Characterisation and modelling of a Distributed Raman Amplifier (DRA) in an OTDM/WDM system

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This paper describes the application of Distributed Raman amplification (DRA) in high capacity systems, based on Optical Time Division Multiplexing (OTDM) over Wavelength Division Multiplexing (WDM).
A theoretical investigation of the performance of a (160 Gbit/s $\times$ *n* λ*) OTDM/WDM system based on the estimated Bit Error Rate (BER) is presented. In this system, the aggregate amount of data increases along the transmission path as single WDM channels (at* $\geq$ *400 GHz spacing) are added at each node. The maximum inter-node distance of the backward pumped DRA is varied between 30 and 100 km and is completely dispersion-managed. Error free transmission (BER* $\leq 10^{-9}$*) is obtained for all channels.*

Introduction

This paper describes the application of Distributed Raman amplification (DRA) in a scalable, multi-terabit optical fibre network for the next generation radio telescopes based on the LOFAR (LOw Frequency ARray) concept [1]. The architecture of the LOFAR network is a six-fold star with three short and three long arms. New channels (carrying the data of an antenna station) will be added in optical nodes along the way to the central data processor unit. Distributed along the long arms (circa 250 km), the data of 28 stations will be added, while the short arms (circa 65 km) carry the data of 14 stations [2].
Raman amplification has been successfully implemented in long haul telecommunication systems operating around 1.55 μm [3]. However, in the investigated system, the aggregate amount of data increases along the transmission path as single WDM channels (at $\geq$ 400 GHz spacing) are added at each node.
The data, as presented in this work, is obtained from numerical simulations using the Virtual Photonics Integrated software. In this study, where the focus is on 160 Gbit/s transmission using DRA, the OTDM multiplexing and demultiplexing functions are simplified to a transmitter / receiver pair operating at 160 Gbit/s line-rate.

(160 Gbit/s $\times$ 3 λ) OTDM/WDM system

The system under investigation contains three transmitters along the transmission span. Each transmitter generates a 2^7-1 PRBS (Pseudo Random Bit Sequence) RZ (Return-to-Zero) data pattern at 160 Gbit/s. The peak power of the optical pulses with soliton shape is 8 mW, while the (fwhm) pulse duration is $\frac{1}{4}\times$bit time (1.56 ps). The WDM channels are spaced at 400 GHz, the absolute wavelengths are λ_1=1549.3 nm, λ_2=1552.5 nm and λ_3=1556.5 nm respectively.
The chromatic dispersion of each TWRS (True Wave Reduced Slope) fibre span is compensated using a DCF (Dispersion Compensation Fibre) module. The composite fibre

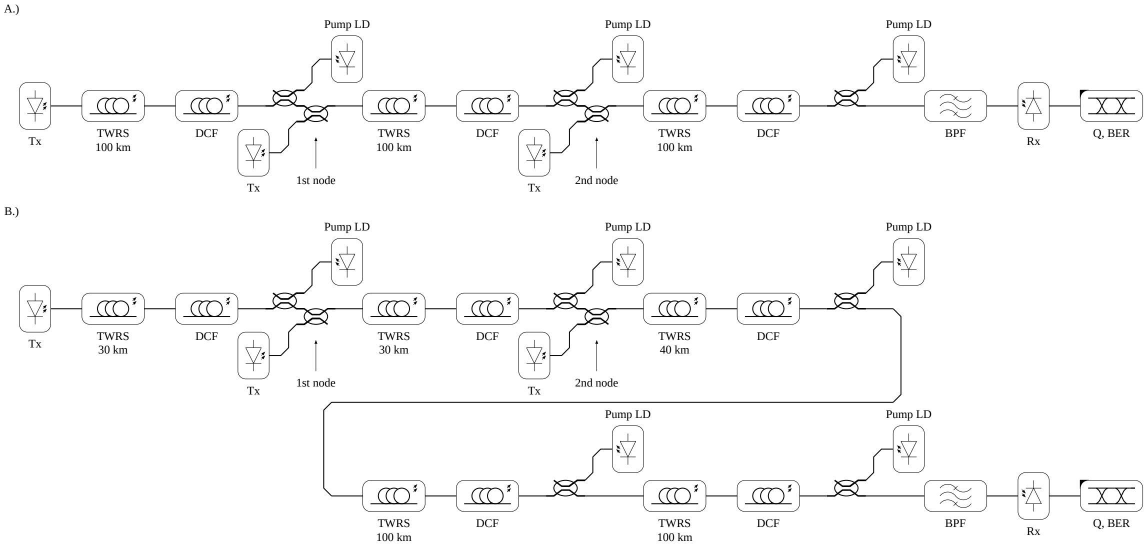

Figure 1: Set-up of 160 Gbit/s × 3 λ OTDM/WDM system a) 3×100 km, and b) $(30+30+40) + 2 \times 100$ km

spans are backward pumped at λ_{pump}= 1454.4 nm using a single pump LD (Laser Diode). The pump wavelength λ_{pump} is 110 nm (blue) shifted in order to obtain a maximum gain at the signal wavelengths [3]. A pump power of approximately 800 mW is needed to compensate fibre and coupling losses of a composite 100 km span. In the add-nodes, 3 dB couplers are used. Per 100 km of TWRS fibre a DCF module of 4.7 km is applied. The small core area (15×10^{-12} m^2) of the DCF (compared to 55×10^{-12} m^2 for TWRS) enhances the Raman amplification process [4].

In the first case (see Figure 1a), the three channels λ_3, λ_2 and λ_1 are introduced at 300, 200, and 100 km from the receiver. At each add-node, an optical bandpass filter is applied.

In the second case (Figure 1b) the channels are added at 300 (λ_1), 270 (λ_2) and 240 km (λ_3) from the receiver. In this case, the 30 and 40 km spans are dispersion compensated and pumped individually. Subsequently, the composite signal is sent over two 100 km spans to the receiver end.

At the receiver, the WDM channels are demultiplexed. The receiver provides both data and clock recovery. The system performance is evaluated by estimating the Bit Error Rate (BER) using the Gaussian approximation. The influence of Inter Symbol Interference (ISI) is also taken into account.

Results and discussion

160 Gbit/s × 3 λ OTDM/WDM over 3 × 100 km

The spectra of the transmitted signal and the received signals are shown in Figure 2. In the receiver section the individual WDM channels are demultiplexed using optical filters with 3 dB bandwidth of 3 nm. The suppression of the neighbouring channels in this demultiplexer is ≥ 20 dB.

The Bit-Error-Rate curves for the first case are shown in Figure 3. For all channels, the

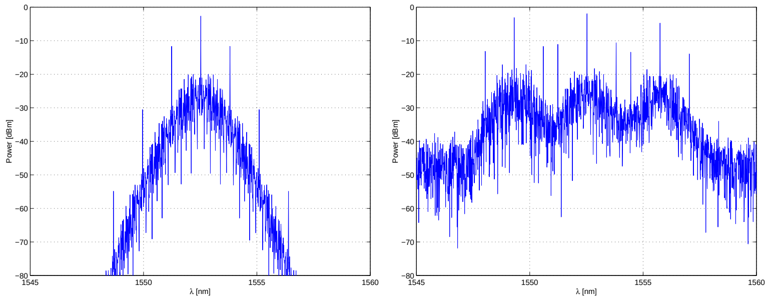

Figure 2: Spectrum of 160 Gbit/s and composite spectrum of channel 1,2, and 3 at the receiver section

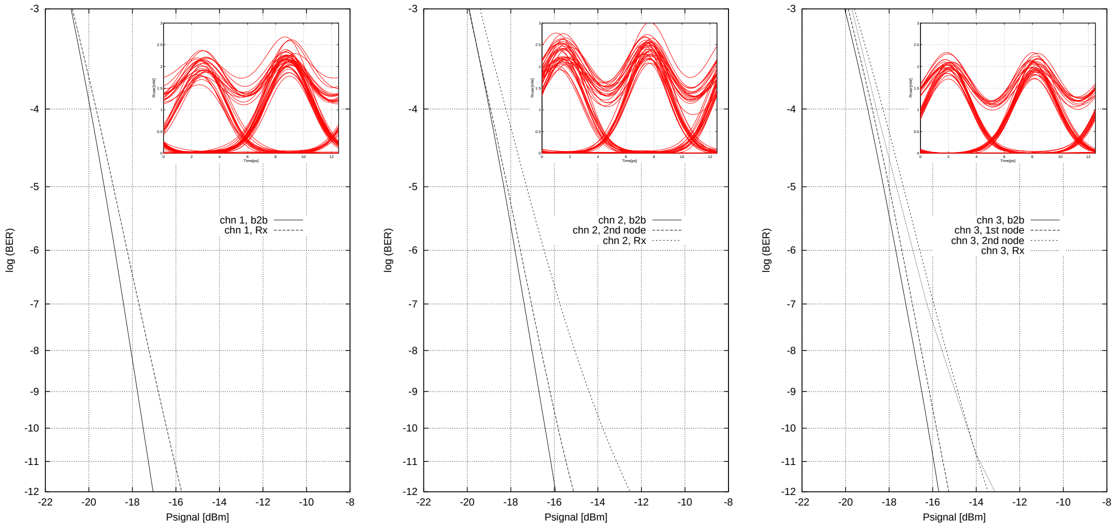

Figure 3: Bit-Error-Rate curves (1^{st} case). a) channel 1: B2B and Rx; b) channel 2: B2B, 2^{nd} node and Rx; c) channel 3: B2B, 1^{st}, 2^{nd} node and Rx. Each inset shows the corresponding eye-diagram at the receiver.

BER of the received signals are compared with the BER of the transmitted signal (Back-to-Back, B2B). For channel 2 and 3, the BER of the signals at the intermediate add-nodes is also depicted. The BER graphs indicate an increasing penalty as the number of add-nodes and hence the transmission distance increases. The maximum penalty of 2.4 dB is obtained for the central channel λ_2. Error free transmission (BER $\leq 10^{-9}$) is obtained for all three channels.

160 Gbit/s × 3 λ OTDM/WDM over (30+30+40) + 2 × 100 km

In Figure 4, the Bit-Error-Rate curves for the second case are shown. The performance of the transmitted signal (B2B) is compared with the BER of signals at a distance of 200 km, 100 km before and at the receiver.

Due to the additional coupling losses (pump-signal WDMs) the performance is slightly deteriorated.

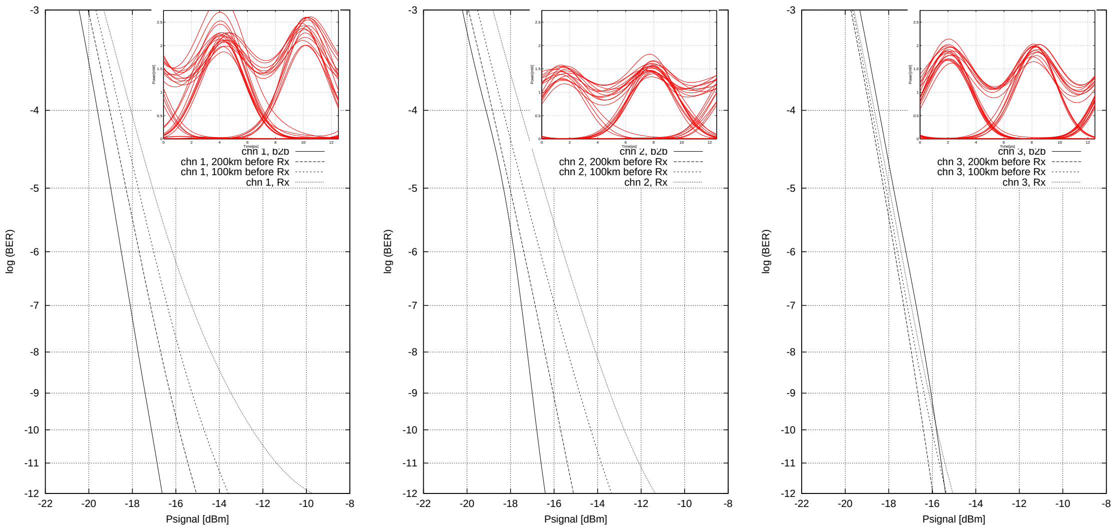

Figure 4: Bit-Error-Rate curves (2^{nd} case). a) channel 1 b) channel 2 c) channel 3 B2B, 200 km before, 100 km before and at the Rx. Each inset shows the corresponding eye-diagram at the receiver.

Conclusion

A theoretical investigation of the performance of a (160 Gbit/s $\times$ n λ) OTDM/WDM system was presented. In this system, the aggregate amount of data increases along the transmission path, as single WDM channels (at $\geq$ 400 GHz spacing) are added at each node. The maximum inter-node distance of the backward pumped DRA is varied between 30 and 100 km and is completely dispersion-managed. A maximum penalty (based on the estimated Bit Error Rate) of 2.4 dB was obtained for the 3×100 km system. For the $(30+30+40) + 2 \times 100$ km transmission, a maximum penalty of 4.0 dB was observed. These simulation results indicate that the use of DRA in aggregate OTDM/WDM systems is feasible.

Acknowledgements

Part of this work was carried out within the framework of the B4-RETINA project.

References

[1] J.D. Bregman, ”Concept design for a low frequency array”, *SPIE Proc. of Astronomical Telescopes and Instrumentation 2000, Radio Telescopes*, Vol. 4015, Mar. 2000.

[2] A.M.J. Koonen and H. de Waardt and J.G.L. Jennen and J. Verhoosel and D. Kant and M. de Vos and A. van Ardenne and E.J. van Veldhuizen, ”A very high capacity optical fibre network for large-scale antenna constellations: the RETINA project”, *Proceedings of the 6th European Conference on Network & Optical Communications*, Ipswich, UK, June 2629, 2001.

[3] S. Namiki and Y. Enimori, ”Ultrabroad-band Raman amplifiers pumped and gain-equalized by wavelength-division-multiplexed high-power lasers”, *IEE J. Sel. Topics Q. Electron.*, Vol. 7, No. 1, pp. 3–16, 2001.

[4] Agrawal, G.P., ”Nonlinear fiber optics” Academic Press, 3rd edition, 2001.