, numerically, and experimentally [4–8]. In this paper we present the first experiment in which APRZ transmission at 40 Gb/s is demonstrated on an installed DWDM system designed for transmission at 10 Gb/s.

Field experiment setup: The APRZ transmitter, depicted in Fig. 1(a), is implemented as a pulse generator (an actively mode-locked ring laser) producing 2.7-ps pulses, followed by a MZM for data modulation and by a phase modulator driven by a 20-GHz sinusoidal signal. The resulting sine-APRZ [6] is shown in Fig. 1(b). The data signal is a PRBS of length $2^{31} - 1$, obtained by time multiplexing four 10-Gb/s PRBS sequences of length $2^{31} - 1$, properly delayed. The amplitude, $\Delta \phi$, and delay, $\Delta \tau$, of the phase modulation is controlled by means of a variable attenuator and a tunable delay line. The experiment is run in two steps. In a first step the signal from the APRZ transmitter is launched directly into the transmission link. In a second phase, a wavelength multiplexer (MUX) is placed between the transmitter and the link. The MUX acts as a Gaussian filter of order 1.5, with 3-dB pass band of 75 GHz, as shown in Fig. 1(c). The experiment is run over an installed six-span link between the cities of Stockholm and Hudiksvall, in Sweden. The link, depicted in Fig. 2, being designed to oper-
ate at 10 Gb/s, is dispersion under-compensated, specifically by 800 ps/nm per way. In order to operate at 40 Gb/s, additional dispersion-compensating fibre (DCF) is placed at the transmitter (pre-compensation) and at the receiver (post-compensation). Moreover, total dispersion is fine tuned (per-channel compensation) by a fibre-Bragg-grating-based tunable dispersion compensation (TDC) unit at the receiver, with a 3-dB pass band of 150 GHz. At the receiver side, in the second step of the experiment, the signal is passed through the wavelength de-multiplexer (DEMUX). This acts as a 4th-order Bessel filter with 3-dB pass band of 50 GHz. (The DEMUX is removed for the first step of the experiment.) The signal is then attenuated to a power level $P_r$, pre-amplified, filtered (and dispersion compensated) by the TDC, detected, and electrically de-multiplexed. Receiver sensitivity is measured as the minimum $P_r$ in order to achieve an average BER $= 10^{-5}$ for the four channels, which would allow error-free recovery with standard forward error correction, e.g. RS(255,239). The transmission performance is evaluated in terms of power penalty, i.e. degradation in receiver sensitivity with respect to back to back ($-33$ dBm). When measuring back-to-back sensitivity, the TDC is replaced with a Fabry-Perot filter with 142-GHz 3-dB bandwidth.

The transmission system is also modelled numerically ($VPI$ $Transmission$-$Maker$): a train of Gaussian pulses is phase-modulated by a sine wave, and data-modulated by a 1024-bit de Bruijn binary sequence (DBBS). The SSMF in the link has dispersion $D = 16.5$ ps/nm/km, dispersion slope $S = 0.06$ ps/nm$^2$/km, non-linearity index $\gamma = 2.1$ W$^{-1}$/km, and loss $\alpha = 0.25$ dB/km. The DCF
has $D = -82.5 \text{ ps/nm/km}$, $S = -0.18 \text{ ps/nm}^2/\text{km}$, $\gamma = 4.3 \text{ W}^{-1}/\text{km}$, and $\alpha = 0.7 \text{ dB/km}$. The BER is evaluated assuming Gaussian noise in the receiver.

**Numerical simulations:** In order to find the optimum pre-compensation, the system is studied numerically. Fig. 3(a) shows power penalty versus pre-compensation, for RZ, and for APRZ with $\Delta \phi = \pi/2$, for transmission with and without MUX-DEMUX. The optimum is found at 1280 ps/nm, for both modulation formats (RZ and APRZ), both with and without MUX-DEMUX. The value $\Delta \phi = \pi/2$ was chosen because it was found to be optimum in similar systems [5–8]. Indeed simulations run for transmission over the present link, with 1280 ps/nm pre-compensation, confirm that $\Delta \phi = \pi/2$ is optimum here too, see Fig. 3(b).

With these values of pre-compensation and phase-alternation amplitude, RZ and APRZ are compared with respect to non-linear tolerance. The results, presented in Fig. 3(c), show that APRZ attains a considerable improvement ($> 5$ dB) in non-linear tolerance over RZ, both with and without MUX-DEMUX.

**Field Experiment:** Having fixed the pre-compensation to 1280 ps/nm, the non-linear tolerance of RZ and $\pi/2$-APRZ is studied experimentally. Initially, the transmission with no MUX-DEMUX filtering is studied. The launch power into the SSMF is gradually increased from 2 dBm up to 12 dBm (the power into the DCF is kept 5 dB lower throughout the experiment). The results are shown in Fig. 4(a). At launch-power levels below 6 dBm no significant change in sensi-
tivity was observed when applying phase modulation, and only RZ penalty is plotted. Here, the system is ASE-noise-limited and performance improves with increasing launch power. For higher power levels, however, non-linear effects start to become important and the performance enhancement of APRZ over RZ becomes visible. While RZ transmission is dominated by non-linear effects and performance degrades with increasing launch power, APRZ’s performance remains substantially constant over the launch-power range between 6 dBm and 12 dBm, which was the power limit for the in-line amplifiers. This suggests that both ASE noise from in-line amplifiers and non-linear effects are small over this range. These results are in good agreement with the numerical results shown in Fig. 3(c). In the experiment, however, a launch-power-independent 3.5 dB "background" penalty is observed. Potential causes of this may be third-order dispersion (TOD), polarisation mode dispersion (PMD), and group-delay ripple (GDR) in the TDC. In the numerical simulations TOD was modelled, but not PMD, nor GDR, and the background penalty was less than 1 dB.

Next, transmission on the complete system is considered. The signal is now passed through the MUX at the transmitter and through the DEMUX at the receiver (see Fig. 2). The results, shown in Fig. 4(b), were collected for few launch-power values, due to time constraints, but they are in good agreement with the simulation results of Fig. 3(c). The MUX placed at the transmitter acts as a narrow-band filter, broadening the pulses to approximately 8 ps. Long pulses are less tolerant to non-linear impairments [9] and indeed non-linear effects are now dominating RZ transmission already at 3 dBm launch
power, and make transmission not viable at 5 dBm (BER $> 10^{-5}$ for any received power). Applying phase modulation reduces the impact of non-linear effects significantly, and an increased error-free power range is obtained. This increased power tolerance (at least 5 dBm) can be translated into transmission over longer distances.

**Conclusion:** We report the first 40-Gb/s APRZ transmission experiment over an installed DWDM link designed for 10 Gb/s, over a distance of 820 km. The experiment confirms the significant non-linear tolerance of APRZ, even with MUX-DEMUX filtering.

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References


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Figure captions:

Fig. 1 — Experiment set-up

(a) 40-Gb/s APRZ transmitter and receiver

(b) resulting APRZ signal’s intensity and phase. The dotted line refers to a signal with phase misalignment, \( \Delta \tau \). Throughout the experiment \( \Delta \tau \) was monitored to be 0 [6]

(c) frequency response of MUX and DEMUX

Fig. 2 — The installed link between the cities of Stockholm and Hudiksvall. The dashed boxes in the figure represent the nodes, where amplification by means of EDFA and dispersion compensation by means of DCF is accomplished

Fig. 3 — Simulation results:

(a) 820-km transmission penalty versus dispersion pre-compensation for RZ (dashed line) and for APRZ with \( \Delta \phi = \pi/2 \) (the original 10-Gb/s design had 960 ps/nm pre-compensation)

(b) penalty versus phase-modulation amplitude, \( \Delta \phi \), for optimum pre-compensation, 1280 ps/nm

(c) power penalty for RZ and \( \pi/2 \)-APRZ. Bottom (top) plots are obtained
with (without) 75-GHz MUX at the transmitter and 50-GHz DEMUX at the receiver

Fig. 4 — Experimental results: power penalty versus launch power over the 820-km link

(a) with no MUX-DEMUX

(b) with 75-GHz MUX and 50-GHz DEMUX
Figure 1:
Figure 2:
Figure 3:
Figure 4: