10 Gbit/s multimode fiber link using power-efficient orthogonal-frequency-division multiplexing

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Abstract: Orthogonal Frequency Division Multiplexing (OFDM) can provide electronic dispersion compensation of optical paths. However, it requires a high bias to convert bipolar electrical signals to unipolar optical signals, so is inefficient in optical power for a given electrical signal to noise ratio. We present a novel method of transmitting OFDM signals over multimode fibers that increases electrical SNR by 7 dB for a given optical power. Using simulations, we show a 1.8 dB sensitivity benefit over 10 Gbit/s NRZ (Non-Return to Zero) and demonstrate compensation of inter-modal dispersion in a 300-m multimode fiber that cannot support NRZ.

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

References and links

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1. Introduction

There is an increasing interest in using electronics to compensate for imperfections in optical systems, such as Electronic Dispersion Compensation (EDC), particularly when installed plant needs to be upgraded. For example, decision-feedback equalizers (DFE) or feed-forward equalizers (FFE) are now proposed to enable 10-Gbit/s to reach over 300-m of multimode fiber [1]. However, there are still some doubts over whether DFE/FFE schemes will be able to compensate for the wide variety of multi-mode fiber characteristics [2].

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Orthogonal-Frequency Division Multiplexing (OFDM) [3], which also relies on digital signal processing, is widely adopted in RF-wireless systems such as cell-networks, digital-audio broadcasting and digital-video broadcasting [4], because it is resilient to multipath propagation. OFDM can equalize optical fiber channels suffering from inter-modal dispersion [5]. OFDM is a form of multiple-subcarrier modulation (MSM) proposed by Carruthers and Khan [6]. They used a few sub-carriers separately biased or clipped before being combined to modulate an optical signal. This biasing was necessary as intensity-modulated optical signals are unipolar [7] but is inefficient in optical power, because the bias carries no information.

González *et al*. [8] studied using OFDM over a free-space link, because it allows hundreds to thousands of optical carriers to be generated and detected using digital signal processing, notably the Fast Fourier Transform (FFT). This vastly improves the performance of MSM due to the large numbers of carriers. Digital signal processing is also compact and stable compared with analog microwave methods. Unfortunately, because OFDM has a high Peak-to-Average Power Ratio (PAPR) [9, 10] the bias required to ensure infrequent clipping is large compared to signal. For example, González *et al*. applied a bias 9 dB greater than the r.m.s. value of the raw OFDM waveform. A high bias power is costly in terms of transmitters and optical amplifiers (if used) and can present eye-safety problems. As a solution, Chanda *et al*. [9] have proposed symmetrical clipping and windowing to reduce the bias by around 3.5 dB.

In this paper, we present a non-obvious alternative biasing technique that substantially reduces the mean optical power, providing superior performance to NRZ while allowing OFDM algorithms to be utilized for optical paths. Using simulations we demonstrate that a 7-dB reduction in received optical power can be achieved for the same electrical signal-to-noise ratio (SNR_E) by simply optimizing the biasing of the OFDM system and that a 1.8 dB sensitivity advantage can be gained over NRZ for the zero dispersion case. All the advantages of OFDM remain, such as its ability to adaptively equalize dispersive channels and to adaptively allocate different data rates to each channel depending on their capacities.

2. OFDM systems

OFDM can transmit a single high-speed data channel, or equivalently, multiple lower-speed data channels [3]. Figure 1 shows the principle of OFDM. Each data channel is encoded onto a separate RF subcarrier: the subcarriers lie on integer multiples of $1/(T_{block})$, where T_{block} is the duration of on of the parallel data bits, so are orthogonal. The waveforms of the individual subcarriers are summed to produce a block of transmitted waveform for each set of parallel data bits. At the receiver, each subcarrier is separated in the frequency domain then decoded. In dispersive channels power will cross from one block into adjacent blocks, causing inter-block interference. This is prevented simply by placing guard intervals between the blocks, which reduces the aggregate data rate slightly.

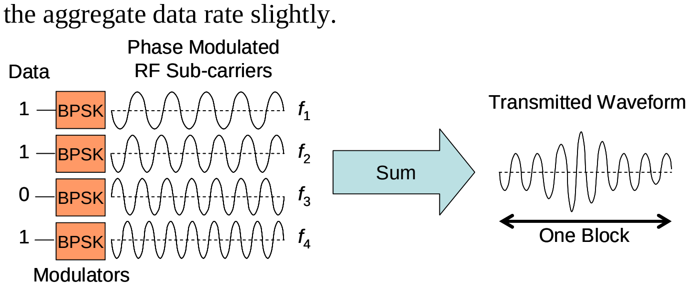

Fig. 1. Principle of OFDM transmitter illustrated with binary phase-shift keying.

Figure 2 shows a practical implementation of OFDM that uses discrete Fourier transforms [3] to generate and sum the RF subcarriers. The first step is to convert the single or multiple channels into N parallel data paths. Each data path is then modulated onto a single electrical carrier frequency, f_k, for example using Quadrature-Amplitude-Modulation (QAM), to encode pairs of data bits as four possible phases of f_k. An efficient method of modulating onto a comb of electrical carriers is to use an inverse fast Fourier transform (IFFT). If each QAM channel is presented to an input of the IFFT, the IFFT will produce an output comprising of a complex-valued (Inphase, I, and Quadrature, Q) parallel data streams. This can be converted into I and Q analog waveforms using parallel-to-serial conversion followed by digital-to-analog conversion (DAC). These analog waveforms are superpositions of all of the carriers and can be up-sampled and simultaneously converted to a real-valued waveform by mixing with another RF carrier, f_{RF}, using an I-Q mixer to produce an RF signal comprising a band of OFDM subcarriers centered on f_{RF}. Zero-padding of the IFFT can be used to obtain a brick-wall RF spectrum and upconversion can be replaced by feeding complex-conjugates of the QAM channels to the inputs of the IFFT [9]. For optical systems, the OFDM band can be intensity-modulated onto an optical carrier.

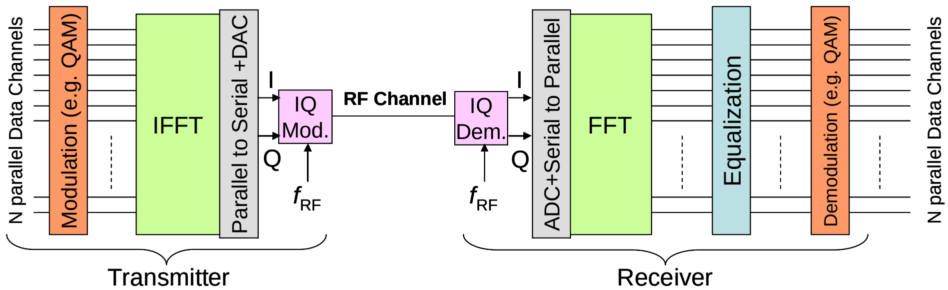

Fig. 2. Implementation of electrical OFDM using discrete Fourier transforms.

At the receiver, the RF band is downsampled and converted to baseband I and Q waveforms by mixing with a 0-degree and 90-degree phase of a local oscillator at f_{RF}. A fast Fourier transform (FFT) converts the I and Q waveforms to subcarriers. Each subcarrier is equalized to compensate for phase and amplitude distortion due to the optical and electrical paths. Equalization is achieved using a separate complex multiplication for each subcarrier. Once equalized, the QAM is demodulated to produce a parallel set of data channels.

3. Simulating the effect of bias level

To quantify the effect of varying the bias level compared with the modulation depth, we developed a simulation as shown in Fig. 3 using VPIsystems' VPItransmissionMaker V6.5.

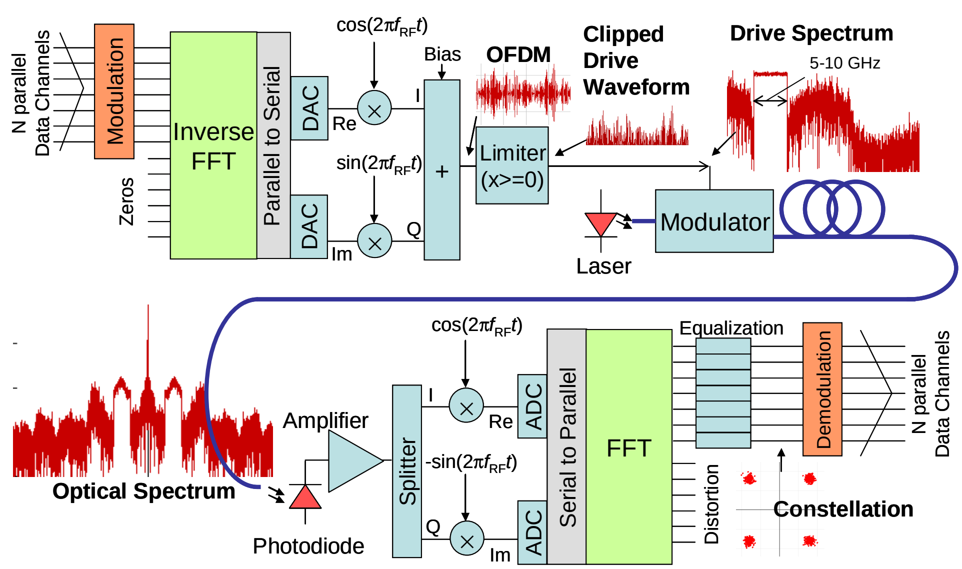

Fig. 3. Optical OFDM system block diagram including waveforms and spectra.

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The optical path included an externally-modulated laser with a linearized modulator, a fiber and a photodiode with transimpedance amplifier. We fully compensated for multipath dispersion in the multimode optical fiber and phase distortion in the receiver using the equalizer and a suitable training sequence: thus the simulations in Section 4 were performed assuming perfect equalization: Section 5 and Section 6 compare equalized and unequalized systems. Methods for adaptive equalization and training are discussed extensively in [8]. The dominant noise sources were thermal and shot noise in the receiver.

The data rate was 10 Gbit/s and was coded with 4-QAM. Each block carried 1024 bits (512 QAM symbols). The higher-frequency inputs of the IFFT are packed with zero-values to produce an upsampled and interpolated output waveform over a 80-GHz simulation bandwidth. The RF OFDM band is fed through a bias tee and a limiter/clipper. The drive spectrum for zero bias (Fig. 3 inset) shows the brick-wall OFDM spectrum and intermodulation distortion caused by the clipping. The received optical spectrum (inset) shows two sidebands each containing the RF subcarriers with amplitude distortion due to multipath interference in the fiber. The mean transmitted power was set to be 1-mW and the link loss was initially set at 0 dB to indicate the effect of clipping on the performance of the system. A photodiode (1 A/W responsivity) fed a transimpedance amplifier (10 pA/root-Hz input noise).

4. Improving system performance using zero bias

A relevant measure of the performance of received-power-limited systems (e.g. due to eye safety, transmitter performance, amplifier performance), is the *signal power squared divided by variance* of the electrical signal levels at the output of the receiver for a fixed optical power. Figure 4 plots this against bias level for a noise-limited system with f_{RF} equal to 10 GHz. Traditional systems operate to the right-side of the graph, with a bias level sufficient to avoid clipping. However, we have shown that better performance is obtained with zero bias, because the quality of the signal ($signal^2/variance$) per unit optical power is much larger. This is because the optical signal carries a far deeper modulation when clipped, which translates to a stronger electrical signal at the receiver, so a better signal-to-noise ratio. The inset constellation diagrams confirm the improvement.

Further simulations showed that the maximum ($signal^2/variance$) under zero-bias clipping and obtained with high received powers depends on the RF sub-carrier frequency, f_{RF}, divided by the OFDM bandwidth, Δf_{OFDM}. The closer the lower-end OFDM band is to DC, the worse the noise due to clipping. This is because low-order intermodulation products due to clipping fall at difference frequencies between the OFDM carriers, and these are strongest near DC (as shown in the inset of Fig. 3). Thus, the OFDM channels should be placed above the difference frequencies between the highest and lowest OFDM channels, and f_{RF} should be at least $1.5\times \Delta f_{OFDM}$. However, in the limit of high link losses, the advantage of zero-bias OFDM is independent of $f_{RF}/\Delta f_{OFDM}$. In the following simulations we reduced f_{RF} to 7.5 GHz to increase spectral efficiency and reduce the demands on the modulator.

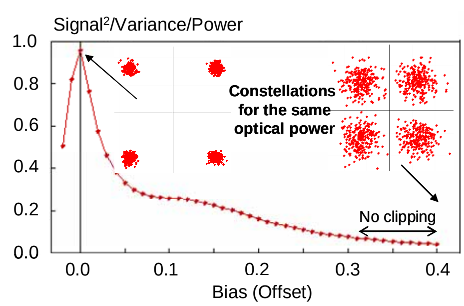

Fig. 4. Signal quality over optical power versus bias level.

To investigate the effect of zero bias on signal quality over a range of link attenuations, the ($signal^2/variance$) versus link attenuation was simulated for conventional and zero-bias

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OFDM systems. Because the transmitter power is fixed at 0 dBm, the attenuation (dB) can also be read as received power (dBm). The increased performance of our system can be used to increase link length, but can also be traded for laser power, modulator losses, passive optical-network splitting losses and receiver sensitivity.

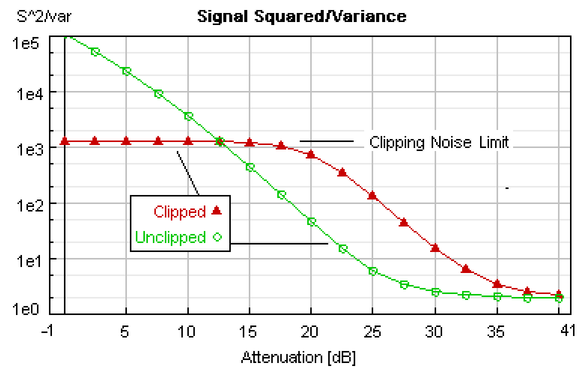

Fig. 5. Signal quality versus link attenuation for clipped and unclipped OFDM systems.

Figure 5 shows that for low link attenuations, the traditional high-bias (no clipping) system gives the best signal quality, because clipping introduces a variance to the received signal that cannot be improved by reducing the attenuation ('Clipping Noise Limit'). That said, either system would provide excellent bit-error ratios (BERs) for low link attenuations. However, for attenuations greater then 20 dB (or equally, lower-power transmitters, lossy modulators or less-sensitive receivers), the zero-bias system allows an extra 7.2 dB of attenuation for the same signal quality. Residual errors can be corrected with appropriate error-correction coding.

5. Equalization of 300-m of multimode fiber

We compared a 10 Gbit/s zero-bias OFDM system and a 10-Gbit/s NRZ system, using the same 300-m multimode fiber. The fiber was modeled using VPItransmissionMaker's *MultiModeFiber* which calculates the modes in a fiber and their relative delays, then calculates the impulse response of the fiber from the launch conditions of the source. The fiber and launch conditions were chosen to give a completely closed NRZ eye, as shown in Fig. 6 (left): the fiber's profile parameter was 1.8 and the launch condition was a 16-μm FWHM Gaussian spot axially-offset by 5 μm. The receivers were noiseless to compare the ultimate performance of the systems for short links.

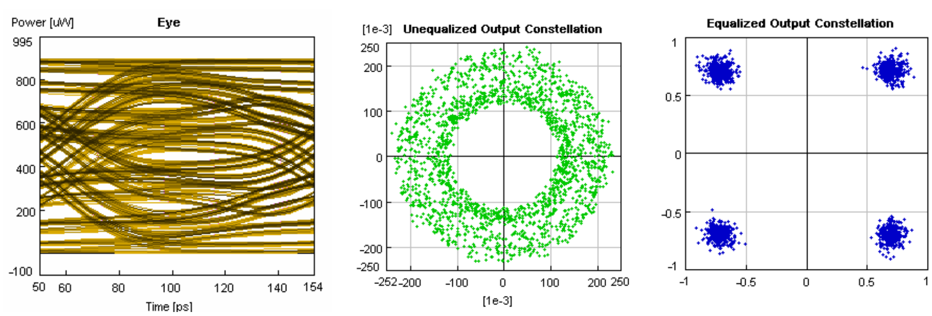

Fig. 6. (left) NRZ system; (centre) unequalized OFDM; (right) equalized OFDM.

Figure 6 also shows the unequalized and equalized constellations for the zero-bias OFDM system. The equalization was trained for 1-block using a known sequence. The unequalized constellation shows a >6-dB amplitude fluctuation across the OFDM band (compared with the optical spectrum in Fig. 3) and an evenly distributed phase error. The equalized constellation shows a lower amplitude variance around each symbol and well-defined phases: the QAM

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symbols could be recovered with very few errors in contrast to the NRZ system. In the presence of receiver noise, equalization of the amplitude would give OFDM sub-channels with varying electrical signal-to-noise ratios. Adaptive sub-channel rates, common to electrical OFDM systems, could optimize the overall capacity of the system.

6. Sensitivity comparison with NRZ

This section compares the receiver sensitivity of the clipped OFDM system with and without fiber with a conventional Non-Return to Zero (NRZ) system. The NRZ system is only simulated without fiber (back-to-back) because it could not support transmission over 300 m of fiber. The transmitter powers were 1 mW. The BER estimated assuming Gaussian noise-pdf's for the NRZ system versus the BER estimated by counting errors for the OFDM systems. All OFDM simulations used 10 blocks per loss setting, so that the effect of the bit pattern could be judged. The NRZ system used a 4-th order Bessel filter at 75% of the bit rate.

Figure 7 shows the plots of BER versus link loss. The equal gradients of the lines indicate that Gaussian noise dominates. The back-back OFDM system shows a 1.8-dB improvement in receiver sensitivity over the back-back NRZ system for high error rates: low error rates could not be counted in the OFDM simulation. The 300-m OFDM system has a 1-dB penalty over the NRZ back-back system, caused by the nulls in the fiber's baseband transmission spectrum. These are equalized out [3], but cause some OFDM channels to have a degraded signal-to-noise ratio, which dominates the overall system performance.

The OFDM RF bandwidth is 5 GHz, compared with 7.5 GHz -3dB bandwidth of the NRZ system. The OFDM system avoids low-frequencies, which may be useful in situations with strong noise sources (such as fluorescent lamps with electronic ballasts). The OFDM equalizer can also cope with frequency-dependent phase and amplitude of the receiver and transmitter, allowing more of the modulator's bandwidth to be used.

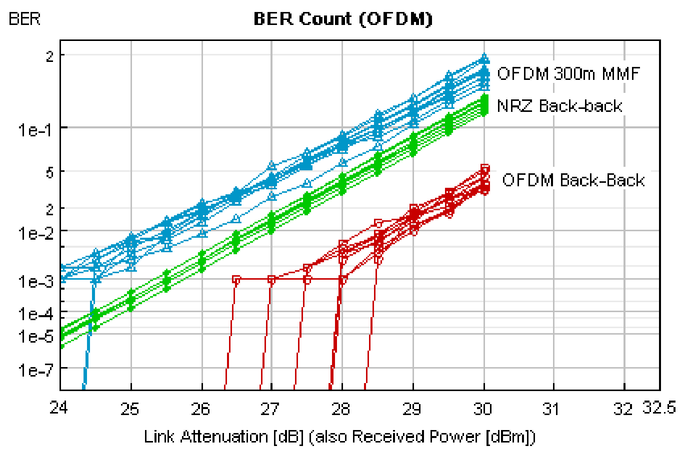

Fig. 7. BER versus link loss (1-mW transmitted power) for NRZ and OFDM systems.

6. Conclusions

We have proposed a new method of transmitting OFDM signals over optical channels by using zero bias. Although this leads to clipping noise, the system has a 7-dB sensitivity advantage over unclipped OFDM and a 1.8 dB advantage over NRZ, for a constant optical power. The inherent characteristics of OFDM can compensate for frequency-dependent amplitude and phase characteristics of the channel, so offers a robust and adaptive method of increasing the performance of multimode optical fiber systems.

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