Orthogonal-frequency-division multiplexing for dispersion compensation of long-haul optical systems

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Abstract: We show using simulations that a combination of Orthogonal Frequency Division Multiplexing (OFDM) and Optical Single Sideband Modulation (OSSB) can be used to adaptively compensate for chromatic dispersion in ultra-long-haul 10 Gbps Standard Single-Mode Fiber (S-SMF) links. Additionally, for optical noise limited systems with Forward-Error Correction, OFDM can accept an Optical Signal to Noise Ratio (OSNR) 0.5 dB lower than NRZ systems providing the optical carrier is suppressed.

OCIS codes: (060.4080) Modulation, (060.4510) Optical communications

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1. Introduction

Electronic Dispersion Compensation (EDC) can be used to upgrade optical links without the need to replace outside plant, so offers considerable installation-cost savings over optical dispersion compensators, as only the ends of the link need modification [1]. Electronic predistortion [1-4] is a recent development of EDC where the transmitter's modulator creates an optical signal that has already propagated through a simulated dispersion-compensating fiber, so arrives at the receiver undistorted, even after transmission through 5120 km of Standard Single-Mode Fiber (S-SMF) [4]. However, this method requires a reverse feedback path from receiver to transmitter and a specialist optical modulator with dual drives.

EDC without a feedback path has been implemented at 10.7 Gbps using Maximum-Likelihood Sequence Estimation (MLSE) [5] for dispersions up to 2500 ps/nm, or approximate 150-km of S-SMF. For longer distances, EDC at the receiver works well when combined with Optical Single Sideband, OSSB modulation [6] (also known as Vestigial Side-Band, VSB, modulation) because the optical phase is translated to an electrical phase signal by the photodiode; whereas in a double-sideband system, the two optical sidebands destroy this direct relationship. Hui [7] has used *N*-channel microwave subcarrier multiplexing and shown that the dispersion-limited transmission length is increased by a factor of N^2. However, the spectral efficiency (and *N*) was limited by the quality of the RF filters, and the optical power efficiency was limited to avoid clipping at the modulator [7].

Orthogonal-Frequency Division Multiplexing (OFDM) [8] has been widely adopted in RF-wireless systems such as cell-networks, digital-audio broadcasting and digital-video broadcasting because it is resilient to multipath propagation. OFDM takes advantage of digital signal processing of fast-Fourier transforms (FFTs) to achieve high sub-carrier density (*N*) and computationally-efficient phase and amplitude equalization using only one complex multiplication per OFDM subcarrier. OFDM has been demonstrated for multimode [9, 10] and free-space optical links [11]. However, it is commonly thought that OFDM imposes a severe receiver sensitivity penalty as it requires high mean optical powers to convert bipolar OFDM to unipolar optical signals [12].

Recently, we showed by simulation [13] and analysis [14] that the received electrical OFDM signal can be improved by around 7 dB for a given transmitted optical power by asymmetrically-clipping the OFDM signal before it modulates an optical carrier. Asymmetrically-clipped OFDM is resilient to dispersion and has a thermal-noise limited receiver sensitivity 1.8 dB better than NRZ. Intermodal dispersion in a 10 Gbit/s multimode-fiber link can be equalized using the properties of OFDM with only a small penalty for dispersion-compensation. The system proposed in [13, 14] could not equalize intramodal (chromatic) dispersion, because it used double-sideband modulation.

In this paper, we demonstrate by simulation that a novel combination of (unclipped) OFDM and OSSB/VSB can be used to compensate for intramodal chromatic dispersion in ultra long-haul communication systems (10 Gbps, 4000 km). If carrier suppression is used, the system is also efficient in terms of optical power, with a receiver sensitivity (when signal-spontaneous amplifier noise is dominant) equal to, or better than, a Non-Return-to-Zero (NRZ) system. The OFDM system does not require a feedback path and could take advantage of well-established OFDM techniques such as adaptive cyclic prefixes/guard-bands and adaptive channel rates [8] to dynamically self-optimize transmission capacity over a variety of fiber plant including dynamically-switched all-optical networks.

2. Optical OFDM system

OFDM transmits a serial high-speed data channel by dividing it into blocks of data then using Fourier transform techniques to encode the data on separate subcarriers in the frequency domain [7]. Our system using OFDM over an optical channel is shown in Fig. 1. Each block of data is presented as *N* parallel data paths to the OFDM transmitter. The *N* paths are modulated onto *N* equally-spaced subcarriers using Quadrature-Amplitude Modulation (QAM). This is similar to Hui's subcarrier multiplexed system [6]; however, it overcomes the complexities and practicalities of multiple microwave mixers by using an inverse-FFT (IFFT) to generate a dense comb of OFDM sub-carrier frequencies: each QAM data channel is presented to an input of the IFFT; the IFFT produces a complex-valued time domain waveform containing a superposition of all of the sub-carriers. This waveform is modulated onto an RF-carrier, f_{RF}, using an *I-Q* modulator, producing a real-valued waveform comprising a band of sub-carriers displaced from DC (see inset). Next, this band is modulated onto an optical carrier using a linear optical modulator. In contrast to our earlier system [13], the output of the optical modulator is filtered to remove all frequencies other than the upper side-band (or lower sideband if preferred) and an attenuated (suppressed) optical carrier.

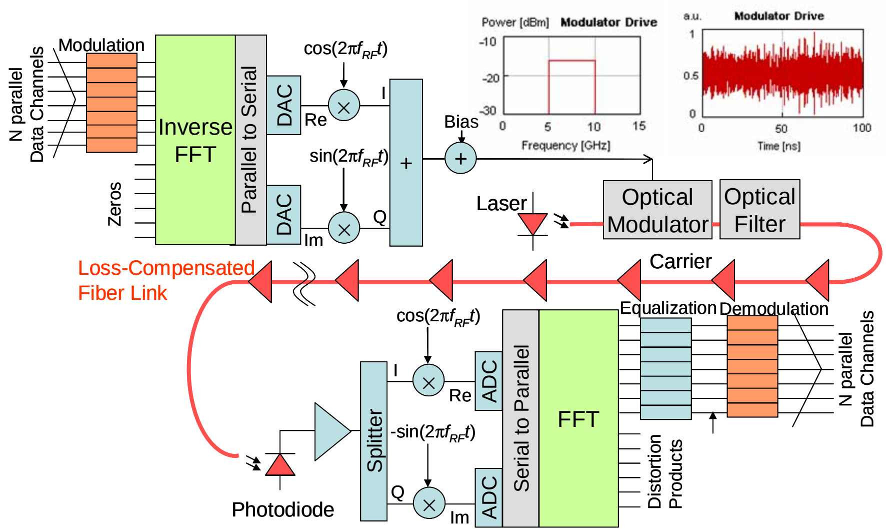

Fig. 1. Optical OFDM system block diagram.

After propagation through the fiber link, the photodiode produces an electrical waveform. This is converted to *I* and *Q* components by mixing with 0º and 90º phases of a local oscillator at f_{RF}. The *I* and *Q* waveforms are then converted to OFDM subcarriers using a FFT, which, if the transmitter and receiver FFT windows are synchronized in time, acts as a set of closely-spaced narrowband filters. The periodic boundary conditions of the simulator enforce this synchronization. In a real system, a cyclic prefix is added to each transmitted block after the IFFT, so that the relative delays between the received OFDM-subcarriers (due to fiber dispersion) can be accommodated without destroying the orthogonality of the OFDM sub-carriers [8]. For a 4000-km link of S-SMF at 1550 nm, the relative delay over the OFDM band is 2560 ps, requiring prefixes that extend the block by only a few percent.

Once in the frequency-domain, each channel is equalized to compensate for phase and amplitude distortion due to the optical and electrical paths. This is easily achieved by using a separate complex multiplication for each channel. The multiplication coefficients can be determined by training the system with a known data sequence or by introducing pilot channels to the OFDM band to estimate the dependence of optical phase on frequency. After equalization, each QAM channel is demodulated to produce *N* parallel data channels. These can be converted into a single data channel by parallel to serial conversion.

3. Simulation

VPIsystems' VPItransmissionMaker™WDM V6.5 was used with the following parameters. The data rate was 10 Gbps and the block length was 1024 bits, though the block length could

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be reduced considerably for computational efficiency in the actual system. 4-QAM was used. The higher-frequency inputs of the IFFT are packed with zero-values to give trigonometric interpolation by a factor of 16, producing a waveform with a spectrum with low side-lobes. In a real system, low side-lobes could also be achieved by using an interpolation filter after the IFFT, which would reduce the size of the IFFT, hence the processing required.

An RF carrier, f_{RF}, of 7.5 GHz gave a band of optical OFDM sub-carriers 5-10 GHz above the optical carrier at 193.1 THz. Increasing f_{RF} gave no advantage, but increased the optical bandwidth of the channel, so reduces the spectral efficiency for OFDM WDM systems. The spectral efficiency is 0.66 bit/s/Hz if 5-GHz guard bands are used between the WDM channels. The gap in the spectrum from 0-5 GHz has two purposes: (1) it displaces the signal band from the region (0-5 GHz) where second-order intermodulation products due to photodetection fall; (2) it allows a non-brickwall (i.e. realizable) optical filter with 5-GHz wide passband-stopband transitions to be used to suppress the carrier. The mean transmitted power is 1-mW and the 4000-km link is loss-compensated by placing optical amplifiers every 80 km. The amplifiers are noiseless until the sensitivity comparison of Fig. 6. The total dispersion is 64 ns/nm. The photodiode has a responsivity of 1 A/W and is noiseless to show the distortion products due to the carrier suppression and other components. The effect of fiber nonlinearity is not included, but is considered in the Discussion section.

The bias level and modulation depth were set so that the OFDM signal was transmitted with no clipping of its peaks [12]. Figure 2 shows the optical spectrum. The optical modulator produces a double sideband spectrum with a strong carrier. After the filter and first optical amplifier there is a much stronger upper sideband. The optimum receiver sensitivity is obtained when the power in the optical carrier equals the power in the upper sideband.

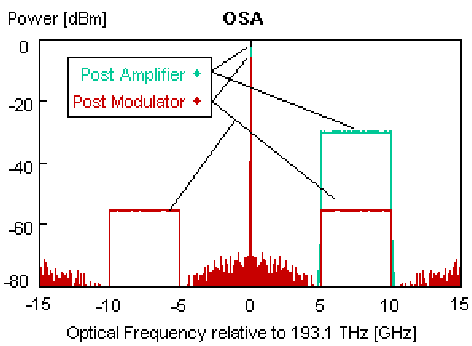

Fig. 2. Optical spectra: after modulator (dark red); after first amplifier (light green).

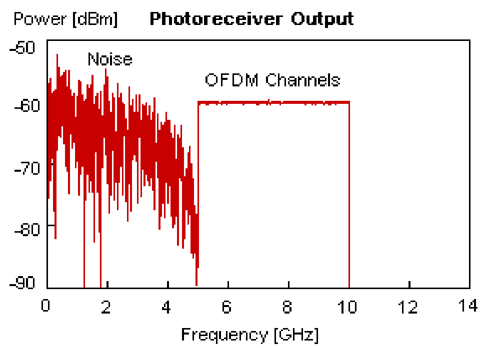

Fig. 3. RF spectrum after the photodiode. The 'noise' is due to intermodulation distortion.

Figure 3 shows the RF spectrum after the photodiode. This contains the 5-10 GHz OFDM band and a DC to 5 GHz band of 'noise' due to intermodulation distortion products from the nonlinear mixing of pairs of OFDM sub-carriers due to the square-law photodiode. The number of mixing products increases close to DC as there are more pairs of closely-spaced OFDM sub-carriers than pairs of widely-spaced sub-carriers. For the same reason, the 2nd-order mixing products fall to zero beyond 5 GHz. Higher-order mixing products cause some distortion within the OFDM band. These can be reduced relative to the wanted signal by increasing the optical carrier power with respect to the sideband [7]; however, increasing the carrier power also reduces the received electrical signal strength for a fixed optical power.

3.1 Dispersion compensation

The ability of the OFDM equalizer to correct for fiber dispersion was tested by first training the system by transmitting a block of data that is known to the receiver and comparing the received QAM-symbols with their expected values. The differences were stored in a training file and are shown in Fig. 4 for all 512 OFDM channels. The phase characteristic is quadratic

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with frequency, as expected for fiber chromatic dispersion. After training, the system was run with random data and errors counted.

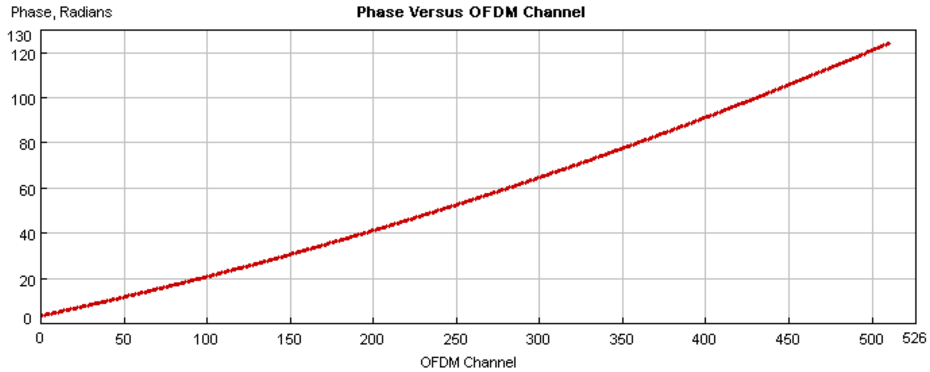

Fig. 4. Phase dependence of the fiber link stored in the training file and used for equalization.

Figure 5 shows the received electrical-signal constellations with and without phase equalization. The unequalized constellation shows that the phases of the received electrical subcarriers are spread over a circle due to the fiber's dispersion inducing a frequency-dependent phase shift. The equalized constellation shows the QAM symbols are tightly grouped. The slight spread in amplitudes and phases is due to the higher-order intermodulation products and can be reduced by increasing the carrier power [7]. Clearly, the OFDM equalizer has successfully compensated for the phase errors caused by fiber dispersion.

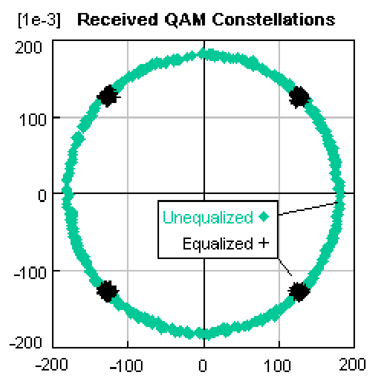

Fig. 5. Electrical constellations before and after equalization.

3.2 Noise performance

Long-haul amplified systems are usually designed so that optical amplifier noise dominates over noise generated by the electronic receiver. For this reason we estimated the Bit Error Ratios (BERs) of NRZ and OFDM systems subject to the same Optical Signal to Noise Ratio (OSNR) at the receiver input. OSNR was defined as the signal power divided by the unpolarized noise power within a bandwidth of 12.5 GHz. The OFDM system used a 10-GHz bandwidth brickwall optical filter before the receiver, which is the minimum bandwidth that can pass the carrier and OFDM band: the NRZ system used a 20-GHz brickwall optical filter. The NRZ system also used a 7.5-GHz 4^{th}-order electrical Bessel filter, optimum sampling, optimum thresholding (i.e., close to the zero level) and perfect extinction (zero power in the '0' bits), to give optimum performance. The errors were counted by comparing transmitted and received data bits. Up to 800,000 bits were used per point, enabling BERs below 10^{-5} to be estimated.

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Figure 6 plots BER versus OSNR for both systems. For a BER of 10^{-3} (which can be improved by Forward-Error Correction coding), the NRZ system requires a 0.5-dB better OSNR. This advantage of OFDM over NRZ reduces to zero for lower BERs, but only if the NRZ system's threshold is optimized to take advantage of the low variance of the zero-bits for high extinction ratios. If the NRZ threshold is placed midway between the 1 and 0 levels (as it would for poor extinction ratios), OFDM has a 1.6-dB advantage over NRZ at all OSNRs. Plots of the variance of the symbols for OSNRs up to 20 dB suggest that a BER floor does not occur for OFDM.

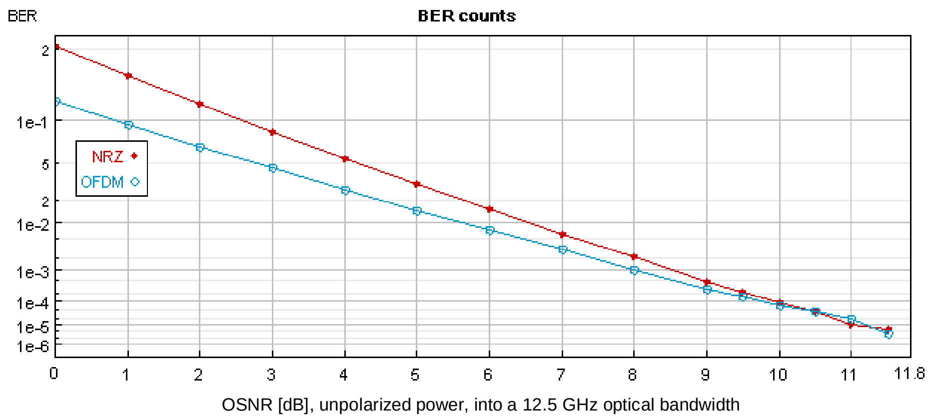

Fig. 6. BER vs. OSNR (dB) for OFDM (lower, open circles) and NRZ systems (upper, dots).

4. Discussion

The simulations assumed that the optical power was not sufficient to cause significant nonlinearities [15]. Four-wave-mixing (FWM) products [7] will impart phase errors on the OFDM sub-carriers: the close spacing of the sub-carriers will mean that walk-off will not mitigate FWM. Initial nonlinear simulations show that although the walk-off is small, the effect of FWM is not large until a signal power of 1 mW is reached, because the power of each of the *N* OFDM sub-carriers is very low. As with conventional systems, detailed parametric studies are required to identify optimal designs for long-haul WDM systems using OFDM; these are beyond the scope of this initial paper.

An advantage of OFDM not highlighted by Fig. 6 is that by replacing dispersion compensating fibers with EDC, fewer optical amplifiers are required, thus the OSNR should improve for the same transmission distance. A disadvantage is that high-rate OFDM requires multiple digital signal processors (using off the shelf technology), though custom integrated circuits [5] will reduce component counts and could lead to compact transceivers. However OFDM is well suited to high speed computation because transmission of data blocks allows parallel processing and the main receiver component is an FFT which can be implemented very efficiently using digital signal processors.

5. Conclusions

OFDM is a well-established technology that can compensate for the frequency-dependent amplitude and phase characteristics of a communications channel, so offers a robust and adaptive method of increasing system performance. We have shown that a combination of OFDM and suppressed-carrier OSSB transmission could be used to dispersion compensate ultra-long haul optical links, with a 0.5 dB power sensitivity advantage over a back-back NRZ system with a perfect extinction ratio and optimized threshold at a BER of 10^{-3}.

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