curves, the additional Rake branches gave the VSB system a substantial performance gain.

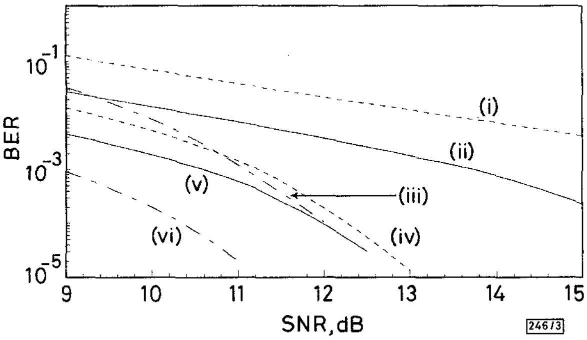

**Fig. 3** *BER performance in PCS 6-path multipath fading channel*

(i) VSB system with three Rake branches, $\sigma_I^2/\sigma_N^2 = 1$
(ii) DSB system with three Rake branches, $\sigma_I^2/\sigma_N^2 = 1$
(iii) VSB system with six Rake branches, $\sigma_I^2/\sigma_N^2 = 1$
(iv) VSB system with three Rake branches, no MAI
(v) DSB system with three Rake branches, no MAI
(vi) VSB system with six Rake branches, no MAI

*Conclusion:* Using simulations, it was shown that the VSB/QPSK/W-CDMA scheme can provide a significant saving in bandwidth compared with that required for the DSB system, without serious performance degradation in the frequency flat fading channel. However the VSB scheme showed serious performance degradation compared to its DSB counterpart in the multipath fading environment. The presence of MAI caused the performance gap between the two systems to widen even further. It is suspected that the intersymbol interference (ISI) caused by multipath reception and MAI impaired the spectrum reconstruction process in the VSB/QPSK/W-CDMA receiver. To compensate for the VSB system's poor performance, additional path diversity techniques were used. The use of additional Rake branches was found to be very effective in improving the VSB system's performance. In this case there is a definite trade-off between spectral efficiency and system complexity.

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# Collision-induced timing jitter reduction by periodic dispersion management in soliton WDM transmission

E.A. Golovchenko, A.N. Pilipetskii and C.R. Menyuk

*Indexing terms: Jitter, Soliton transmission, Wavelength division multiplexing*

The authors propose to use dispersion management to reduce collision-induced timing jitter in soliton WDM transmission. The performance of dispersion-managed fibres is compared numerically to dispersion-decreasing and uniform dispersion fibres with up to eight channels, and it is shown that dispersion management can provide the best performance.

The principal source of errors in soliton wavelength-division-multiplexed (WDM) transmission is collision-induced timing jitter [1 – 3]. Because standard transmission lines have lumped amplification, the four-wave mixing fields from soliton collisions grow uncontrollably, even when the spacing between amplifiers is much smaller than the soliton collision length, adding amplitude and timing jitter to the jitter due to ideal soliton collisions. In [2], it was proposed that dispersion-decreasing fibre (DDF) could be used to reduce the four-wave mixing fields and thus reduce the influence of soliton-soliton collisions. In this Letter, we show that dispersion management is a viable alternative to DDF. Dispersion-managed fibres, i.e. fibres with dispersion maps that alternate in sign, have long been used in non-return-to-zero transmission [4], and recent work indicates that it has advantages for soliton transmission as well [5 – 7]. Remarkably, our computational results show that in some cases solitons in dispersion-managed fibres can actually suffer less impairment than solitons in ideal DDF with the same average dispersion.

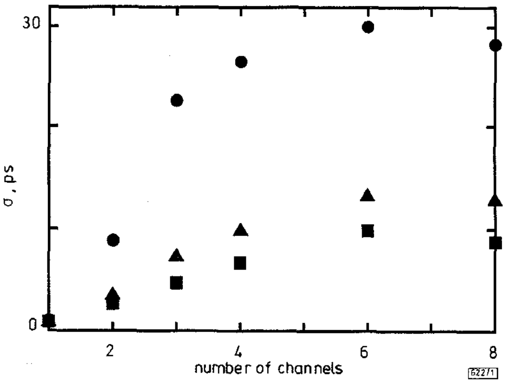

**Fig. 1** *Standard deviation of timing jitter averaged over all channels against number of channels at z = 5000km for uniform dispersion fibre, dispersion-managed fibre, and dispersion-decreasing fibre*

Channel spacing is equal to 12 pulse spectral widths
● uniform dispersion fibre
▲ dispersion-managed fibre
■ dispersion-decreasing fibre

To date, we have carried out computer simulations with up to eight WDM soliton channels with no in-line filtering. Each channel was filled with a pseudo-random 32bit sequence of 20ps solitons spaced in time by 5FWHM. The amplifier spacing was 40km, fibre losses were 0.2dB/km, the path-averaged anomalous dispersion was $D$ = 0.5ps/nm-km with $D'$ = 0. The amplifiers exactly compensated for the fibre loss. We studied a fibre with uniform dispersion, a DDF with an ideal exponential taper, and a periodically dispersion-managed fibre. The dispersion map that we propose consists of a 35km fibre with normal dispersion $D$ = –2ps/nm-km which is followed by a 5km fibre with $D$ = 18ps/nm-km. The map consisting of the two fibres with alternating dispersion is not necessarily optimal. Our choice was based on the simplicity of such a map which can be easily constructed from standard telecommunication fibre with zero dispersion ~$\lambda$ = 1.3µm and a dispersion-shifted fibre. We do not include Gordon-Haus timing jitter to focus on collision-induced timing jitter. The length of the dispersion map was not long enough to require power-enhanced solitons [8]; so, the path-averaged power and duration of the solitons was approximately the same in all cases. To reduce the initial partial collision, the soliton sequences in neighbouring channels were shifted by half a time slot. The simulations were carried out using a split-step Fourier method to solve the nonlinear Schrödinger equation. We simulated signal propagation up to 5000km.

We found that for a single channel all three dispersion maps perform the same. Fig. 1 shows timing jitter averaged over all channels against the number of channels when the channels are spaced apart by 12pulse spectral widths. The system with DDF has slightly better performance than the system with dispersion-managed fibre, which in turn performs much better than the system with uniform dispersion fibre. The collision length of the pulses in neighbouring channels in this case is close to the amplifier spacing, so that the collisions are resonant, leading to large residual frequency shifts of the solitons in the uniform dispersion fibre [1]. DDF completely eliminates the residual frequency shifts and relaxes the condition on the amplifier spacing [2]. The dispersion-managed fibre significantly reduces the residual frequency shifts because the collisions are incoherent. Owing to the alternating sign and large local magnitude of the dispersion, solitons that are colliding repeatedly but rapidly pass through each other with phases that are incoherently related on each pass. The effect is to strongly reduce the residual frequency offset relative to the constant dispersion fibre. Moreover the total collision length becomes larger and the resonance condition on amplifier spacing is disrupted. Overall, this leads to timing jitter reduction and to less spread in the timing jitter from channel to channel. Additionally, soliton interactions in the same channel are reduced. The large difference between a system with three or more channels and a two-channel system is due to three-soliton collisions [9] that cause an energy exchange between channels.

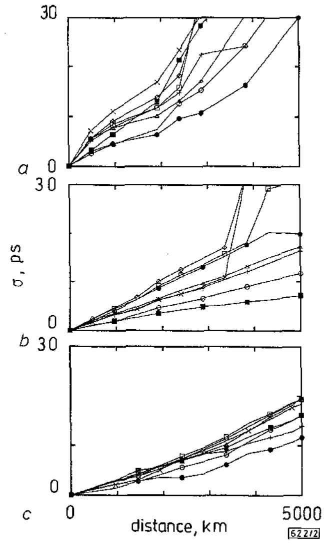

**Fig. 2** *Standard deviation of timing jitter against propagation distance for eight-channel WDM system with channel spacing equal to 6 pulse spectral widths*

*a* Uniform dispersion fibre
*b* Dispersion decreasing fibre
*c* Disperison managed fibre
Channels numbers: ○ 1, □ 2, ◇ 3, × 4, + 5, △ 6, ● 7, ■ 8

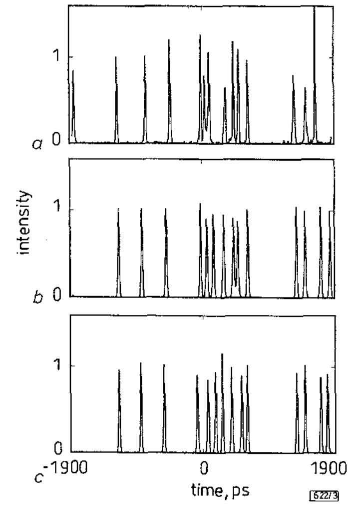

**Fig. 3** *Pulse trains in demultiplexed 4th channel of eight-channel WDM system at 5000km*

Pulse intensity is normalised to intensity of average soliton in transmission line with lumped amplification
*a* Uniform dispersion fibre
*b* Dispersion decreasing fibre
*c* Disperison managed fibre

Fig. 2 shows the calculated standard deviation of the timing jitter against transmission distance for an eight-channel WDM system with a channel separation equal to six pulse spectral widths. Remarkably, for this case the dispersion-managed fibre demonstrates the best performance. This fact is surprising since the behaviour of solitons in an ideal DDF is described exactly by the unperturbed nonlinear Schrödinger equation. The timing jitter in the side channels for DDF is low, but drastic errors occur in the central channels - the channels that are most strongly affected by the collisions. The central channel's pulse train is shown in Fig. 3. The amplitude jitter in the dispersion-managed fibre is larger than in the dispersion-decreasing fibre, as is the power of the four-wave mixing field, as shown in Fig. 4. Nevertheless, the dispersion-managed solitons are less impaired overall. Figs. 2 and 3 show that the system with dispersion-decreasing fibre suffers large impairments when timing jitter brings solitons in the same channel close enough together to strongly interact.

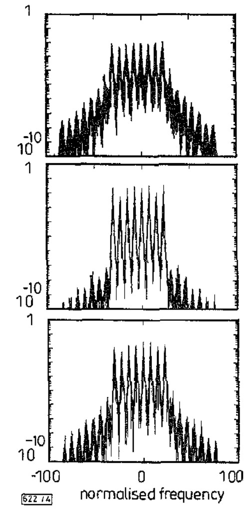

**Fig. 4** *Spectrum of eight channel WDM system at z = 5000km on logarithmic scale with channel spacing equal to 6 pulse spectral widths*

Pulse intensity is normalised to the intensity of average soliton in transmission line with lumped amplification
*a* Uniform dispersion fibre
*b* Dispersion decreasing fibre
*c* Disperison managed fibre

We now briefly consider the implications of our results for system design. Our results are consistent with previous work [2] which showed that DDF drastically improves system performance. Unfortunately, the tradeoff is that DDF must be carefully positioned in a system and requires a special manufacturing process, so it is expensive and therefore not attractive to system designers. Our new results indicate that dispersion-managed fibre, which is just a combination of standard and dispersion-shifted fibres with alternating dispersion signs, performs comparably or even better than DDF, drastically simplifying the system design.

We conclude that dispersion management is a highly promising technology for WDM soliton transmission.

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# Design and demonstration of hybrid AM-VSB/digital WDM video trunking system with cascaded EDFAs

Hongxing Dai, Jinyi Pan and Chinlon Lin

*Indexing terms: Wavelength division multiplexing, Video signals*

The authors have analysed and designed a five-channel (one AM-VSB and four 2.5Gbit/s baseband digital) hybrid WDM system, with cascaded in-line EDFAs for high capacity video trunking applications. Simultaneous transmission of high quality AM-VSB signals with CNR > 50.5dB and four 2.5Gbit/s digital channels with negligible power penalty over 105km of standard singlemode fibre is demonstrated.

Recently, there has been an increasing interest in hybrid wavelength division multiplexing (HWDM) technology for delivering both AM-VSB and digital video signals through separate wavelength channels [1 – 3]. An HWDM video trunking system offers flexibility in utilising the fibre bandwidth to increase the network capacity. With HWDM technology, analogue video signals carried on the fibre backbone trunking network can be directly interfaced with the hybrid fibre coax (HFC) distribution network, without going through the complicated and costly signal format conversion.

In the design of an HWDM system with cascaded in-line EDFAs, the major challenge is to meet the stringent carrier-to-noise ratio (CNR) requirements for analogue channels while maintaining adequate transmission performance for digital channels. Previous work on hybrid AM-VSB/M-QAM video trunking with cascaded EDFAs has shown that high quality analogue video transmission (CNR $\simeq$ 50dB with negligible distortion) is achievable with each in-line EDFA operating in deep saturation ($P_{in} \geq$ 3dBm) [4, 5]. In an HWDM system, however, the desired operating point for the analogue channel leads to a dramatic difference in optical signal levels between analogue and digital channels at the input of in-line EDFAs, owing to the relatively low output power used in digital lightwave transmitters. Consequently, the operating point of each in-line EDFA is dominated by the analogue channel and the digital channels benefit only from the saturated gain, rather than the much higher small-signal gain as in a purely digital system with cascaded in-line amplifiers. From a system design point of view, it is important to balance the optical signal level requirements for both analogue and digital channels by appropriately choosing a target link power budget to adequately ensure the AM channel's CNR and the digital channel's signal-to-noise ratio (SNR) at the optical receivers.

In this Letter, we analyse and design a five-channel (one AM-VSB and four 2.5Gbit/s baseband digital) hybrid WDM system with two cascaded in-line EDFAs. With the operating point of each in-line EDFA determined through a computer simulation, we demonstrate the simultaneous transmission of high quality AM-VSB signals with CNR > 50.5dB and four 2.5Gbit/s digital channels with negligible power penalty over 105km of standard singlemode fibre.

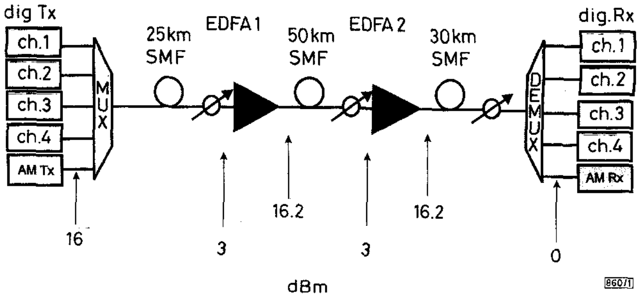

**Fig. 1** *5-channel hybrid WDM system with four 2.5Gbit/s digital channels (at 1546.2, 1547.8, 1549.4 and 1551nm, channel spacing ~1.6nm) and one AM-VSB channel (at 1557.4nm)*

In-line EDFAs pumped at 980nm with 70mW pump power; operating point for analogue channel is indicated along the link

Fig. 1 shows a schematic diagram of the HWDM link under consideration. The four digital channels are placed at 1546.2, 1547.8, 1549.4 and 1551nm, with channel spacing of ~1.6nm (200 GHz), as used in the MONET project [6]. The single analogue channel is placed at 1557.4nm, which is near the long end of the EDFA gain spectrum to take advantage of the larger saturated gain and, more importantly, is well separated from the digital channels to minimise cross talk penalty. The output power of the analogue laser transmitter, which uses an externally modulated DFB laser with a built-in mechanism for stimulated Brillouin scattering suppression (SBS), is 16dBm; that of the digital transmitter is 0dBm. The input optical power of the analogue channel is set at 3dBm at both in-line EDFAs. The WDM multiplexer (MUX) and demultiplexer (DEMUX) used here are interference-filter based devices with an insertion loss varying between 2.5dB (at the AM channel) and 4.5dB for the concerned wavelength span and adjacent channel isolation ≥ 35dB.

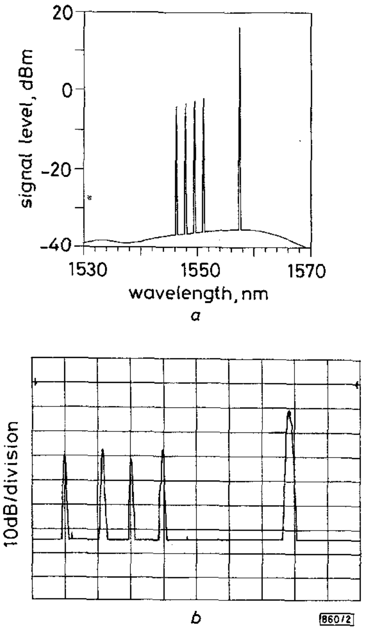

**Fig. 2** *Spectral output for 5-channel hybrid WDM system*

*a* Simulated output of second EDFA
*b* Spectrum measured in front of DEMUX
Centre 1552.60nm, span 16.35nm

To understand the effect of the gain saturation of the cascaded in-line EDFAs on both analogue and digital channels, we first simulated the EDFA performance with a spectrally resolved numerical model [7]. Fig. 2*a* shows the spectral output after the second in-line EDFA. As expected, the amplifier is saturated by the analogue optical channel with a saturated output power of 16.2dBm. Conversely, the digital channel outputs are between –2 and –4.1dBm, where the signal level difference (>2dB) is due to the accumulated gain differential along the EDFA cascades. For the analogue channel to be received at 0dBm optical power after