Reducing Cyclic Prefix Overhead in Optical OFDM Systems

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Abstract *Simulations show that by pre-compensating for dispersion, using bands transmitted with timing offsets and a single-band receiver, the cyclic prefix to be reduced in optical OFDM systems without compromising their dispersion-compensation ability.*

Introduction

Optical Orthogonal Frequency Division Multiplexing (O-OFDM) using digital Fourier transforms (FTs) can compensate for large amounts of dispersion in long-haul communications systems [1]. However, a Cyclic Prefix (CP) must be added to each OFDM Symbol before transmission to accommodate the time spread of the OFDM subcarriers due to fibre dispersion. The CP ensures that the subcarriers remain periodic within the receiver's FT window, to eliminate Inter-Carrier Interference (ICI), caused by phase discontinuities within a window. The CP adds an overhead to the transmission, requiring additional optical bandwidth and reducing receiver sensitivity. To reduce the overhead, long OFDM symbols can be used, but this requires longer FTs (i.e. more silicon) and increases the phase noise sensitivity of coherent O-OFDM systems, unless the phase noise is corrected before the receiver's FT [2]. Thus, reducing the length of the CP, without reducing the dispersion that can be compensated, would be advantageous.

One method of reducing the CP overhead is to use several separate frequency bands to transmit a given data rate [3], thus reducing the bandwidth of each band, hence the differential group delay (DGD) across each band. Each band should processed separately at the receiver to avoid ICI, with each band's FT window properly aligned.

This paper introduces a method of reducing the CP duration using a single modulator at the transmitter and a single FT at the receiver. ICI is avoided by precompensating for the fibre's DGD. This method can be applied to both coherent [4] and direct-detection (DD) [5] O-OFDM.

Theory

The transmitted signal is digitally processed in bands. Each band uses a separate inverse-FT then the bands' waveforms are time-shifted before transmission using a single modulator. Two bands will be described for simplicity, as shown in Figure 1. The transmitted subcarriers (top of figure) are split into 'red' and 'blue' bands. Each band has a CP at the beginning of its symbol. The red band is transmitted first, with the blue band's CP starting when the red band's CP has ended. At the receiver (bottom of figure), each band has spread in time because of the fibre's DGD. This is shown as a slanting of the bands in the figure. The highest-frequency of the red band and the lowest-frequency of the blue band experience almost zero relative time-shift. The lowest-frequency of the red band is delayed: highest-frequency of the blue band is advanced. Importantly, if the FT window of the receiver is timed appropriately, as illustrated, all subcarriers will be periodic within the FFT window. This ensures zero ICI. To achieve zero ICI with a single band (or without the timing offset) would require a CP of double the duration. The two-band method also works for lower DGD, with the same delay values; as can be seen if the slant of the bands is reduced.

Further advantage can be obtained by using more than two bands. The required CP is simply the CP duration of a single band's CP, divided by the number of bands. The relative delay between two adjacent bands should equal the CP for each band,

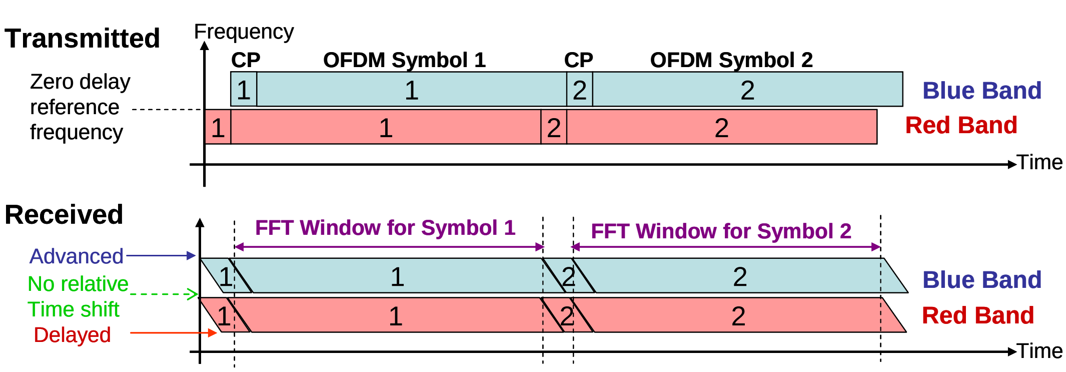

Fig 1: Principle of using delayed bands to reduce Cyclic Prefix (CP) duration.

and should be calculated from the fibre's dispersion map. Some tolerance to dispersion variations could be obtained by overlapping the CPs of the bands.

Simulation Example

VPIsystems' VPItransmissionMaker™WDM V7.1 simulated a Direct-Detection O-OFDM system. The data rate was 60 Gbps, carried with 4-QAM, and the OFDM symbol length was 1024 bits. The CP was 1/16 of the symbol, or 1.07 ns. This is equal to the DGD of 280-km of fibre over the entire 30-GHz bandwidth of the subcarriers: a 2-band system has half the bandwidth per band, so the same CP overhead will support 580-km of fibre. Noise was not included. The equalisers were trained with 15 OFDM symbols. Figure 2 shows the spectrum. The DD carrier was obtained by frequency-shifting the laser line [6].

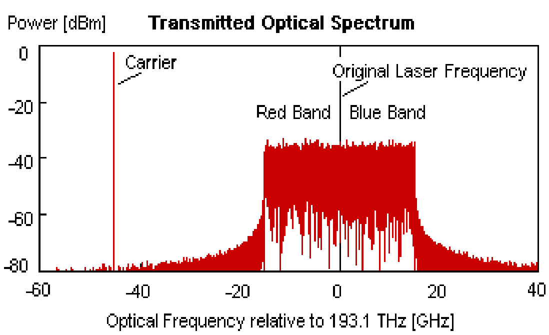

Fig. 2: DD-O-OFDM transmitted spectrum.

Figure 3 is the average Q over all subcarriers versus fibre length (D = 16ps/nm/km), calculated as $10\log_{10}$(Cartesian mean^2/variance). For bivariate Gaussian distributions, 10^{-3} Bit Error Ratio requires Q=9.8 dB. The single-band system's Q starts to decrease when its CP duration is less than the DGD for 30-GHz bandwidth. The two-band system's Q decreases when CP < DGD for 15-GHz bandwidth. The two-band's Q remains around 9-dB higher than the single band system beyond these turning points.

Both systems appear to support fibre lengths more than double the expected limit, as only some subcarriers will slip outside the FT's window due to dispersion, causing interference from the same subcarrier in adjacent OFDM symbols. However, even the carriers that remain within the FT's window will be degraded because of the broadband spectral pollution caused by taking the FT of an aperiodic subcarrier (i.e. a subcarrier that has slipped out of the FT window so the phase discontinuity between OFDM symbols appears within the FT window). Thus, practically, the CP should be designed to accommodate the DGD of the sub-band if ICI is to be reduced to zero, so that the best performance can be obtained in the presence of noise [7] and fibre nonlinearities.

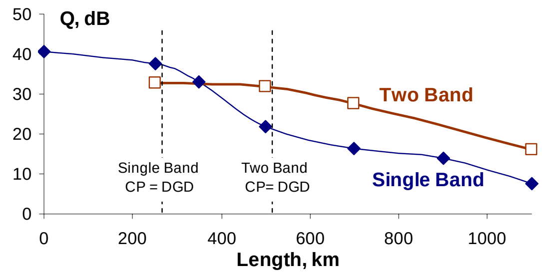

Fig. 3: Averaged Q versus fibre length

Conclusion

Using multiple OFDM bands at the transmitter is a successful strategy for improving the dispersion tolerance for a given CP overhead provided the bands are displaced in time to compensate for fibre's DGD. If the bands are not displaced (as in the single-band result), some subcarriers will become aperiodic within the receiver's FT window, and so will degrade. They will also pollute 'periodic' subcarriers due to spectral leakage.

Acknowledgement

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References

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