Experimental investigation on the nonlinear tolerance of root M-shaped pulse in spectrally efficient coherent transmissions

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Abstract: We experimentally demonstrate improved intra-channel nonlinearity tolerance of the root M-shaped pulse (RMP) with respect to the root raised cosine (RRC) pulse in spectrally efficient 128 Gbit/s PDM-16QAM coherent transmission systems. In addition we evaluate the impact of dispersion map and fiber dispersion parameter on the intra-channel nonlinearity tolerance of the RRC pulse and the RMP via both simulation and experimentation. The RMP is shown to have a better nonlinear tolerance than the RRC pulse for most investigated scenarios except for links with zero residual dispersion percentage per span or the zero dispersion region of a fiber. Therefore, the RMP is suitable for extending the maximum reach of spectrally efficient coherent transmission systems in legacy links in addition to currently intensively studied standard single mode fiber (SSMF) based dispersion unmanaged links.

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References and links

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spectrally efficient transmissions. One of the remaining impairments associated with such systems is the Kerr
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Pulse shaping stands out as a promising nonlinearity mitigation technique since it does not
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Recently, we experimentally demonstrated that the RMP at roll-off factors of 0.2 and 0.5
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1. Introduction

The ever-increasing demand for higher capacity in the Internet has driven the deployment of
100 Gbit/s polarization division multiplexed (PDM) digital coherent optical transmission
systems. One of the remaining impairments associated with such systems is the Kerr
nonlinearity that fundamentally limits system capacity [1,2]. The advent of high speed digital-
to-analog converters / analog-to-digital converters (DACs/ADCs) [3,4] and coherent detection
have enabled advanced digital signal processing (DSP) techniques, implemented at the
transmitter and the receiver, to compensate or mitigate the Kerr nonlinearity. These
techniques include digital back-propagation [5], Volterra-series-based nonlinear equalizer [6]
and perturbation-based pre-distortion [7–9]. The issue with these DSP approaches however is
that they are computationally complex and therefore challenging to implement.

Pulse shaping stands out as a promising nonlinearity mitigation technique since it does not
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optimized pulse (ROP) [11], root M-shaped pulse (RMP) [12] and root Polynomial pulse
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verifications for these pulses were all done at a roll-off factor of 1, which is not suitable for
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Recently, we experimentally demonstrated that the RMP at roll-off factors of 0.2 and 0.5
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standard single mode fiber (SSMF) based dispersion unmanaged links [14]. In this paper, we extend the work in [14] in the following aspects using extensive experimental demonstrations: Firstly, we conducted experiments using a commercial dual polarization transmitter line card instead of using a dual polarization emulator in [14]. Since we used a different transmitter from the work in [12,14], we also included the performance of the RMP at the roll-off factor of 1 for the completeness of study. Secondly, we investigated the nonlinear tolerance of the RMP in links with various dispersion managed scenarios and fibers with different dispersion parameters. Because accumulated chromatic dispersion can be compensated entirely in the digital domain, much of the current work on pulse shaping is primarily done in dispersion unmanaged links using SSMF. However, most of the legacy links deployed prior to the emergence of digital coherent transmission systems typically utilize periodic inline dispersion compensation in varying fiber types [15,16]. Therefore, it is important to study the nonlinearity tolerance of various pulse shapes in these types of links as well. Motivated by this objective, the paper is organized as follows: in Section 2, we describe the characteristics of a spectrally efficient RMP; in Section 3, we describe our experimental setup for comparing the nonlinearity tolerance of the RRC pulse and the RMP in a 128 Gbit/s 16 GBaud PDM-16QAM transmission system; in Section 4, we discuss the nonlinearity performance as a function of dispersion map and fiber dispersion via both simulation and experimentation; finally the paper is concluded in Section 5.

2. Characteristics of the spectrally efficient RMP

The frequency domain expressions for the RRC pulse and the RMP are given by Eq. (1) and Eq. (2) [12]:

\[
\begin{align*}
\text{RRC}(f) &= \sqrt{R(f)} = \begin{cases} 
\frac{\sqrt{T}}{2} & 0 \leq |f| < \frac{1-\alpha}{2T} \\
\frac{\sqrt{T}}{2} \left[ 1 + \cos \left( \frac{\pi T}{\alpha} \left| f \right| - \frac{1-\alpha}{2T} \right) \right] & \frac{1-\alpha}{2T} \leq |f| \leq \frac{1+\alpha}{2T} \\
0 & |f| > \frac{1+\alpha}{2T}
\end{cases} \\
\text{RMP}(f) &= \sqrt{M(f)} = \begin{cases} 
\frac{\sqrt{T}}{2} (1-\beta)T^2 & 0 \leq |f| < \frac{1-\alpha}{2T} \\
\frac{\sqrt{T}}{\alpha(1+\beta)} \left[ |f| - \frac{1-\alpha}{2T} \right] + \beta T & \frac{1-\alpha}{2T} \leq |f| \leq \frac{1+\alpha}{2T} \\
0 & |f| > \frac{1+\alpha}{2T}
\end{cases}
\end{align*}
\]

where \( R(f) \) and \( M(f) \) are the overall frequency response of the raise cosine pulse and M-shaped pulse after matched filtering; \( T \) is the pulse period; \( \alpha \) (0 ≤ \( \alpha \) 1) is the roll-off factor; \( \beta \) (\( \beta \geq 0 \)) is the depth factor of the MP, which is defined as \( \frac{M(\frac{1-\alpha}{2T})}{M(\frac{1+\alpha}{2T})} \) and used to adjust the energy contents between the lower frequency components and the higher frequency components. In what follows, we study the cases at \( \alpha = 0.2, 0.5, 1 \) and use \( \beta = 0.5 \) for the RMP.

Figures 1 and 2 depict the ideal spectra and the 4-level eyediagrams after matched filtering for the RRC pulse and the RMP at roll-off factors of 0.2, 0.5 and 1 respectively. The eyediagrams illustrate both the RRC pulse and RMP after matched filtering are inter-symbol
interference (ISI) free at the optimal sampling point. Their spectra show both pulses occupy the same null-to-null bandwidth. The null-to-null bandwidth definition is used with the assumption that the channel spacing of the systems is designed to avoid any inter-channel interference. Different from the RRC pulse, the RMP has more energy contents at higher spectra. This characteristic translates into a narrower full pulse width at half maximum (FWHM) in the time domain impulse response, as seen in Fig. 3. The narrower FWHM of the RMP causes it to disperse faster than the RRC pulse in the presence of chromatic dispersion (CD). Figure 4 illustrates the evolution of the normalized root-mean-square (RMS) pulse width as a function of transmission distance for the RRC pulse and the RMP with various roll-off factors. Since the pulse shapes become irregular after the transmission, we use the RMS pulse width to quantify the pulse width of an arbitrary pulse shape [17]. Figure 4 was obtained via simulations, in which only CD is considered. The dispersion parameter $D$ is set to 17 ps/nm/km and the symbol separation is set to 62.5 ps (corresponding to a baudrate of 16 Gb/ps). As per Fig. 4, the RMP disperses faster than the RRC pulse at the same roll-off factor. It should be noted as the roll-off factor decreases, the difference in dispersing speed between the RMP and the RRC pulse reduces and consequently the RMP’s nonlinearity improvement over the RRC pulse also reduces. Nevertheless, we still expect a better nonlinear performance using the RMP and this nonlinearity tolerance benefit comes at marginal increase in the computation cost.

Fig. 1. Ideal spectra of the RRC pulse and the RMP at roll-off factors of 0.2, 0.5 and 1.

Fig. 2. Ideal 4-level eyediagrams of the RRC pulse and the RMP at roll-off factors of 0.2, 0.5 and 1 after matched filter.
The rapidly dispersing property of the RMP plays an important role in enhancing its nonlinearity tolerance in links with various dispersion maps and fibers with different dispersion parameters. Specifically, in a link with a small residual dispersion percentage per span (RDPS) or a fiber with a small dispersion parameter, the pulses disperse slowly and are therefore partially overlapped with several adjacent pulses over considerable transmission distances. It has been shown that intra-channel cross phase modulation (IXPM) which is caused by pulse-to-pulse nonlinear interaction dominates in these kinds of links [18]. The IXPM strength is determined by the degree of pulse overlap. When the pulses are minimally overlapped, there is very little pulse-to-pulse IXPM interaction. The strength of the IXPM interaction increases when the pulses start overlapping and the strongest interaction occurs when the pulse width $\sigma$ is comparable to the symbol period $T$ ($\sigma = T$). The IXPM interaction is then weakened when the pulses are further broadened to the point that they are completely overlapped. Since the RMPs can quickly evolve from non-overlapping regime to complete overlapping regime, they spend less amount of the transmission partially overlapped, therefore they suffer less from the effects of IXPM.

In a link with a large RDPS or a fiber with a large dispersion parameter, the pulses are overlapped rapidly. In the anomalous dispersion regime, the higher spectral components travel faster than the lower spectral components. As a result, the lower spectral components of the leading pulse interact with the higher spectral components of trailing pulse, causing another pulse-to-pulse nonlinear interaction called intra-channel four wave mixing (IFWM) [18]. Because the RMPs disperse rapidly, the spectral components of different RMPs will walk off each other rapidly, thus mitigating IFWM interactions. Since the dispersing speed depends on the roll-off factor, we expect that the improved nonlinear tolerance of the RMP with respect to the RRC pulse increases as the roll-off factor increases.
It should be noted from Fig. 3 that the RMP has a slower decay rate than the RRC pulse, which will lead to a modulated signal with a large peak-to-average power ratio (PAPR). Figure 5 depicts the evolution of the PAPR for the 128 Gbit/s PDM-16QAM signals with different pulse shaping in the first 400 km transmission. The larger PAPR of the RMP shaped signals in the first 100 km transmission would reduce the nonlinearity tolerance of the RMP in links with the zero RDPS or zero dispersion regime of a fiber, where the pulses maintain their shapes during transmission and the primary nonlinearity is PAPR dependent intra-symbol self-phase modulation (ISPM).

Fig. 5. The evolution of the PAPR for the 128 Gbit/s PDM-16QAM signals with the RRC pulse and the RMP shaping at various roll-off factors in the first 400 km transmission.

3. Experimental setup

Fig. 6. (a) Schematic of the experimental setup. (EDFA: Erbium-doped fiber amplifier; VOA: variable optical attenuator; SW: switch; SSMF: standard single mode fiber; LEAF: large effective area non-zero dispersion-shifted fiber; DCF: dispersion compensation fiber; OSA: optical spectrum analyzer; T-T BPF: tunable bandwidth and tunable central wavelength bandpass filter; ECL: external cavity laser; LO: local oscillator; Rx: receiver; DSP: digital signal processing). The optical spectra of the RRC pulse (blue line) and the RMP (red line) at roll-off factors of (b) 0.2, (c) 0.5 and (d) 1.
Figure 6 illustrates the experimental setup for the nonlinearity tolerance comparison of the RRC pulse and the RMP shaped 128 Gbit/s 16 Gbaud PDM-16QAM signals transmitted over links with various dispersion maps and fiber types. The symbol rate is chosen such that we are able to study the performance of the pulses at roll-off factors of 0.2, 0.5 and 1 under the DAC's sampling rate constraint. On the transmitter side offline DSP, 4-tuple of a PDM-16QAM signal were generated from four random 4-level symbol sequences with a length of 93440. Pulse shaping was performed offline in the frequency domain using the overlap-and-save method [19,20] and a fast Fourier transform (FFT) size of 256. A Ciena WaveLogic 3 transmitter card was employed, which contains 4 high speed DACs, a laser, and a dual-polarization IQ modulator. In particular, the pulse-shaped signals were resampled to the DAC sampling rate, quantized to 6 bit resolution and then loaded into the transmitter's memory. The transmitter laser was operating at 1554.94 nm. The electrical waveform at the output of the DACs was applied to the IQ modulator to generate a true PDM optical signal. The transmitter frequency responses are compensated in the build-in Tx DSP of the Ciena WaveLogic 3 transmitter. The PDM-16QAM optical signal was boosted to 23 dBm with a booster EDFA, attenuated by a VOA to get a desired launch power and then launched into an optical recirculating loop.

We employed three different types of link configurations in the recirculating loop according to the scenarios studied in this paper. The first link configuration consisted of 4 spans of 80 km of low loss standard single mode fiber (SMF-28e+ LL) and four inline EDFAs with noise figures of 5 dB. The second link configuration consisted of 4 spans of 80 km of SMF-28e + LL and a piece of inline dispersion compensation fiber connected to the mid-stage of the inline EDFA in each span. In the last span, a TeraXion tunable dispersion compensation module [21] was used along with the DCF to fine tune the residual dispersion. The third link configuration consisted of 4 spans of 75 km of LEAF and four inline EDFAs. The specifications of the SMF-28e+ LL, DCF and LEAF are listed in Table 1.

<table>
<thead>
<tr>
<th>Fiber Types</th>
<th>SMF-28e+ LL</th>
<th>DCF</th>
<th>LEAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation@1555nm [dB/km]</td>
<td>0.18</td>
<td>0.6</td>
<td>0.21</td>
</tr>
<tr>
<td>Dispersion@1555nm [ps/nm/km]</td>
<td>17</td>
<td>-97</td>
<td>4.6</td>
</tr>
<tr>
<td>Effective Area [µm²]</td>
<td>80</td>
<td>20</td>
<td>72</td>
</tr>
</tbody>
</table>

At the receiver, a noise loading EDFA and a VOA were utilized to change the received signal OSNR in the back-to-back (B2B) measurement. An OSA was used to measure the signal OSNR at a 0.5 nm resolution and then it was converted to a 0.1 nm noise bandwidth. The inset spectra were obtained using a complex OSA with a resolution of 0.8 pm. A 0.4 nm tunable bandwidth and tunable central wavelength bandpass filter was employed to reject out-of-band ASE noise accumulated during transmission. The gain of the pre-amplifier was adjusted to ensure that the signal power reaching the coherent receiver remained at 5 dBm. A 0.8 nm BPF was used to filter out the out-of-band ASE noise generated by the pre-amplifier. In the polarization-diversity 90° optical hybrid, the signal was mixed with 15.5 dBm CW light from an ECL LO and the beating outputs were passed through four balanced photodetectors. A 4-channel real-time oscilloscope sampled the signal at a sampling rate of 80 GSa/s and digitized it with 8 bit resolution to bring it back to the digital domain. The digital signals were processed offline using MATLAB. The DSP code started with optical front-end compensation, including the DC removal, IQ imbalance compensation and hybrid IQ orthogonality compensation using the Gram-Schmidt orthogonalization procedure [10]. Next, the signal was resampled to 2 samples per symbol and then passed through frequency domain CD compensation and laser frequency offset compensation based on the FFT of the signal at the 4th power. Sampling frequency offset compensation and timing recovery were carried out using a non-data-aided feedforward symbol timing estimator [22]. Matched filtering was performed in the frequency domain using the same pulse shaping filter used at the transmitter.
A training-symbol-aided decision directed least radius distance (TS-DD-LRD) [23] based fractionally spaced (T/2) equalizer with 15 taps was used for fast convergence of the coefficients. The carrier phase was recovered using the superscalar parallelization based phase locked loop (PLL) combined with a maximum likelihood phase estimation [24]. Finally, the 16QAM symbols were mapped to bits. The BER was counted over 500,000 bits and a soft-decision forward error correction (SD-FEC) (20% overhead) BER threshold of $2.4 \times 10^{-2}$ was assumed [25].

4. Results and discussion

4.1 B2B performance

Figure 7 illustrates the BER versus the OSNR performance for the 128 Gbit/s PDM-16QAM signals with the RRC pulse and RMP shaping at various roll-off factors in the B2B configuration. At the SD-FEC threshold, the implementation OSNR penalties compared to theory for the RRC pulse and the RMP at roll-off factors of 0.2, 0.5 and 1 are (0.89 dB, 0.94 dB), (0.76 dB, 0.78 dB) and (0.84 dB, 0.94 dB), respectively. We observe that the RMP has a slightly larger OSNR penalty than the RRC pulse at the same roll-off factor because the effective number of bits (ENOB) of the DAC decreases at higher frequencies thus introducing more quantization noise to the pulse with more energy contents at higher frequencies. We also observe for both pulses that there are slightly larger OSNR penalties at roll-off factors of 0.2 and 1 compared to the 0.5 roll-off factor case. The larger OSNR penalty at a roll-off factor of 0.2 stems from the fact that the pulse with a smaller roll-off factor is more susceptible to timing jitter. At a roll-off factor of 1 the larger OSNR penalty is attributed to the fact that a pulse with a larger bandwidth is affected more by the reduced ENOB of the DAC at higher frequencies.

![Fig. 7. Measured BER versus OSNR for the 128 Gbit/s PDM-16QAM signals with the RRC pulse and the RMP shaping at various roll-off factors in the B2B configuration.](image)

4.2 The impact of dispersion maps

In this section, we study the impact of dispersion maps on the nonlinearity tolerance of the 128 Gbit/s PDM-16QAM signals with the RRC pulse and the RMP shaping in the SMF-28e+ LL link. The nonlinearity tolerance can be evaluated using two metrics, namely the BER versus launch power for a pre-set transmission distance and the achievable transmission distance versus launch power at the SD-FEC BER threshold. First, we compare the BERs of the RRC pulse and the RMP shaped signals over a range of launch powers when the transmission distance is fixed at 1600 km (5 loops). This transmission distance is chosen such that the optimum BERs of all pulse shapes are below the SD-FEC threshold. Figure 8 depicts the experimental results at RDPS of 0, 25% and 100%. In the zero RDPS regime, all the
pulses have optimal BERs at −4 dBm, ranging from $1.42 \times 10^{-2}$ of the RMP ($\alpha = 0.5$) to $1.70 \times 10^{-2}$ of the RMP ($\alpha = 1$), as shown in Table 2. Although the RMP has an inferior ISPM tolerance compared to the RRC pulse at large roll-off factors due to its large PAPR, it disperses more rapidly than the RRC pulse within each span because of the large dispersion of SSMF. Hence, the RMP has a similar nonlinearity performance when compared to the RRC pulse, with the RMP ($\alpha = 0.5$) performing slightly better. Moreover, the reduced BER of the RMP ($\alpha = 1$) mainly comes from the degraded DAC ENOB at high frequencies, which is reflected in the BER difference at low launch powers. In the large RDPS regime where RDPS are 25% and 100%, the RMP exhibits superior nonlinearity tolerance compared to the RRC pulse at all roll-off factors investigated, as summarized in Table 2. Although the improved nonlinearity tolerance of the RMP is reduced as the roll-off factor decreases, the implementation of the RMP pulse does not require much increase in the computational cost.

![Figure 8](image_url)

**Fig. 8.** Measured BER versus OSNR for the 128 Gbit/s PDM-16QAM signals with the RRC pulse and the RMP shaping at 1600 km transmission distance in the SMF-28e+ LL link.

**Table 2. Summary of Optimal BER for the 128 Gbit/s PDM-16QAM Signals with the RRC Pulse and the RMP Shaping at 1600 km Transmission Distance**

<table>
<thead>
<tr>
<th>RDPS</th>
<th>Pulse Type</th>
<th>$\alpha = 0.2$</th>
<th>$\alpha = 0.5$</th>
<th>$\alpha = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>RRC</td>
<td>1.62 $\times 10^{-2}$</td>
<td>1.54 $\times 10^{-2}$</td>
<td>1.57 $\times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>RMP</td>
<td>1.58 $\times 10^{-2}$</td>
<td>1.42 $\times 10^{-2}$</td>
<td>1.70 $\times 10^{-2}$</td>
</tr>
<tr>
<td>25%</td>
<td>RRC</td>
<td>1.35 $\times 10^{-3}$</td>
<td>1.10 $\times 10^{-3}$</td>
<td>8.9 $\times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>RMP</td>
<td>1.13 $\times 10^{-3}$</td>
<td>7.5 $\times 10^{-3}$</td>
<td>4.7 $\times 10^{-3}$</td>
</tr>
<tr>
<td>100%</td>
<td>RRC</td>
<td>3.7 $\times 10^{-3}$</td>
<td>3.0 $\times 10^{-3}$</td>
<td>2.6 $\times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>RMP</td>
<td>3.1 $\times 10^{-3}$</td>
<td>2.2 $\times 10^{-3}$</td>
<td>1.0 $\times 10^{-3}$</td>
</tr>
</tbody>
</table>

Secondly, we compare the achievable transmission distance at the SD-FEC BER threshold as a function of launch power. The experimental results are shown in Fig. 9. Note that since the signals can only be transmitted over integer number of loops (320 km) in our experiment, the transmission distances were interpolated to obtain a finer distance resolution. We define the maximum reach as the achievable transmission distance at the optimal launch power. In accordance with the results in Fig. 8, Fig. 9 shows that in the zero RDPS regime the maximum reach of all of the pulses are similar, ranging from 1802 km for the RMP ($\alpha = 1$) to 1910 km for the RMP ($\alpha = 0.5$). In the large RDPS regime, such as 25% and 100%, the maximum reach is considerably extended using RMP shaping, as summarized in Table 3, because of the RMP's improved tolerance to IFWM. Another observation from Table 3 is the percentage of the extended maximum reach achieved by using the RMP increases almost linearly with the increasing roll-off factor at 0.2, 0.5 and 1.
Fig. 9. Measured achievable transmission distance versus launch power for the 128 Gbit/s PDM-16QAM signals with the RRC pulse and the RMP shaping in the SMF-28e+ LL link.

Table 3. Summary of Maximum Reach for the 128 Gbit/s PDM-16QAM Signals with the RRC Pulse and the RMP Shaping and Correspondent Extended Reach Percentage Using the RMP

<table>
<thead>
<tr>
<th>RDPS</th>
<th>Pulse Type / Extended Reach Percentage</th>
<th>α = 0.2</th>
<th>α = 0.5</th>
<th>α = 1</th>
</tr>
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<tbody>
<tr>
<td>0%</td>
<td>RRC (km)</td>
<td>1861</td>
<td>1888</td>
<td>1859</td>
</tr>
<tr>
<td></td>
<td>RMP (km)</td>
<td>1866</td>
<td>1910</td>
<td>1802</td>
</tr>
<tr>
<td></td>
<td>Extended Reach Percentage</td>
<td>0.27%</td>
<td>1.17%</td>
<td>−3.07%</td>
</tr>
<tr>
<td>25%</td>
<td>RRC (km)</td>
<td>2033</td>
<td>2153</td>
<td>2304</td>
</tr>
<tr>
<td></td>
<td>RMP (km)</td>
<td>2149</td>
<td>2454</td>
<td>2951</td>
</tr>
<tr>
<td></td>
<td>Extended Reach Percentage</td>
<td>5.40%</td>
<td>13.98%</td>
<td>28.08%</td>
</tr>
<tr>
<td>100%</td>
<td>RRC (km)</td>
<td>2970</td>
<td>3124</td>
<td>3371</td>
</tr>
<tr>
<td></td>
<td>RMP (km)</td>
<td>3132</td>
<td>3490</td>
<td>4292</td>
</tr>
<tr>
<td></td>
<td>Extended Reach Percentage</td>
<td>5.45%</td>
<td>11.72%</td>
<td>27.32%</td>
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</tbody>
</table>

Finally, we conducted simulations in order to investigate the maximum reach of different pulses under differing RDPS scenarios. The results illustrated in Fig. 10 were obtained by adjusting the length of the DCF in each span to sweep the RDPS from 0% to 100%. For each RDPS we obtained the maximum reach using the method we discussed above. The key parameters for the simulations are the same as those in the experiments which are shown in Table 1. In accordance with the experimental results, in the zero RDPS regime, all the pulses have comparable maximum reaches. In the small RDPS regime (RDPS < 20%), the maximum reaches firstly decrease and then increase as the RDPS increases for all the pulses except the RMP (α = 1). The decreased maximum reaches are attributed to the IXMP effect when the pulses disperse and overlap with each other. The RMP has a reduced amount of decreased maximum reach compared to the RRC pulse at the same roll-off factor. The amount of the decreased maximum reach also depends on the roll-off factor. The smaller the roll-off factor, the larger the decreased maximum reach value. All of these phenomena can be explained by the fact that the RMP has a better IXPM tolerance than the RRC pulse and the tolerance is enhanced as the roll-off factor increases. In the large RDPS regime, the maximum reach increases as the RDPS increases and the RMP has a larger maximum reach than the RRC pulse at all roll-off factors investigated. Figure 11 depicts the extended maximum reach percentage using the RMP over the RRC pulse at various RDPS values. The extended maximum reach percentage increases for RDPS less than ~20% and becomes nearly constant for RDPS larger than ~20%.
4.2 The impact of fiber dispersions

In the following, we investigate the impact of fiber dispersion on the nonlinearity tolerance of the 128 Gbit/s PDM-16QAM signals with the RRC pulse and the RMP shaping. We experimentally compare their nonlinearity performance in a LEAF link using the aforementioned two metrics, in addition to the SMF-28e’ LL link. Figure 12(a) presents the BER as a function of the launch power for the RRC pulse and the RMP shaped signals at 1500 km (5 loops) transmission distance. By using the RMP shaping instead of the RRC pulse shaping, the optimal BERs can be improved from $21.09 \times 10^{-3}$, $39.6 \times 10^{-3}$ and $37.7 \times 10^{-3}$ to $39.6 \times 10^{-3}$, $36.2 \times 10^{-3}$ and $33.8 \times 10^{-3}$ at roll-off factors of 0.2, 0.5 and 1, respectively. Figure 12(b) presents the achievable transmission distance of the RRC pulse and the RMP shaped signals for different launch powers. It can be observed that the RMP shaping can extend the maximum reach by 5.1%, 12.7% and 23.8% at roll-off factors of 0.2, 0.5 and 1, respectively, compared to the RRC pulse shaping. These results demonstrate that the RMP has an excellent nonlinearity tolerance in the LEAF link as well.
Fig. 12. (a) Measured BER versus OSNR at 1500 km transmission distance; (b) measured achievable transmission distance versus launch power for the 128 Gbit/s PDM-16QAM signals with the RRC pulse and the RMP shaping in the LEAF link.

We employ simulations to get a broader picture of how fiber dispersion affects the nonlinearity tolerance of the RMP. The fiber dispersion parameters in the simulation vary from 0 ps/nm/km to 17 ps/nm/km. In order to eliminate the effects from other fiber parameters, we set the attenuation of the fiber at 0.2 dB/km, the effective area at 80 µm², and the length per span at 80 km. From the results shown in Fig. 13, one can see in the zero dispersion regime the maximum reach of the RMP (α = 1) is slightly smaller than others as it has a larger PAPR. In the small fiber dispersion parameter regime (D < 3 ps/nm/km), the maximum reaches of the RMP (α = 0.2), RRC (α = 0.2) and RRC (α = 0.5) first decrease and then increase as the dispersion parameter increases because they disperse less rapidly and experience IXPM. In the large fiber dispersion parameter regime the maximum reach of all the pulses increases as the dispersion increases and the RMP has an improved maximum reach over the RRC counterpart at the same roll-off factor. The extended maximum reach percentages by employing the RMP shaping instead of the RRC pulse shaping for a variety of dispersion parameters are illustrated in Fig. 14. The extended maximum reach percentage increases as the dispersion parameter increases and saturates at 2, 3 and 5 ps/nm/km for roll-off factors of 0.2, 0.5 and 1, respectively.

Fig. 13. Simulated maximum reach versus fiber dispersion parameter for the 128 Gbit/s PDM-16QAM signals with the RRC pulse and the RMP shaping.
5. Conclusion

In this paper, we investigate the impact of dispersion map and fiber dispersion parameter on the nonlinearity performance of the spectrally efficient PDM-16QAM signal transmission using the RMP, with respect to the RRC pulse. The study shows that, due to its excellent IXPM and IFWM tolerance, the RMP outperforms the RRC pulse in most RDPS regimes except for the zero RDPS regime. The study also reveals that the RMP surpasses the RRC pulse for most fiber dispersion parameters except for the zero dispersion regime. Consequently, the RMP can improve the nonlinear tolerance of the spectrally efficient PDM-16QAM transmissions in most legacy links beside the SSMF based dispersion unmanaged links.