This behaviour corresponds with previous demonstrations [13]. All of the roll off factors tested performed similarly in terms of BER and sensitivity. The highest spectral efficiency tested is 3.2 bit/s/Hz when $\alpha_{DL} = 0.25$, resulting in a channel bandwidth of 3.125 GHz. After accounting for the RS(255,223) overhead, the information spectral efficiency is reduced to 2.8 bit/s/Hz.

The eye diagrams in Fig. 3(b) demonstrate the effect of $\alpha_{DL}$ on the signal in the time domain. A larger roll off factor broadens the pulse width in time and in turn increases the eye opening of the multilevel signal. A smaller $\alpha_{DL}$ value decreases the pulse width and the channel's bandwidth, but leads to increased timing sensitivity at the receiver. In this case, the impact of $\alpha_{DL}$ is minimized by adding a timing and SFO correction block in the DSP stack.

### *4.2. Uplink*

The uplink channel is a 2.5 Gbaud 16-QAM signal on a 2.97 GHz RF subcarrier. A 64th order FIR filter pre-compensates for the RSOA bandwidth roll off prior to quantization. The OLT launch power $P_{OLT\_Tx}$ was fixed at 5 dBm while characterizing the performance of the upstream transmission. As shown above in Fig. 3, this launch power provides an excellent downlink performance while staying below the threshold power for stimulated Brillouin scattering (SBS) [22]. This $P_{OLT\_Tx}$ corresponds to a RSOA input power $P_{RSOA\_in} = -10.7$ dBm, which is greater than the RSOA's saturation power of $-17$ dBm. The ONU gain is $\sim 12.9$ dB resulting in an upstream $P_{ONU\_Tx} = 2.2$ dBm. After transmission through the ODN, the received power at port 3 of the circulator is measured to be $P_3 = -7.6$ dBm.

In Fig. 4 we present the BER performance of the 10 Gb/s upstream transmission with both remote CW seeding and symmetric transmission with wavelength reuse from a portion of the modulated downlink signal. The impact of the uplink SRRC roll off factor is verified for $\alpha_{UL}$ from 0.25 to 1.00, with resulting channel bandwidths ranging from 3.125 GHz to 5 GHz, respectively. The downlink $\alpha_{DL}$ was fixed at 0.50 for symmetric operation.

Fig. 4. Uplink BER performance of the upstream after transmission over a 20 km PON with (a) CW seeding, and (b) full-duplex transmission. Normalized electrical power spectra are inset, as well as an equalized constellation for $\alpha_{UL} = 0.25$.

In Fig. 4(a), the uplink with remote CW seeding achieves a BER below the FEC threshold at $-11$ dBm of received power. This represents a 2 dB improvement over our initial demonstration [20] due to the new timing and SFO correction block. The addition of a DFE eliminates any residual ISI and further reduces the sensitivity to $-13.5$ dBm. In both cases the BER performance reaches a floor for received powers greater than $-9$ dBm due to noise limitations.

Figure 4(b) demonstrates the uplink performance during full-duplex transmission. As a result of reusing the modulated downlink signal, the penalty is only a $\sim 1.5\times$ increase in BER. On the other hand, the uplink receiver sensitivity degrades to $-7$ dBm without post-compensation, a 4 dB power penalty compared to the CW seeding case. Adding a post-compensation DFE block at the OLT receiver removes any residual ISI in the uplink signal and significantly improves the receiver sensitivity, requiring just $-12.5$ dBm of power to operate below the FEC threshold. In terms of power penalty, the difference between CW seeding and symmetric transmission is reduced to only 1 dB when a DFE is used at the OLT receiver. Similar to the downlink channel, the uplink performance is quite insensitive to roll off for $\alpha_{UL} \geq 0.25$. For the remaining analysis, we will assume the use of a DFE at the OLT receiver in order to maintain BERs well below the FEC threshold.

### 4.3. Comparison with the Shannon limit

Figure 5(a) is an example of the BER performance of both the downlink and uplink channels with respect to $E_b/N_0$, the signal to noise ratio (SNR) per bit of information after the FEC overhead has been removed [23]. To calculate $E_b/N_0$ for each data set, the frequency domain spectrum is first calculated from the captured time domain signals. Integrating over the channel bandwidth and subtracting the average noise power from the signal results in the gross SNR per symbol, $E_s/N_0$. The SNR per bit of information is then given by

$$\frac{E_b}{N_0} = \frac{E_s}{N_0} \frac{1}{\log_2(M)} \frac{n}{k}, \tag{1}$$

where $M = 16$ is the QAM order and $(n,k) = (255,223)$ are the block lengths for the RS FEC coding.

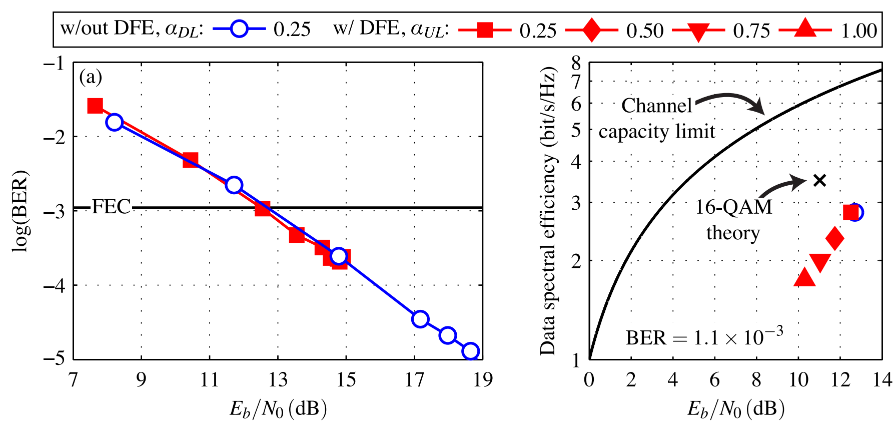


Fig. 5. (a) BER vs. $E_b/N_0$ for the downlink and uplink channels. (b) Comparison of the 16-QAM SCM WDM PON performance with different SRRC roll off factors to Shannon's channel capacity limit. We also include the best theoretical 16-QAM RS(255,223) FEC coded signal to achieve the BER threshold [23]. Note that the added overhead for the RS(255,223) FEC has been taken into account for both the spectral efficiency and $E_b/N_0$.

For the downlink channel, we see that as $E_b/N_0$ increases with launch power and the BER steadily drops below the FEC threshold at 12.7 dB. The uplink BER reaches below the FEC threshold at $E_b/N_0 = 12.5$ dB. In this case, $E_b/N_0$ does not increase beyond 15 dB because the uplink signal power is limited by the gain saturated RSOA.

Furthermore, in Fig. 5(b) we can use these $E_b/N_0$ values to compare the performance of this SCM WDM PON with Shannon's channel capacity limit [23], $E_b/N_0 > \frac{2^r-1}{r}$, where $r$ is the channel's spectral efficiency. Here the design trade off between bandwidth and energy is evident, as the highest spectral efficiency requires $\sim 2.2$ dB greater $E_b/N_0$ than the lowest one.

### *4.4. Discussion*

This 16-QAM SCM WDM PON solution improves on previous demonstrations [13, 17] by increasing the channels' net spectral efficiency up to 2.8 bit/s/Hz, while still maintaining a simple wavelength reuse scheme and commodity IM/DD transceivers at both the OLT and ONU. Guard bands of up to 1 GHz ($\alpha_{UL} = 0.25$) isolate the uplink channel from surrounding noise sources, including low frequency RB beat noise [24] and inter-channel crosstalk from the downlink signal [14]. The noise can then be efficiently filtered out in DSP during the down-conversion and SRRC matched filtering stages. Notably, these improvements are achieved without any additional optical components or significant impact to the channel's BER compared to previous demonstrations.

Although 2.8 bit/s/Hz is the highest net spectral efficiency achieved in this investigation, it is not necessarily the highest possible. As evident in Fig. 5(b), increasing the uplink channel's spectral efficiency further would require larger $E_b/N_0$. This, however, could prove difficult given that the maximum value obtained in this investigation was $\sim 15$ dB. Achieving a larger $E_b/N_0$ by increasing $P_{OLT\_Tx}$ beyond 5 dBm would limit any gains because of additional RB and SBS [13]. Further reducing $\alpha$ also narrows the eye opening and increases the receiver's sensitivity to timing jitter. At 10 Gb/s data rates, $\alpha = 0.25$ provides adequate guard bands to separate the data channels from noise and crosstalk without impacting performance. The architecture's flexibility allows the signal bandwidths to be engineered to achieve the network operator's quality of service (QoS) requirements. In the future, this could open the possibility of increasing baud rates, or possibly mixing and matching the QAM order, baud rate and pulse shaping to achieve the network operator's desired specifications.

## 5. Conclusion

In this paper we present a 10 Gb/s SCM WDM PON architecture using DSP to maximize the performance of economical IM/DD transceivers, achieving net spectral efficiencies up to 2.8 bit/s/Hz per channel. We characterize the system's performance over a single feeder 20 km PON with both remote CW seeding and full-duplex transmission scenarios and achieve BERs below the RS(255,223) FEC threshold. The pulse shaped 16-QAM channels facilitate guard bands, providing robust resistance to upstream impairments and leading to a small 1 dB power penalty for reusing the downlink modulated signal as a seed source. To the best of our knowledge this is the highest reported spectral efficiency for a 10 Gb/s SCM WDM PON.