Improving Sensitivity and Spectral Efficiency in Direct-Detection Optical OFDM Systems

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Abstract: Analysis and simulations show that boosting the carrier power relative to the sideband just prior to photodetection, using an optical filter, will significantly increase the sensitivity and spectral efficiency of direct-detection optical orthogonal frequency-division multiplexed systems.

OCIS codes: (060.2330) Fiber optics communications (060.4080) Modulation

1. Introduction

Optical Orthogonal-Frequency Division Multiplexing (O-OFDM) [1] is an electronic dispersion compensation method that is potentially very computationally-efficient and could scale to extremely high data rates [2]. Recent demonstrations with offline processing have shown compensation of 4160 km of standard single-mode fiber at data rates up to 52.5 Gbit/s using coherent receivers [3], which theoretically allow Optical Signal to Noise Ratios (OSNRs) down to 2.82 dB for 10 Gbit/s [4]. Although they have far simpler receiver architectures, direct-detection receivers [5] require up to 9-dB additional OSNR, depending on the optical bandwidth of the receiver [4].

This paper shows that a modified optical filter function at the receiver can provide substantial improvements in receiver sensitivity for direct-detection OFDM systems. It can also allow the transmitted carrier level to be reduced, so that more optical power is devoted to the sideband, so that 3.8-dB less OSNR is required. Furthermore, the frequency gap between the carrier and the subcarrier sideband can be reduced without penalty, which improves the spectral efficiency of the system. Thus, this method provides some of the advantages of coherent OFDM whilst maintaining the simplicity of direct-detection OFDM. Interestingly, this method may also be applicable to other modulation formats where the carrier is spectrally distinct from the information sidebands.

2. Noise theory of optical OFDM

Optical OFDM uses tens to hundreds of closely-spaced subcarriers. These are generated digitally in the electrical domain using an inverse Fast Fourier Transform, then mapped onto the optical domain using one of several different modulation schemes. The result of modulation is a transmitted band of optical subcarriers with or without an optical carrier, corresponding to coherent [6] or direct-detection optical OFDM [1], respectively. For coherent O-OFDM an optical carrier generated by a local oscillator is added at the receiver and optimally is strong compared with the received subcarriers. In direct-detection systems, optimally the power of the optical carrier is equal to the summed power of all OFDM subcarriers for low OSNRs [7].

Fig. 1 shows how the ASE, carrier and subcarriers intermix upon photodetection to produce electrical noise. The ASE is unpolarized and is band-limited by an optical filter, extending from B_{NL} below the carrier (f_c) to B_{NH} above it. The subcarriers have a bandwidth B_{SC} and there is a gap, B_{gap}, between the carrier and the subcarriers. The middle spectra indicate the components of the optical spectrum that mix to produce the electrical spectra on the right. These are indistinguishable in the actual electrical signal, but are separated in this analysis. They are [4]:

a) *Carrier×subcarriers*. This is the desired electrical OFDM signal, bandwidth B_{SC}.
b) *Subcarriers×subcarriers*. This produces a band of unwanted tones close to DC, bandwidth B_{SC}. In direct detection systems, these are arranged to fall away from the wanted tones by placing a spectral guard band with $B_{gap}>B_{SC}$ between the optical carrier and the OFDM subcarrier band.
c) *Carrier×ASE* (one polarization). The carrier and all ASE noise falling under the subcarrier band, in the same polarization, mixes into the bandwidth of the electrical OFDM signal. In an ideal system, this component would determine the noise limit of the system. Similarly, noise in the lower side band could also mix into the electrical subcarriers bandwidth to give "image beat noise". A homodyne receiver can remove image noise.
d) *Subcarriers×ASE* noise (in same polarization). SC tones mixing with noise below them will always produce some in-band electrical noise. A balanced coherent receiver will reject this noise component entirely.
e) *ASE×ASE* (either polarization). This contribution is large close to DC and falls to zero at a point equal to the bandwidth of the noise. A balanced coherent receiver will reject this noise component entirely.

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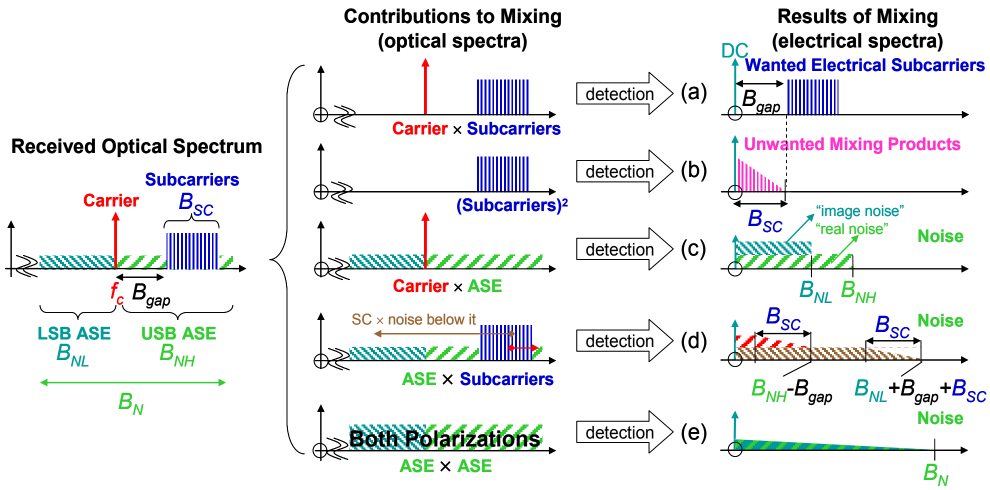

Fig. 1. Direct-detection OFDM received optical spectrum (left), its components (middle) and the results (right) of photodetection in the electrical domain.

3. Improved direct-detection optical OFDM system

It is clear from Fig. 1 that a strong carrier will cause noise mechanism (c) to dominate, as is the desirable situation with coherent O-OFDM. In direct-detection O-OFDM it is detrimental to transmit a strong carrier, as this leaves less power for the sidebands, causing a reduced electrical signal to noise ratio [7]. A novel solution to this dilemma is to boost the level of the carrier relative to the sidebands following the receiver preamplifier. This can be achieved using an optical 'boost' filter with a stronger attenuation in the subcarrier frequency range than at the carrier frequency. This may be counterintuitive as the subcarrier band is attenuated by this filter; however, an optical amplifier (A2) can be used to reamplify the subcarriers. This amplifier will introduce negligible extra noise in a long-haul system.

A 512-subcarrier, 4-QAM, 10 Gbit/s system [1], shown in Fig. 2, was simulated using *VPItransmissionMaker*. Noise-loading accounted for the accumulated ASE in a long-haul system. The boost filter is a variable-rejection bandpass filter around the carrier. The ASE filter has a bandwidth of 50-GHz. The OSNR is measured over 12.5 GHz. Fig. 3 illustrates the effect on the electrical signal quality, Q (Q=9.8 dB for BER=10^{-3}), of boosting the carrier relative to the sideband. Over 2-dB of improvement in Q can be obtained using only a 10-dB boost.

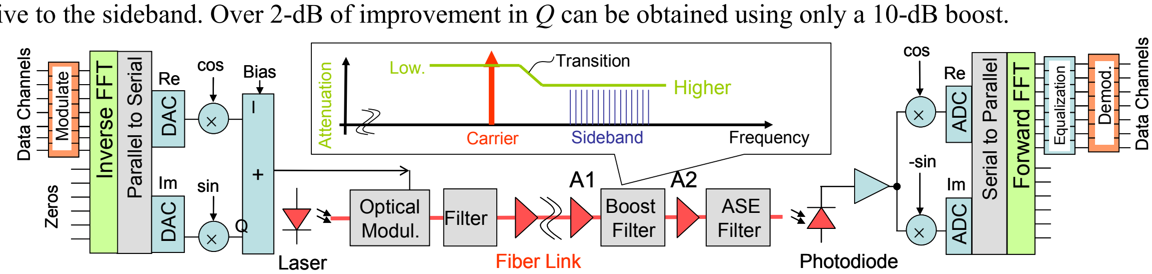

Fig. 2. Direct-detection O-OFDM system showing preamplifier (A1), boost filter (Response inset), and compensating amplifier (A2).

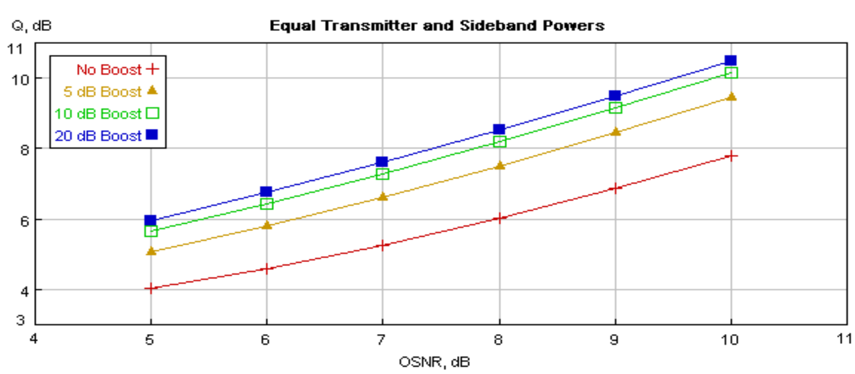

Fig. 3. Effect of boosting the carrier relative to the sideband when the sideband and carrier powers are equal at the transmitter.

Boosting also allows the carrier level of the transmitter to be lowered with respect to the sideband power without penalty. Indeed, because more power is devoted to the subcarriers, *Q* can be increased further. Fig. 4 plots *Q* versus carrier suppression at the transmitter for 10-dB OSNR. Without boosting, carrier suppression leads to a degraded *Q*: boosting provides the expected benefit at zero carrier suppression (Fig. 3) and this benefit is slightly improved using up to 5 dB of carrier suppression at the transmitter. Further carrier suppression degrades the OSNR of the carrier itself, which will affect all electrical subcarriers thus significantly degrades their average *Q*.

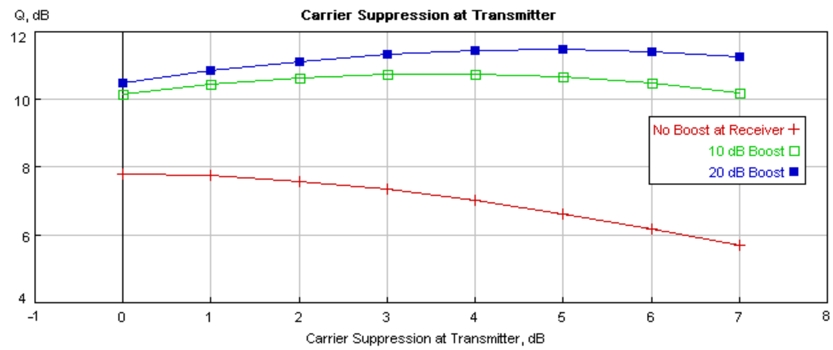

Fig. 4. Effect of suppressing the carrier at the transmitter then boosting it at the receiver.

Because noise mechanism (b) (*subcarriers*×*subcarriers*) is suppressed relative to the signal level (a) when the carrier is boosted, it is possible to reduce the bandwidth of the frequency gap between the carrier and the sidebands. Fig. 5 shows that a halved gap ($B_{gap}=B_{sc}/2$) lowers *Q* by around 2 dB when no boosting is used; however, the *Q* can be regained and even improved when boosting is used. Thus the total bandwidth of carrier plus sideband is reduced from 10 GHz to 7.5 GHz without penalty. Further reductions may be possible, but some gap is required for the filter's transition region, unless it is allowed to extend into the sideband region.

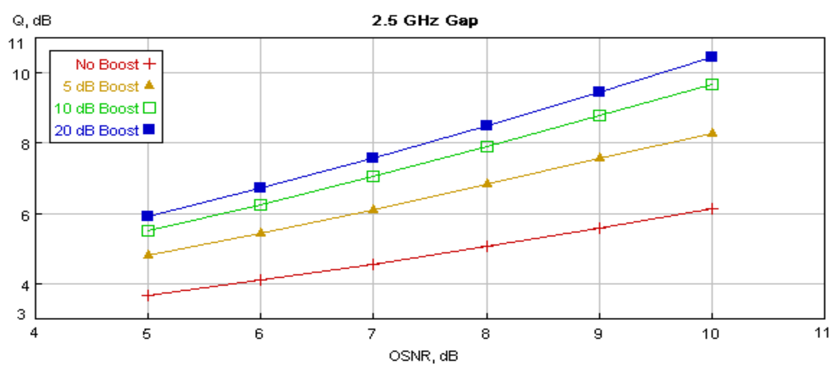

Fig. 5. Use of a boosted carrier to compensate for a reduced gap between the carrier and the sideband.

4. Conclusions

A simple optical filter can be used to improve direct-detection OFDM systems to provide some of the advantages of coherent optical OFDM without the complexity of a coherent receiver. This technique should also work for other modulation schemes where there is a gap between the carrier and the information-bearing sideband or sidebands.

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