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Orthogonal Frequency Division Multiplexing for Adaptive Dispersion Compensation in Long Haul WDM Systems

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Abstract: Simulations show orthogonal frequency division multiplexing (OFDM) with optical single sideband modulation can adaptively compensate for dispersion in 4000-km 32×10Gbps WDM SMF links with 40% spectral efficiency. OFDM requires no reverse feedback path so can compensate rapid plant variations.

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1. Introduction

Electronic Dispersion Compensation (EDC) can adaptively compensate for dispersion in fiber links and networks, so reduces outside plant complexity and engineering design while increasing operational flexibility [1]. For example, in Electronic Predistortion (PD) [1-4] a digital processor calculates the optical signal waveform that will become a perfect waveform at the receiver once it has propagated along 5120 km of standard single-mode fiber (S-SMF) [4]. Unfortunately, predistortion requires a reverse feedback path. This means that rapid variations caused by thermal drift, vibration, optical network switching, and polarization rotation cannot be compensated for.

Orthogonal-Frequency Division Multiplexing (OFDM) [5] has been rapidly and widely adopted in RF-wireless systems such as cell-networks, digital-audio and digital-video broadcasting because it is resilient to multipath propagation and phase distortion and requires no reverse path. OFDM has been demonstrated for multimode [6] and free-space optical links [7]. However, standard OFDM requires a high bias [7] to convert bipolar electrical to unipolar optical signals, which degrades receiver sensitivity by more than 5 dB. We have recently presented a method [8, 9] to overcome this limitation, giving OFDM a 1.8-dB sensitivity advantage over NRZ.

The question remains whether OFDM technology could be used to compensate for chromatic dispersion in single-mode fiber links. Previous work has shown that EDC at the receiver works for long-haul links if combined with Optical Single Sideband (OSSB) modulation [10] because OSSB maps optical phase distortion to electrical phase distortion, and this can be compensated for electrically. For example, Hui [11] has used N-channel microwave subcarrier multiplexing to increase dispersion tolerance by M^2; but M was limited by the quality of the RF filters [11]. OFDM enables an extremely large M, because the subcarriers are generated and detected using digital processing. An open question is whether this narrow subcarrier spacing prevents walk-off from mitigating nonlinear effects [12], so limiting the its performance in WDM systems.

In this paper, extensive simulations including fiber nonlinearity demonstrate that OFDM combined with OSSB/VSB can compensate for chromatic dispersion high-capacity ultra long-haul WDM systems, without using a feedback path. Our results predict that 4000-km systems with 80-km spans and 32 or more WDM channels could give Q>11.4 dB using OFDM. Thus OFDM technology could bring substantial benefits to all optical fiber systems.

2. OFDM theory

The theory of OFDM is widely reported [5, 6, 9]. One WDM channel of our system is shown in Figure 1.

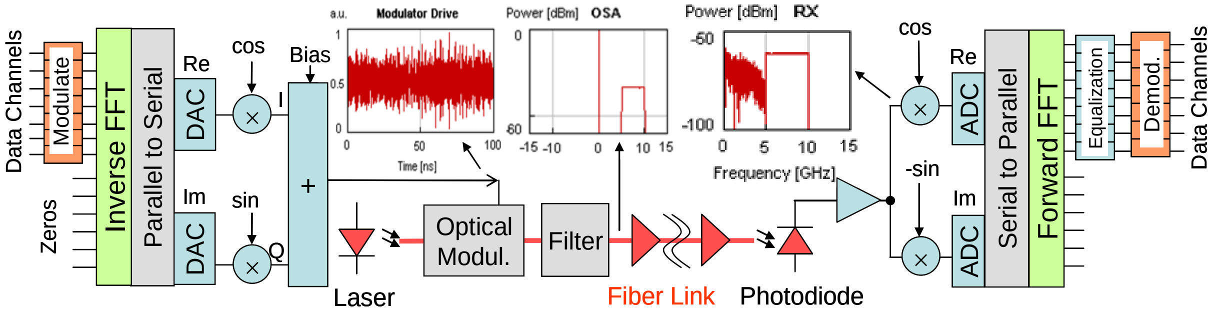

Fig. 1. Optical OFDM system (1 WDM channel shown) including representative waveforms and spectra.

Data is presented in parallel to a set of Quadrature Amplitude Modulators (4-QAM), then onto the inputs of an inverse Fast Fourier-Transform (iFFT). This transform generates a waveform that is a superposition of all the modulated sub-carriers (each carrying 20 Mbps). Zero padding provides an interpolated waveform with a well-controlled spectrum. We displace the OFDM sidebands from the optical carrier by modulating them onto a 7.5-GHz RF subcarrier to give an RF sideband from 5 GHz to 10 GHz, so practical optical filters can be used for carrier and sideband suppression. Unlike our previous optical OFDM designs [8, 9], the modulator drive and bias is adjusted to prevent positive and negative clipping of the OFDM waveform (see left inset). The optical carrier is suppressed to increase the electrical received power for a given optical power, and so the receiver sensitivity is improved. Simulations showed that the best receiver sensitivity is when the power in the optical carrier equals the power in the OFDM sideband. Suppressing the carrier means that the intermixing of OFDM sub-carriers upon photodetection gives significant distortion. However, because the OFDM band is displaced by 5 GHz from the optical carrier, the distortion products fall mainly outside the OFDM band, as shown in the right-most inset of Fig. 1.

A WDM comb of up to 32 10-Gbit/s channels is assembled by displacing each optical carrier by 15 GHz, giving 5-GHz guard-bands. The fiber link consists of 80-km spans of 16 ps/nm/km dispersion fiber with 0.2 dB/km loss and a nonlinear coefficient of 2.6×10^{-20} m^2/W. The loss of each span is compensated with an optical amplifier with a noise figure of 6 dB. The amplifier noise was modeled as a single polarization, because *signal×spontaneous* noise was assumed to be the dominant. The WDM channels were demultiplexed with 10-GHz bandwidth optical filters.

At the receiver, the photodiode output is converted to I and Q components by mixing with a 0° and 90° phase of a 7.5 GHz local oscillator. A fast Fourier transform (FFT) converts I and Q into the frequency domain, separating the QAM channels, so each channel can be phase and amplitude equalized using a single complex multiplication.

The system was simulated using VPItransmissionMaker™. The q-factor [13] was calculated as the average variance of the I and Q components of the electrical signal, divided by the square of the average of the mean amplitudes of the I and Q components. The Bit Error Ratio (BER) can be estimated from $0.5\times\mathrm{erfc}(q/\sqrt{2})$ [12], and this estimate agreed well with actual BER counts (when the error rates were sufficiently high). The results were averaged over all simulated channels: the outer channels had slightly better q-factors. We define Q (dB) = $20\log(q)$.

3. Results

Fig. 2 shows the combined received constellations for a two WDM channels operating at -7 dBm per channel over 4800 km of S-SMF fiber. Before equalization (Fig 2a) the constellation points are spread over all phase angles because of fiber dispersion. The equalization is a two-stage process.

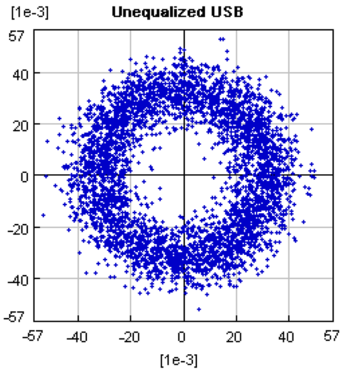

Fig. 2a. Received constellation before dispersion equalization.

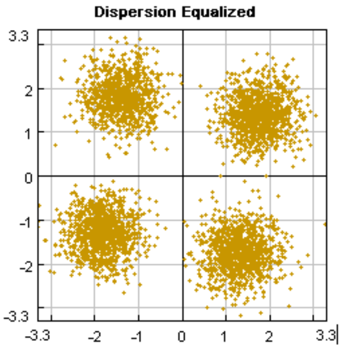

Fig. 2b. Received constellation after dispersion equalization.

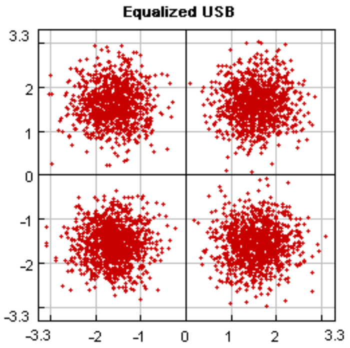

Fig. 2c. Received constellation after phase rotation equalization.

The first equalization step is to remove the effect of fiber dispersion and also any phase distortion due to electrical components. This is achieved by training the system with a known sequence, then comparing the phases of all received symbols with the transmitted symbols. The difference is recorded in a training file and shows a quadratic dependence with sub-carrier frequency, as expected from fiber dispersion. Fig. 2b shows the effect of subtracting the phase correction factors from a received signal; the four groups of points are distinct. However, there is an equal rotation of all OSDM sub-carriers due to the shift in mean refractive index with total optical power. This could be removed during equalization using a single OFDM sub-carrier as a pilot tone (giving Fig. 2c), or by adjusting the phase of the receiver local oscillator.

Fig. 3 plots the minimum and maximum fiber launch powers required to achieve a Q of 11.4 dB, for different numbers of WDM channels. The results were calculated by averaging the data from all WDM channels to get the best estimate in each case. Systems will operate with $Q > 11.4$ dB between these two limits. The noise limit is nearly independent of the number of WDM channels, following standard noise theory for amplifier chains [12], except when nonlinearity increases the minimum signal at long lengths for multiple WDM channels. The receiver sensitivity is 0.4 dB better than threshold-optimized, perfect-extinction NRZ. The nonlinear limit (upper set of traces) decreases with the number of WDM channels and decreases approximately 2 dB per doubling of fiber length.

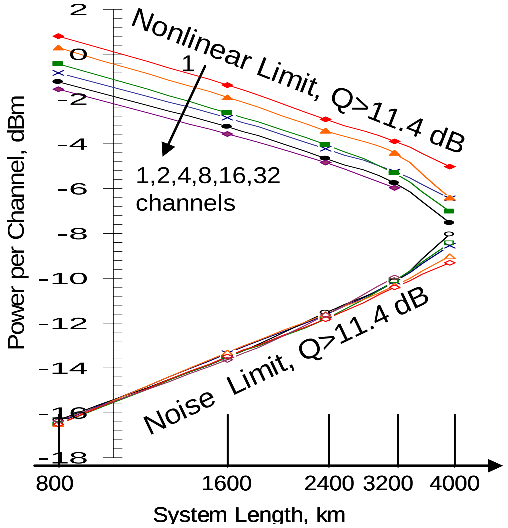

Fig. 3. Min. and max. input powers for Q=11.4 dB.

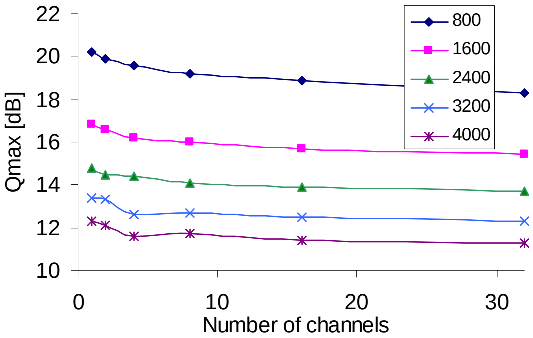

Fig. 4. Maximum Q versus number of channels.

Fig. 4 plots the maximum Q (for an optimum input power) versus number of WDM channels for each fiber length. The reduction of *Q(max)* is around 0.4 dB for each doubling of the number of channels. It is clear from this graph that the number of channels could be increased to the bandwidth of the optical amplifiers without a significant increase in nonlinear penalty.

Actual systems will require a cyclic-prefix [5] to be appended to each block of data, so that the fractional time displacement (from fiber dispersion) between OFDM sub-carriers within a WDM channel will not affect the periodicity of the signals presented to the receiver's FFT. Fortunately, this will only add a small overhead (approx. 2.5 ns for 4000 km) to the block duration (100 ns for 1024-bit blocks).

4. Conclusions

We have shown that OFDM using suppressed-carrier OSSB can be used to compensate for dispersion in ultra-long haul WDM optical links and that fiber nonlinearity does not strongly affect the OFDM signals, even though their sub-carriers are spaced by only 10 MHz. Thus, OFDM could be an attractive technology for adaptive compensation of systems with rapid variations, either environmental or deliberate, such as in optically-switched networks, as it does not require a feedback path with its intrinsic time delay.

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