Impact of Analogue Pre-filtering for Spectral Roll-off improvement in spectral efficient transmitter

Amandeep Kaur, Fatima C. Garcia Gunning

Tyndall National Institute, University College Cork, Dyke Parade, Cork, Ireland T12 R5CP

e-mail: amandeep.kaur@tyndall.ie

ABSTRACT

Spectral shaping plays a significant role in enabling high spectral efficiency of optical transmission systems. However, most of the spectral shaping methods reported so far have remained very complex using digital processing techniques that requires a large number of filter taps for optimal performance. In this paper, we show how the spectral roll-off factor can be reduced using a wavelength selective switch (WSS) at the transmitter side. We discuss the impact and limitations when using this method. The study investigates the practicalities of WSS generated optical filters at transmitter side via VPI simulations, evaluating the performance in terms of receiver sensitivity and BER.

Keywords: Nyquist-WDM, optical filters, WSS, BER, Power Penalty.

1. INTRODUCTION

The explosive growth in internet traffic and data hungry internet applications has surged the demand for higher capacity. Over the past few decades, a significant capacity increase has been achieved with the revival of the various multiplexing techniques along with the coherent optical communication by making full utilization of the available degree of modulation freedoms in optical networks [1]. To cope up with the ever growing traffic demands, researchers are still exploring new technologies for high capacity transmission. To get the maximum capacity out of an optical network, multiple carriers are packed together as tightly as possible and this technique is termed as superchannels. Compatible with existing networks, technologies like all optical orthogonal frequency division multiplexing (AO-OFDM) and Nyquist-WDM have attracted attention to create superchannels by making more efficient use of available bandwidth while retaining both spectral and temporal orthogonalities [2]. In superchannels, the channel spacing is reduced to its absolute minimum to increase the number of channels that can be transmitted simultaneously within a constrained available bandwidth, and therefore, narrow filtering has become a real concern for current optical networks.

Nyquist-WDM is more commonly implemented in optical transmission systems as it is easier to implement than AO-OFDM. For Nyquist-WDM, the ideal spectral shape for each sub-channel in the frequency domain is rectangular with the channel spacing (Δf) close to the baud rate (Br), therefore confining the signal to its Nyquist bandwidth. The pulse within each N-WDM sub-channel possesses a sinc-like shape in the time domain with zero-crossing points at integer multiples of the symbol period without inducing inter-symbol interference (ISI) [3].

So far, N-WDM systems have been demonstrated using digital signal processing (DSP) techniques with the implementation of large number of the filter tap coefficients to restrict the signal to Nyquist bandwidth [4]. Schmogrow performed Nyquist filtering in the digital domain using 2048 taps digital filter [5]. Generally, a Nyquist pulse is characterized by a parameter called roll-off factor α ($0 \leq \alpha \leq 1$), which determines the bandwidth of the Nyquist pulse. The lower α values results in narrower spectral width, and are therefore particularly advantageous in terms of spectral efficiency. The Nyquist pulses with roll-off factor of 0.01 have been achieved with digital Nyquist filter with tap length of 64 [6]. N-WDM with channel spacing (Δf) equal to 1.1* Baud Rate has been realized using 57-tap digital FIR filter with roll-off factors from 0.1 to 0.2 at 28 Gbaud [7]. To reduce roll off factor from 10% down to 0.1%, the number of filter taps increased from 320 to 1000 for the lowest roll-off factor [8]. Nevertheless, in general the real implementation of a large number of digital filters is very complex and expensive.

In this paper, we have reported a different approach to minimize the complexity and potentially cost of current state-of the-art, by performing spectral shaping in the optical domain with the use of programmable optical filters such as a wavelength selective switch (WSS) at the transmitter side. We assume that WSS can help reducing the number of filter taps in the electronic domain. However, we expect limitations due to the WSS's accuracy and resolution. Here, we investigated the impact of such limits on reducing the spectral roll-off. The concept of achieving Nyquist WDM using narrow optical filtering techniques has been already in practice [9-11]. However, as far as we understand, the reduction of spectral roll with WSS has not been fully explored yet.

2. SPECTRAL ROLL-OFF FACTOR REDUCTION

Filtering with WSS is a quite versatile as innumerable different filter profiles could be tested without requiring any physical changes to the experimental setup. WSS is already widely used in reconfigurable optical add-drop multiplexers (ROADM) to route the various wavelength-multiplexed channels to their desired destinations and for the controlled pre-filtering at the transmitter sides [12-14]. In this work, we tried to study the accuracy of the output response of WSS. For this purpose, a desired filter specification was provided as a filter response input to WSS to compare desired and realized filter profile. The accuracy of the filter representation is measured in terms of roll-off factor. The primary task is to determine the maximum possible steepness of roll-off factor. To carry out this experiment, an Erbium-doped fibre amplifier (EDFA) is used to produce amplified spontaneous emission (ASE) signal, which is fed to a WSS (Finisar WaveShaper 1000s) to emulate the filter shape. A raised cosine (RC) filter shape was realized in Matlab and then uploaded into the WSS by using software called WaveManager and the output is measured with an optical spectrum analyser (OSA). The filter profile has a center frequency of 193.1 THz. The impact of roll-off factor on the spectral shape, considering RC filters with different -3dB bandwidth (B_{FWHM}) ranging from 10 GHz to 60 GHz has been included in this work. The B_{FWHM} is normalized by the bandwidth resolution (r) of WSS which is 10 GHz for our case. The roll-off factor is calculated by using formula 1-(B_{FWHM}/B_T) where B_T is total bandwidth of the filter.

It is clear from Fig. 1(a) that WSS does not have a spectral roll-off steep enough to reproduce the same output as the desired one. The reason behind this is that for narrow bandwidth filters, the accuracy and resolution of the WSS plays a role, hence preventing the desirable filter output. In Fig. 1 (a) the programmed filter bandwidth was the same as the WSS's bandwidth resolution. There is a sharp steepness in roll-off factor for B_{FWHM}/r=1 and the output produced by WSS is not rectangular as seen in Fig. 1(a). Next, a filter profile with B_{FWHM}/r=5 was uploaded to the WSS and it is found that as the filter bandwidth become broader, the steepness in roll-off factor improves, as shown in Fig. 1(b).

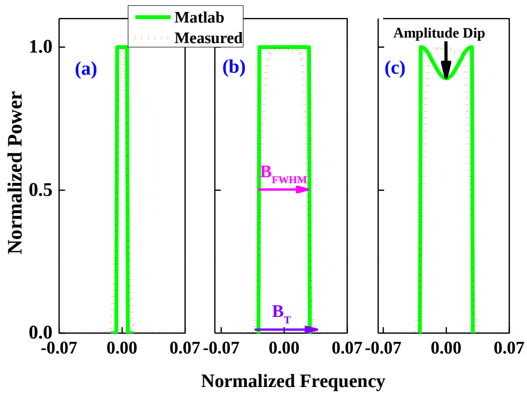

Figure 1. RC spectrum at B_{FWHM}/r= (a) 1 and (b) 5 (c) Representation of Amplitude Dip.

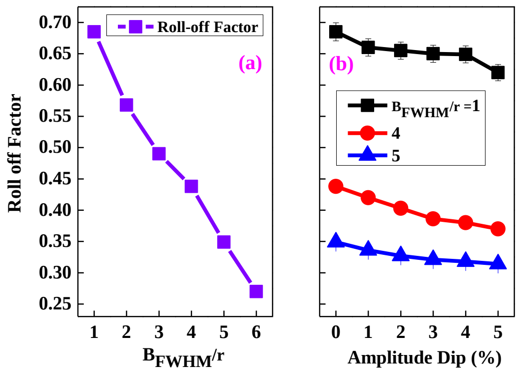

Figure 2. Roll-off factor vs B_{FWHM}/r (a) and (b) Roll-off Factor Reduction with Amplitude Dip.

To measure the steepness, the roll-off factor is plotted against B_{FWHM}/r as shown in Fig 2 (a). The roll-off factor varied from 0.68 to 0.27 for filter when B_{FWHM}/r changed from 1 to 6. It can be estimated from the results that for the narrow filters, the roll-off factor is too high, thus hindering the generation of RC filter with sharp transition. Therefore, we can manipulate the programmed filter profile, designing a filer that would counter-effect these observations.

To overcome this problem, we tried to optimize the input profile of the filter so that WSS would be able to produce output as an approximation of the input filter with the steepest slope. The RC filter profiles are created, each differing in attenuation against signal power from 0 to 5% but only at the center of the filter. This difference in attenuation at centre of filter against signal power refers to the amplitude dip as shown in Fig. 1(c). With the introduction of amplitude dip, the response of WSS becomes closer to the square function required which results in improvement in steepness of the WSS. To study the impact of amplitude dip on the roll-off factor in detail, we analysed RC spectral shape with B_{FWHM}/r=1, 4 and 5. It can be seen from the Fig. 2(b) that, for B_{FWHM}/r=1, the roll-off factor reduced from 0.69 to 0.61 when amplitude dip changed from 0 to 5 %. Hence, there is 10.1 % reduction in roll-off factor by this method. Furthermore, for B_{FWHM}/r=4, the roll-off factor dropped from 0.44 to 0.36, therefore, improving the WSS output response by 8%. Similarly, at B_{FWHM}/r=5, the roll-off factor reduced by the factor of 5%.

3. ASSESSMENT OF FILTER PENALTY IMPACT ON OPTICAL NETWORK.

We demonstrated a single channel transmission system based on 10 Gbit/s NRZ-OOK data modulation, using $LiNbO_3$-based modulator and a pseudo-random bit-sequence (PRBS) sequence of 2^7-1 to evaluate the performance of our proposed WSS generated filter. The NRZ modulated signal is passed through WSS filter for pre-spectral shaping. This filter is optical band pass filter (OBF) in which transfer function of WSS generated RC, Butterworth and Gaussian filters profiles have been loaded by co-simulation with Matlab. The setup for the filter emulation implemented on a Matlab®/VPI-TransmissionMaker® co-simulation platform is shown in Fig. 3.

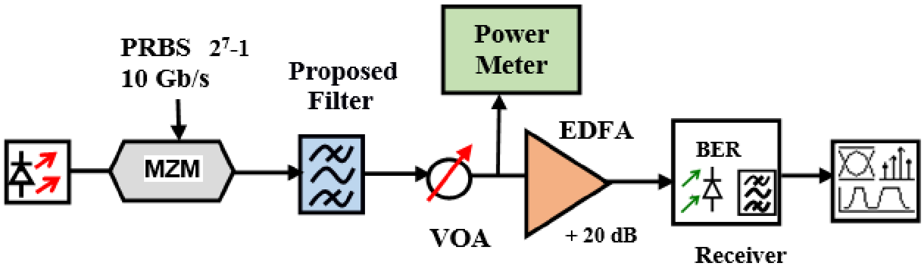

Figure 3. Configuration of Single Channel Transmission with Proposed filter.

The parameters of system components are kept close to real conditions for practical results. As signal propagates through the WSS, there can be a significant power penalty resulting from the filter. Due to the undesirable design, the filters can also induce optical crosstalk from the neighbouring channels [15]. Therefore, it is important to properly characterize the performance of the filter before implementing it in complex superchannels. The spectrally shaped signal is then amplified by Erbium doped Amplifier (EDFA) having 20 dB gain with noise figure of 3 dB to compensate for losses. The signal is received by typical PIN photodetector based direct detection receiver with responsivity of 0.8 A/W. The thermal noise of 10e-10 A/W and shot noise have been taken in to account. The received signal is then passed through a post-detection electrical low pass 2nd order Bessel filter with bandwidth of 75 GHz. The performance of the proposed system is assessed in terms of receiver sensitivity and bit error rate (BER) in back-to-back (B2B). To characterize the WSS channel shape in optical transmission system, three filter profiles like Gaussian, Butterworth and RC has been tested by carrying out simulations.

The performance of RC filter with B_{FWHM}/r=1 at different data rates is shown in Fig. 4. The data rate was varied from r to 6×r without changing filter bandwidth. It can been seen in Fig.4, for the given value of r to achieve target BER of 10^{-9}, the required received power is -34.06 dB. There is 1.38 dB and 2.46 dB power penalty in received power when data rate got doubled and tripled respectively to achieve same BER.

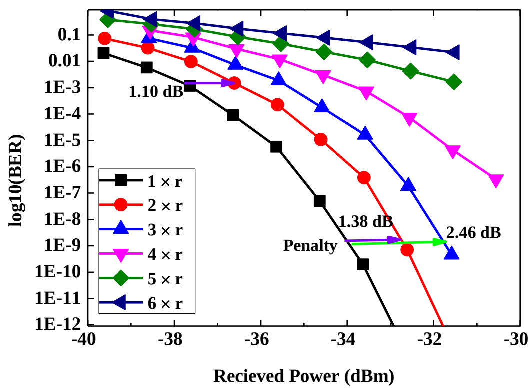

Figure4. RC filter with $B_{FWHM}/r_{=}$ 1 at different data rates.

While considering, the BER of 10^{-3}, the power penalty is approx. 1.5 dB, between r and 3×r which is acceptable for system performance. A relatively larger BER floor for case of higher bit rates is observed as compared to lower data rates. As indicated, the transmitter with a low data rate can improve its performance for fixed channel width. For example, the simulation here used a 10GHz filter, with 10, 20, 30 Gbit/s data. The simulations show that, although a penalty is seen for the first 3 cases, it is small and easily recovered. However, for a sharper and narrower filter in comparison to the data rate, the penalties are much increased.

Looking at this issue further, we explored the impact of different B_{FWHM}/r on the system performance. It is found that for the lower values of B_{FWHM}/r, the power penalty is high as compared to broad bandwidth filters. A power penalty of 1.85 dB is measured between B_{FWHM}/r =1 and 6 as shown in Fig. 5. As the filter become narrower, the performance of system deteriorates.

The different filter shapes will have different impact on signal transmission. In the scope of this work, the performance of different filters have been compared in terms of receiver sensitivity and BER as depicted in Fig. 6. When all the filters are aligned perfectly with the laser's central frequency, the RC filter outperform among other filters with 1 dB power improvement at target BER of 10^{-9}, but with a reduced penalty at BER of 10^{-3} of

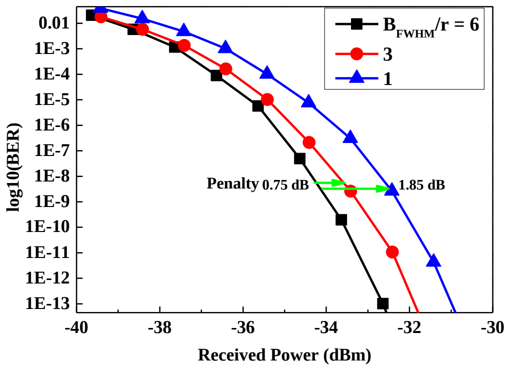

Figure 5. RC filter with different B_{FWHM}/r at 10 Gbps.

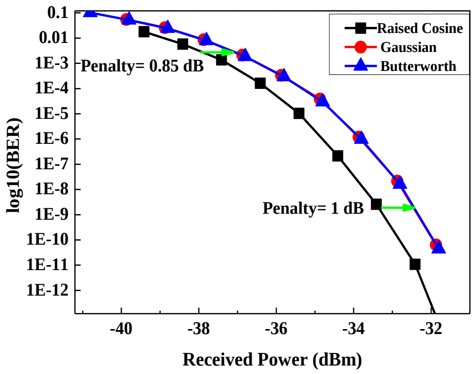

Figure 6. Receiver Sensitivity with different optical filter profiles at B_{FWHM}/r=1 at 10 Gbps.

0.85 dB. The Gaussian and Butterworth performed almost similar to each other. Hence, RC filter is assumed to be a better choice for the optical pre-filtering in complex superchannels.

4. CONCLUSION

We studied the accuracy of the output response of WSS and also investigated the impact of limitations on reducing the spectral roll off. In this work, a method of reducing spectral roll-off by introducing amplitude dip in input filter response of WSS has been discussed. For filter with B_{FWHM}/r =1, the roll-off factor has been reduced by factor of 10.1 % when amplitude dip changed from 0 to 5%. We simulated an optical system to observe the total power penalty caused by different types of WSS generated filters. From the simulation results, we can see that the penalty induced by Gaussian and Butterworth filters is 1 dB larger than that caused by RC filter. The results are also in agreement that in the case of narrow optical filtering, the induced penalty increases for reduced filter bandwidths. It is concluded that WSS is a flexible programmable optical filter but its performance is always limited by low spectral resolution. Breaking this resolution limitation while retaining narrow bandwidth operation would significantly improve the filtering experience with WSS.

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