40-Gb/s field transmission through 540 km SSMF using the APRZ modulation format

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Abstract: We report the first field transmission experiment using the APRZ modulation format for 40-Gb/s transmission through 540 km SSMF, which confirms the improved nonlinear tolerance of APRZ. The optimum phase-modulation amplitude in this experiment is \( \pi/2 \).

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1. Introduction

A major source of impairments in dispersion-managed (DM) 40 Gb/s transmission systems is non-linear effects [1], especially 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 [2]. IFWM is a phase-sensitive process and several phase-modulation techniques have been proposed to improve the tolerance to IFWM [3-5]. One such technique is the alternate-phase return-to-zero (APRZ) modulation format [5] in which the optical phase between consecutive bit-slots alternates between two values. The exact shape of the phase variation can be different in different implementations [5-7]. In the transmitter used for this field experiment phase alternation is obtained by means of a phase modulator driven by a half-bit-rate clock so that the phase variation is sinusoidal (sine-APRZ). The key APRZ parameters are the amplitude of the phase modulation, \( \Delta \phi \), which determines the relative phase shift of the IFWM contributions, and the relative delay, \( \Delta \tau \), between the phase variation and the RZ pulses. The inset in Fig. 1 illustrates sine-APRZ with an aligned and a delayed phase variation. It is noteworthy that in the case of \( \Delta \phi=\pi \), and \( \Delta \tau=0 \), sine-APRZ reduces to a generalised carrier-suppressed RZ (CSRZ) [8], in which the phase variation is sinusoidal and the duty cycle is a free parameter. In sine-APRZ the effective phase modulation, defined as the weighed average of the phase over the bit slot, is

\[
\Delta \phi_{\text{eff}} = \Delta \phi(t) \cos \left( \frac{\pi t - \Delta \tau}{T} \right) A(t) \, dt,
\]

(1)

Fig. 1 – The field experiment is performed on a fibre link between Kista, outside Stockholm, and the city of Gävle. Eight SSMF spans connect a number of nodes along the way, where re-amplification and dispersion compensation is performed. The transmitter and receiver are located in the Acreo transmission laboratory in Kista. The inset shows intensity and phase of the transmitted sine-APRZ signal.
where $A(t)$ is the normalised field amplitude ($\int_0^T|A(t)|^2\,dt=1$), and $T$ is the bit slot length. If the points of maximum and minimum phase deviation coincide with the bit-slot centres, then $\Delta \phi_{eff} \equiv \Delta \phi$. If the phase variation is delayed, $\Delta \phi_{eff}$ is reduced and the pulses acquire an effective alternate frequency shift.

2. Field transmission system

The field transmission experiment is performed on a DM link designed for 10 Gb/s, consisting of 8 spans of standard single-mode fibre (SSMF) of varying length (19 to 95 km), totalling 540-km, as shown in Fig. 1. In-line dispersion compensation is accomplished by means of dispersion compensating fibre (DCF) modules, and erbium-doped fibre amplifiers (EDFA) with an estimated noise figure of 5dB are used for re-amplification. At the receiver the total dispersion is brought close to zero by means of fibre Bragg grating based tuneable dispersion compensation (TDC). The APRZ transmitter is implemented as a standard RZ transmitter (an EAM to generate 7-ps pulses, and a MZM for data modulation) followed by a phase modulator driven by a 20-GHz clock signal. The electrical 40-Gb/s data signal is a PRBS sequence of length $2^{31}–1$, obtained by time multiplexing four 10-Gb/s PRBS sequences of length $2^{31}–1$, properly delayed. The amplitude and delay of the phase modulation is controlled by means of a variable attenuator and a tuneable delay line. The $V_x$ of the phase modulator is approximately 6.5V at 20 GHz. At the receiver side the signal is passed through a 142-GHz FP filter, detected, and electrically demultiplexed, giving the four original 10-Gb/s channels. Receiver sensitivity @ BER=10$^{-5}$ is measured (the minimum input power in order to have an average BER=10$^{-5}$ for the four channels), which would allow error-free recovery with standard forward-error correction.

The transmission system is also modelled numerically (VPI TransmissionMaker®). Here a train of Gaussian pulses is phase-modulated by a sine wave, and data-modulated by a 256-bit quasi PRBS. The SSMF in the link has dispersion $D = 16.5$ ps/nm/km, slope $S = 0.06$ ps/nm$^2$/km, nonlinearity index $\gamma=2.1$ W$^{-1}$/km, and loss $\alpha=0.21$ dB/km. The DCF has $D = -82.5$ ps/nm/km, $S = -0.18$ ps/nm$^2$/km, $\gamma=4.3$ W$^{-1}$/km and $\alpha=0.7$ dB/km. At the receiver the signal is passed through a 142-GHz Gaussian filter and attenuated to a power level giving BER=10$^{-5}$. The BER is evaluated assuming Gaussian noise in the receiver.

3. Field experiment results and discussion

Using the standard RZ transmitter (no phase modulator), it is possible to transmit data over the link with a BER below 10$^{-5}$, when the launch power into the SSMF is set to 6 dBm or below (the power into the DCF is kept 6 dB below the power into the SSMF throughout the experiment). However, if the launch power is increased then BER$\leq$10$^{-5}$ is no longer achievable unless the non-linear effects are tackled properly.

As a first step in increasing the non-linear tolerance, we optimise the dispersion map by varying the amount of pre-compensation, while adjusting the amount of post-compensation in order to keep the total dispersion close to zero. The launch power is kept at 6 dBm and 0 dBm, for in-line SSMF and DCF, respectively. For each value of pre-compensation the receiver sensitivity is measured and compared to the back-to-back sensitivity. The results are shown in Fig. 2, where one observes that $-640$ ps/nm pre-compensation represents the optimum value. (For
comparison the results of numerical simulations are also plotted.) Operating with optimum pre-compensation leads to 2 dB receiver-sensitivity improvement for RZ transmission. This margin can be used to increase the launch power by 3 dB, and still be able to transmit RZ pulses with a BER below $10^{-5}$. To investigate non-linear effects, from now on we operate with optimum pre-compensation and 9 dBm launch power.

Next we investigate the effect of phase modulation. The peak-to-peak voltage into the phase modulator is varied from 0V to 10.3V so that the nominal phase alternation, $\Delta \phi$, is varied from 0° to approximately 285°, while $\Delta \tau$ is monitored to be zero. Fig. 3 shows the results. One observes that the penalty-vs-$\Delta \phi$ curve reaches a first minimum at 100°. This corresponds to a $\Delta \phi_{eff}$ very close to $\pi/2$, which has been previously reported to be optimum for similar systems [6,9,10]. The power-penalty reduction is more than 5dB compared to standard RZ, and even larger improvement is obtained for $\Delta \phi=260^\circ$. However such strong phase modulation broadens the spectrum considerably, and may therefore be less suitable for transmission in DWDM systems.

The results obtained above assume that the phase-modulating signal is aligned to the pulse train ($\Delta \tau=0$). In order to evaluate how robust sine-APRZ is to a possible misalignment, we repeat the same experiment, with a delay $\Delta \tau$ of one eighth and one fourth of the bit slot. The results are shown in Fig. 4. It can be observed that the performance of sine-APRZ at $\Delta \phi=100^\circ$ is substantially unaffected by a one-eighth-bit-slot misalignment, while a higher delay causes a 2-dB penalty, but it still gives a good improvement with respect to RZ with no phase modulation.

![Fig. 4 – Power penalty for APRZ transmission on the link, as a function of the phase-modulation amplitude, with 9 dBm launch power, for $\Delta \tau=T/8$, and $\Delta \tau=T/4$: field experiment (solid line) and numerical simulation (dotted line). The vertical dotted line marks $\Delta \phi$ for which $\Delta \phi_{eff}=\pi/2$.](image)

4. Conclusions

We report the first field transmission experiment using the APRZ modulation format. APRZ showed increased non-linear tolerance in addition to what could be obtained by optimising the amount of pre-compensation. The optimum phase shift between adjacent bits was close to $\pi/2$ and the results were shown to be robust to temporal misalignment of the phase modulation.

5. References