Performance of 4-ary ASK in Nonlinear, Multi-Channel Environments

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Abstract: This effort focuses on the comparison of On Off Keying (OOK) to incoherent 4-ary Amplitude Shift Keying (ASK). We show that a 0.4 bits/s/Hz improvement in spectral efficiency is obtained by utilising 4-ary ASK. We determined the filter steepness required to achieve this maximum obtainable spectral efficiency. The comparison of OOK and 4-ary ASK in terms of dispersion tolerance for Non-Return-to-Zero and Return-to-Zero is performed. We also prove that cross phase modulation, on its own, should not affect the maximum obtainable spectral efficiency of 4-ary ASK. Finally, we present simulation work showing that 4-ary ASK can potentially increase the capacity of Kerr effect limited DWDM systems. For the first time, comparison of 4-ary ASK and OOK is performed in the nonlinear regime.

1 Introduction.

Multilevel signalling has been the target of research as a means to extend the capacity of optical communication systems. In [1], incoherent 4-ary ASK was examined as a means to enhance the spectral efficiency of an ideal optical system. The conclusion of the work stressed that gain can only be achieved with steep optical filtering. Work by Walklin and Conradi [2], is focused on the extension of dispersion limited systems. Experimental and theoretical results of the same paper proved that 4-ary ASK, as also other multilevel modulation formats, can be used to extend the system reach. Nevertheless, not much practical interest has been shown on 4-ary ASK, due to the inherent 5 dB back to back penalty, inflicted by the fragmentation of the main eye into 3 different eyes.

In this contribution, we are examining the potential improvement, in terms of spectral efficiency, using steep optical filtering in conjunction with 4-ary ASK. We establish the steepness of the optical filter required to offer this capacity advance, as also the maximum attainable spectral efficiency, in the case of cascaded FP optical filters. Then we extend the work in [2] by examining the threshold, in terms of system dispersion (ps/nm), above which multilevel signalling outperforms OOK. The extension includes Non-Return-to-Zero (NRZ) as Return-to-Zero (RZ) coding schemes. Finally, we complement the above work by focusing on nonlinear effects of Cross Phase Modulation (XPM) and the walk-off effect.

2. Spectral Efficiency

Firstly, we consider a basic system as shown in fig. 1. The optical filter is modelled as a cascade of Fabry Perot optical filters, which in the limit of large number of cascaded filters, leads to a Gaussian response. The photodetector assumed is a P-i-N diode, modelled as a square law device, and the electrical receiver effectively modelled as an integrate and dump receiver.

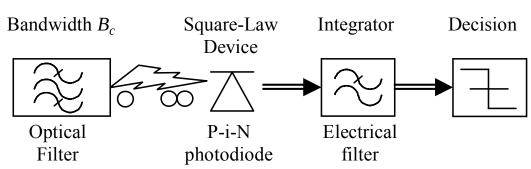

Figure 1. Basic Receiver

Now, by increasing the steepness of the optical filtering process, we examined the effect on the spectral efficiency, as shown in fig.2. Note that the performance is an interplay between adjacent channel interference (ACI) and inter-symbol interference (ISI), so that for each assumed filter, an optimum cut-off frequency exists.

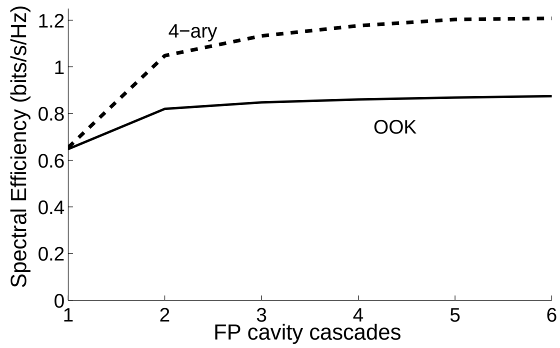

Figure 2. Spectral efficiency vs number of FP cascades, OOK vs 4-ary ASK (back-to-back case).

According to fig. 2, 3 cascaded FP filters (Free Spectral Range of 12 nm) are enough to reach a near optimum spectral efficiency. Further improvement can be obtained by using an electrical filter matched to the detected pulse. Note that the pulses incident to the optical filter are assumed to be Gaussian. The optimum FWHM that are obtained are 60% and 75% for 4-ary ASK and OOK respectively.

3. Dispersion Tolerance

The dispersion tolerance, was first investigated in [2]. Here, we extend the analysis and for the first time NRZ and RZ coded OOK and 4-ary ASK signalling are compared. The system assumed is shown in fig.1, with the introduction of a dispersive fiber followed by an optical pre-amplifier at the receiving end. The main source of dispersion is the fiber, as a single FP optical filter (100 GHz cut-off frequency) is assumed and a 3^{rd} order Bessel electrical filter with a cut off frequency 0.65 T in each case. The optical amplifier assumed has a noise figure of 5.5 dB and a total gain of 22 dB. The extinction ratio of the system is 20 dB. The performance evaluation (BER) is based on a Gaussian approach [3]. This model is found to agree with experimental results, reported in [2], within 1 dB. The patterning effects of the PN sequences are also considered [4], although binary and multilevel de-Bruijn sequences are used in each case.

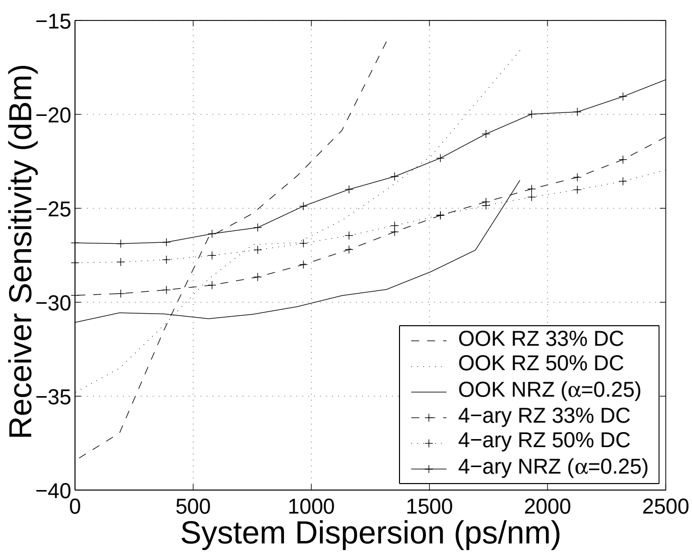

Figure 3. Receiver Sensitivity vs System Dispersion, OOK vs 4-ary ASK, NRZ vs RZ coded formats.

As shown in Fig. 3, OOK outperforms 4-ary ASK for small amounts of system dispersion. However, above 715 ps/nm all the RZ OOK formats lose their advantage to their corresponding 4-ary ASK formats. Finally, above 1800 ps/nm the NRZ OOK format crosses the performance line of the RZ 4-ary ASK formats and 4-ary ASK becomes the dominant format.

4. Walk-off Effect

The enhanced dispersion tolerance the 4-ary ASK modulation format offers, for the RZ format in particular, can be exploited to extend the limit of systems limited by XPM. From [5], a Gaussian pulse spreads as :

$$\alpha = \frac{T_{FWHM}}{T} = \sqrt{1 + L^2 / L_D^2} \tag{1}$$

where T is the symbol period, T_{FWHM} is the Full Width at Half Maximum of the Gaussian pulse, L_D is the dispersion length, defined as:

$$L_D = \frac{T_0^2}{|\beta_2|} \tag{2}$$

T_0 is the 1/e width of the pulse and β_2 is the GVD parameter. In a WDM system, in order to allow for the Cross Phase Modulation to cancel, we demand the transmitted distance to be equal to a multiple of the walk-off length:

$$L_W = \frac{T}{|D|\Delta\lambda} \tag{3}$$

where D the dispersion parameter and Δλ the channel spacing.

From (1)-(3), we can derive an expression for the spectral efficiency by using a constraint for the pulse interference, expressed as the width spread α. This results in a spectral efficiency given by:

$$\eta = \frac{2\pi (DC)^2}{4\ln 2} \frac{R}{B} \sqrt{\frac{\alpha^2}{(DC)^2} - 1} \text{ bits/s/Hz} \tag{4}$$

where R is the bit rate, B is the bandwidth of the modulation format and DC the duty cycle. The optimum duty cycle corresponding to (4) is $\alpha\sqrt{2}$. In Fig.4, we plot the spectral efficiency for α = 1. Clearly, the combined effect of dispersion tolerance and walk-off effect offers a twofold advantage of 4-ary ASK as opposed to OOK. In addition, this result shows that the maximum achieved theoretical limit of 2 bits/s/Hz for 4-ary ASK, even in the presence of noise [6], is not affected by XPM.

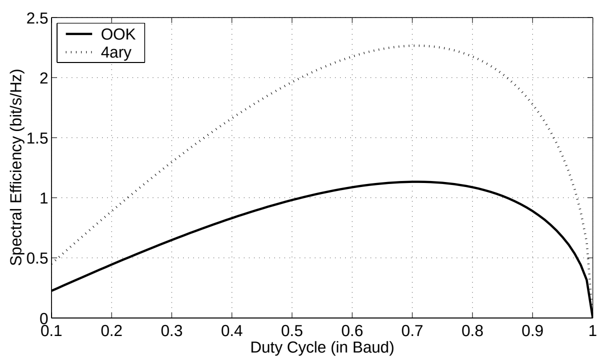

Figure 4. Spectral Efficiency vs Duty Cycle

5. Simulation Results

In order to verify the advantage of 4-ary ASK against OOK in the nonlinear fiber regime, we performed simulations in MATLAB®. We assumed an optical network with total length of 360 km and 8 channels with 50 GHZ channel separation. Fiber loops of 60 km were assumed and a 100% dispersion and attenuation compensation was utilised between loops. At the output, BER measurements were conducted assuming a filtered optical pre-amplifier. In fig. 5, Q_{eq} on the y-axis of each graph refers to the equivalent Q required to produce the measured BER. The comparison between OOK and 4ary ASK shows that although OOK has an initial advantage over 4-ary ASK for low amounts of nonlinear effect, as the power and therefore the impact of the Kerr effect increases, there is a region where 4-ary ASK outperforms OOK. This was observed for RZ pulses with 50%DC and NRZ coded signals. On the other hand, for RZ coded signals with 33% DC no advantage was observed.

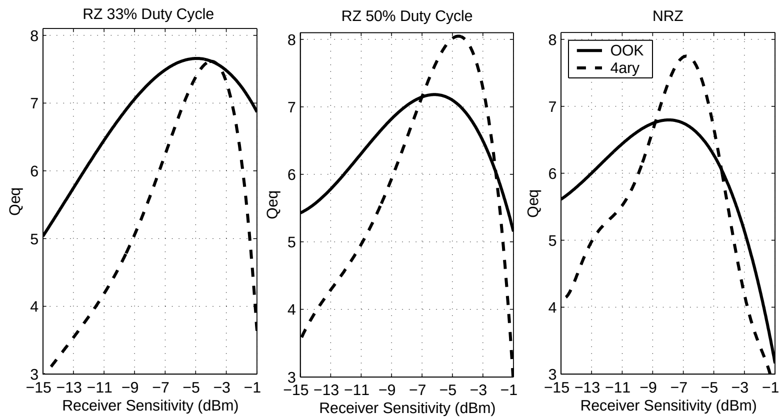

Figure 5. Kerr effect impact as a function of Q versus the receiver sensitivity.

7. Conclusions.

Multilevel signalling has a significant back-to-back penalty of 5 dB, compared to OOK, which makes this signalling scheme less attractive in single channel transmissions. However, an advantage can be gained if 4-ary ASK is utilised to increase the spectral efficiency when steep optical filtering equivalent to 3 or more cascaded FP filters is used. In addition, 4-ary ASK has greater dispersion tolerance and this feature enables its use under certain regimes which are restricted for OOK signalling. This effort showed that 4-ary ASK can be utilised at the edges of the dispersion maps in the system dispersion region above 1800 ps/nm to extend the information capacity. Also, we showed that the effect of XPM should not provide a limit to the theoretical optimum spectral efficiency. Finally, simulation results showed that indeed in DWDM systems, with channel spacing of 50 GHz, performance can be improved under certain operating regions with multilevel signalling.

Future work will include the examining of the four-wave-mixing effect for 4-ary ASK in ultra dense WDM systems.

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