Multi-Carrier Systems for High-Capacity Transmission

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Abstract – We discuss recent advances in multi-carrier transmission systems for high capacity optical networks.

1. Introduction

The design of cost-effective optical transmission systems is increasingly constrained by the trade-off between high capacity and the consequent increased transmission impairments. Multi-carrier techniques [1-4] with channel spacing equal to the symbol rate of each sub-channel, either optically multiplexed (coherent wavelength division multiplexing (CoWDM) [1,2]), or electronically generated (orthogonal frequency division multiplexing (OFDM) [3-5]), offer the prospect of high aggregate capacity and spectral efficiency, with dispersion tolerance scaled with the symbol rate of each sub-carrier. In this paper, we discuss the implementation of multi-carrier optical transmission system and numerically investigate its performance characteristics over existing dispersion managed links limited by fibre nonlinearity. We will also examine electronic signal processing for residual inter-channel crosstalk mitigation and dispersion compensation to establish an optimum signal structure.

2. Transmitters and Receivers

Multi-carrier systems make use of closely spaced orthogonal sub-carriers to carry data. The OFDM technique performs sub-channel multiplexing and de-multiplexing in the electrical domain using digital signal processing (DSP), and transmits and detects the multiplexed signal optically [3-5]. Consequently, the DSP complexity and the modulator and receiver bandwidth scale with the total OFDM capacity.

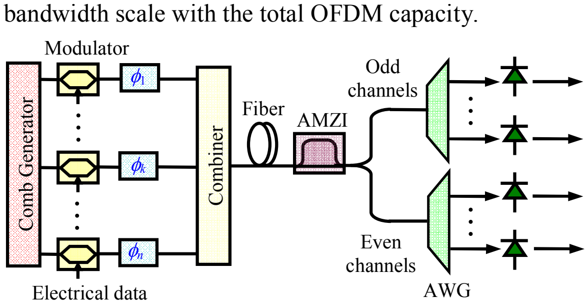

Figure 1: Direct-detection CoWDM system

In contrast, the sub-channels in a CoWDM system are modulated, multiplexed, demultiplexed in the optical domain, as shown in Fig. 1. Sub-carriers are generated by an optical comb generator, with the carrier spacing precisely equal to the symbol rate. The operating speed of the transmitters and receivers only scales with the sub-channel capacity. 600Gbit/s on-off keying (OOK) CoWDM signal transmission with 43Gbit/s per channel was experimentally demonstrated in our group [2].

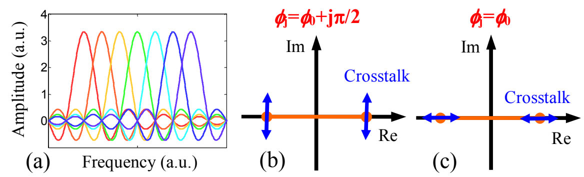

Figure 2: Schematic representation of (a) an example of orthogonal sub-channels, (b) and (c) PSK signals with residual inter-channel crosstalk for different sub-carrier phases.

Orthogonality between OFDM sub-channels is achieved by DSP, and for CoWDM, by combination of optical and electrical components. Fig. 2(a) shows a typical example of orthogonal sub-channels. Stringent design specifications for the CoWDM demultiplexing filter are required for crosstalk free operation. One optimized optical demultiplexer consisted of a half bit delay asymmetric Mach-Zehnder interferometer (AMZI) followed by an arrayed waveguide grating (AWG) (Fig. 1) [1]. However, residual inter-channel crosstalk still exists, the impact of which depends on the phases of the sub-carriers, ϕ_j. Fig. 2(b) and (c) show the constellation map of a PSK signal with residual crosstalk for different sub-carrier phases. Control of the phases of each sub-channel such that each is incremented by π/2 with respect to its neighbour enables the elimination of signal-crosstalk beating at the decision point.

3. Transmission Nonlinearity

Recently, a combination of optical and electrical multiplexing has been proposed to access high capacities [5], allowing scaling of OFDM capacities. The optimum symbol rate per channel will thus be determined by the characteristics of the transmission line. To establish the impact of fibre non-linearity on the optimum symbol rate, numerical simulations were carried out using VPI Transmission Maker v.7.5. The simulations we performed used NRZ modulated CoWDM signals, with varied sub-carrier spacing for a fixed total capacity of 550Gbit/s. This total rate was chosen to allow for 1-TbE transmission with polarisation multiplexing [2]. The transmitter/receiver implementations are shown in Fig. 1, with initial phases of each sub-channel being $\phi_j=\phi_0+j\pi/2$. The simulation conditions ensured a minimum of 16 samples per bit, 1150Gsample/s with 1024 total simulated bits, and 32 bits for each sub-carrier for all simulated channel spacing values. The passively multiplexed signals were transmitted over 2,000km fibre links (Table 1), with an amplifier spacing of 50km and three different dispersion maps, two representative of installed systems: inland [6] and submarine [7], and one without any dispersion compensation [5]. In all cases, residual dispersion compensation was 100%

compensated in the optical domain before photo-detection, although it could also be achieved using electronic signal processing, as shown in Section 4.

Map	Positive Dispersion Fibre				Negative Dispersion Fibre			
	L	*α*	*D*	*γ*	*L*	*α*	*D*	*γ*
1	50	.2	17	1.3	6.6	.38	-127	5
2	33	.187	18.5	1.04	17	.24	-37	3.9
3	50	.2	17	1.3	n/a	n/a	n/a	n/a

Table 1: Fibre parameters used for numerical simulation showing length L (km), loss α (dB/km), dispersion D (ps/nm/km) and non-linear coefficient γ (/W/km).

At the receiver, a 3rd order Gaussian-shaped AWG was assumed with a bandwidth equal to 1.8 times the symbol rate. The overall estimated *Q* factor was obtained by averaging bit error rate (BER) for all channels after individual *Q* estimation of each channel.

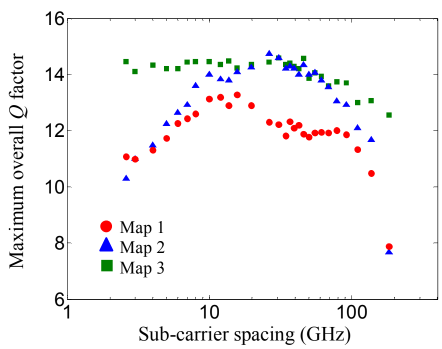

Figure 3: Variation of maximum Q factor with sub-carrier spacing for a fixed total data rate of 550Gbit/s

The simulation results are shown in Fig. 3, which illustrates the variation in *Q* factor with channel spacing. Below 10GHz sub-carrier spacing, inter-channel FWM dominated for Maps 1 and 2, and Map 3 (no in-line dispersion compensation) offered the best performance. For spacing between 10GHz and 100GHz, Maps 2 and 3 performed equally well whereas Map 1 was degraded, likely due to larger self-phase modulation effect. For both existing installed maps, optimum symbol rates may be clearly observed, corresponding closely to the data rates for which the maps were originally designed (10 Gbit/s for Map 1 and 40 Gbit/s for Map 2).

4. Electronic Signal Processing

A further compromise between OFDM and CoWDM relates to the electronic signal processing capabilities at the receiver, which is inherently part of the OFDM detection process. Maximum a posteriori probability (MAP) detection was proposed for CoWDM using channel-by-channel decisions [8]. The proposed MAP detector, as shown in Fig. 4, decodes each sub-channel using the signal levels of the particular sub-channel and of adjacent sub-channels, and can compensate deterministic inter sub-channel crosstalk as well as inter-symbol interference. Each MAP circuit only relies on the information from adjacent sub-channels, and so decoding complexity does not restrict the total data rate.

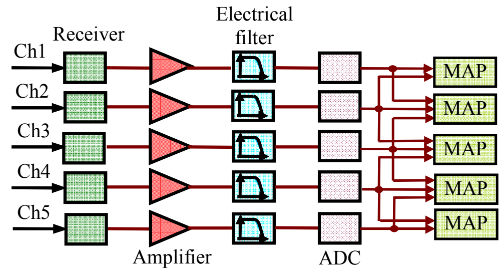

Figure 4: MAP detector in a five-channel CoWDM system

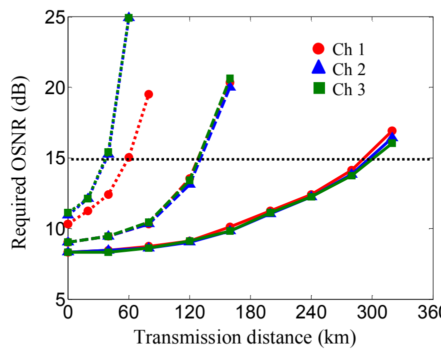

Figure 5: Required OSNR versus fiber length for hard decision (dotted), direct detection with MAP (dashed) and coherent detection with MAP (solid)

Fig. 5 shows the performance of MAP detection in a five-channel OOK-based CoWDM system with 10Gbit/s per channel. This bit rate matches the optimum sub-channel data rate in existing installed links (Fig. 3), and is achievable in modern DSP. The simulation setup was as described above, but with an AWG bandwidth of 0.1nm, and with transmission over single mode fibre without optical dispersion compensation. The results show that MAP detection greatly reduced back-to-back residual crosstalk and extended the transmission reach. In particular, coherent-detection based MAP can achieve optically-uncompensated transmission up to 300km at 15dB OSNR.

5. Conclusions

CoWDM systems, operating at data rate per channel in the region of 10 to 40Gbit/s, minimise the impact of nonlinear effects. This technique, when using MAP detection with reduced residual crosstalk and improved dispersion tolerance, enables a seamless migration from current networks to high capacity networks based on multi-carrier systems. This material was supported by the Science Foundation Ireland under Grant 06/IN/I969.

6. References

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