Generation and Transmission of All-Optical OFDM

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Paper Summary

This paper explores recent methods of generating and transmitting all-optical OFDM signals, based on the requirement to deliver appropriate signals to the receiver. The differences between all-optical OFDM and conventional WDM systems are discussed.

Introduction

Optical OFDM [1-3] (orthogonal frequency division multiplexing [4]) can be generated by optical or electronic means. Recent research has shown that the optimum baud (or symbol) rate of a subcarrier is around 3-5 Gbaud to mitigate fiber nonlinearity [5], dependent on distance [6]. This makes all-optical OFDM [7], where a single low-cost modulator is used for each subcarrier, particularly attractive.

This paper firstly examines the specification of the transmitted signals *from the point of view of the receiver*, which ultimately must be able to separate the subcarriers without inter-(sub)carrier interference (ICI). The eye diagrams from typical WDM and OFDM receivers are compared to illustrate the consequence of allowing OFDM subcarriers to spectrally overlap. A suitable all-optical OFDM transmitter is then presented.

The issue of fiber nonlinearity (NL) degrading OFDM signals is addressed, followed by a discussion of our recent work on compensating NL.

Orthogonal Frequency Division Multiplexing

A conventional OFDM spectrum as seen in many presentations is of a set of subcarriers, each with a sinc spectrum, all separated by the modulation rate (the symbol rate) of each subcarrier (Fig. 1, left). The peak of the desired subcarrier is said to be unaffected by the other subcarriers, as their nulls line up with its peak. Clearly, however, there is spectral energy from neighbouring subcarriers within the desired carrier's passband, so the real situation must be more complex. Indeed, if a cyclic prefix (CP) is added to each symbol, the spectral spacing of the symbols must now be greater than their modulation rate [8], so the peaks and nulls no longer align (Fig. 1, right). Thus the common understanding of what is orthogonal is unsatisfactory, and would preclude cyclic prefixes.

Demultiplexing orthogonally

Firstly, we will consider how the receiver demultiplexes the OFDM signal into subcarriers, which will inform us how to generate and transmit suitable OFDM signals.

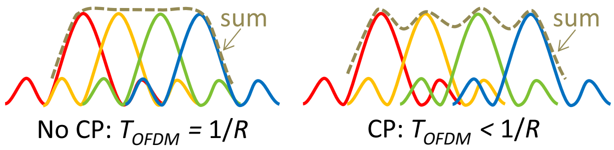

Fig. 1: Overlapping spectra of OFDM subcarriers, without (left) and with (right) cyclic prefixes.

For each consecutive OFDM symbol, k, the receiver has to perform an integration of the product of an analysis function, $a_n(t)$, and the input signal, $s(t)$, to provide an estimate, $d_n(k)$, of the data carried by subcarrier, n:

$$d_n(k) = \int_{t=k/R}^{k/R+T_{OFDM}} s(t).a_n(t-k/R).dt \qquad (1.1)$$

where the baud rate of the incoming data is R and the duration of each symbol is T_{OFDM}. Importantly, T_{OFDM}, can be shorter than $1/R$, to leave space for a guard interval or a cyclic prefix. In conventional OFDM, a_n is a complex exponential function with constant amplitude and a carrier frequency n/T_{OFDM}. If $s(t)$ is a similar function, but modulated in amplitude and phase to carry data, then the imposed modulation can be estimated, without ICI from other subcarriers m, where $m \neq n$.

Eqn. 1 can be implemented in the optical domain, the electrical domain or both, using continuous-time processing or discrete time processing; e.g:

1. An optical filter followed by a sampler. The filter has a sinc response (the transform of a_n) and an impulse response with duration T_{OFDM}. The samples should be taken when the filter's impulse response aligns in time with an OFDM symbol [9].
2. As Case 1 but using an optical Fourier transform, providing *multiple* outputs, implemented with splitters, delays and couplers [10], or an Arrayed Grating Waveguide (AWG) [11].
3. A wideband coherent receiver with an electrical integrate-and-dump filter with integration time T_{OFDM}, synchronized with the incoming OFDM symbols.
4. As Case 3 but with an digital Fourier transform, providing multiple outputs [12]. The sampling rate and receiver must accommodate the bandwidth of many subcarriers.

In Cases 1 and 2, the sampler can be optical or electrical, with the proviso that the bandwidth of the system prior to the sampler must be greater than the bandwidth of all of the subcarriers input to the receiver [11]. This favors optical sampling to avoid needing an extremely widebandwidth optical receiver. In all cases integration time matches the duration of the OFDM symbol.

Comparison with conventional WDM receivers

A conventional WDM receiver uses a bank of filters to demultiplex the WDM signals into individual paths [13]. The paths are received, electronically processed to reduce intersymbol interference and noise bandwidth, and sampled with thresholding. This is similar to Case 1 with an electrical sampler, so why is OFDM special?

A key difference is that a WDM demultiplexer is designed to mostly eliminate optical power from adjacent optical channels (which is possible as they are designed not to overlap), whereas the implementation of Eq.1 in OFDM must accept power from adjacent channels (because they overlap).

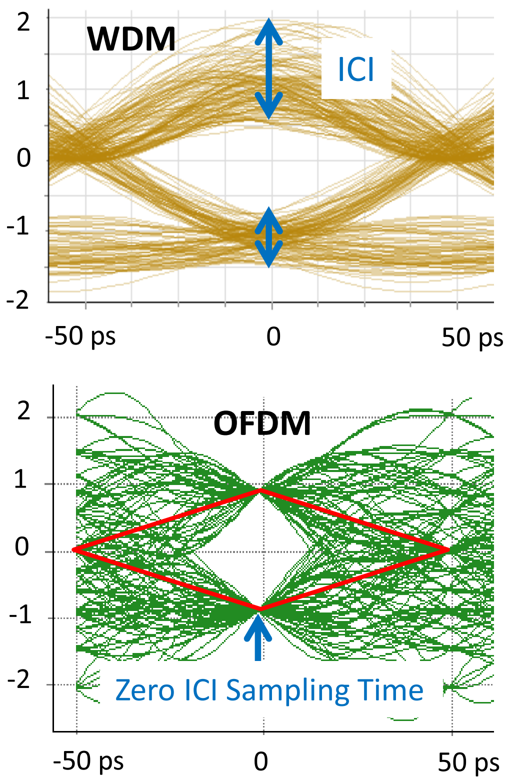

Fig. 2: Conventional WDM (top) and OFDM (bottom) eye diagrams for a QPSK inphase signal at 10 Gbaud.

The question is then: *'How does this power from neighboring subcarriers affect the output of the OFDM demultiplexer*?" Consider the case of a single optical filter (Case 1). We can downconvert the optical signal to inphase and quadrature electrical signals and display them as waveforms, or more informatively, eye diagrams (Fig. 2, bottom). The sampler selects the signal at the time where there is most contrast between the data levels and least variance. In an OFDM signal, the eye is fully open when the integration time window in Eq. 1 aligns with a received symbol: at other times the neighboring subcarriers are not periodic within the integration window, so ICI occurs. Furthermore, the signal component of the eye (shown as a red diamond) reduces linearly with timing offset, as it is a correlation of the filter response and the signal. Thus, an OFDM eye presented to the sampler is only open and interference free for an instant. However, this high quality of signal is essential if higher-order modulation formats are used.

Conversely, a demuxed-WDM channel's eye (Fig. 2, top) can have interference spread across its entire duration, and the sample time is less critical, though perfect orthogonality cannot be obtained. This is a fundamental trade off, and must be considered in conjunction with the performance of the sampler. Coherent WDM [14] improves the WDM eye by arranging that interference occurs only away from the central sample time, somewhat like OFDM.

Generating OFDM signals all-optically

A typical way to all-optically generate OFDM subcarriers is to start with a comb source (such as a mode-locked laser, MLL), demultiplex the frequency lines, then modulate each line before recombination [15]. Unfortunately, a very high (electrical) bandwidth modulator must be used for every subcarrier, because otherwise the slow transitions in phase and amplitude at the symbol boundaries will make each subcarrier non-sinusoidal. Adding a cyclic prefix relaxes this requirement slightly, as it gives some time in which the transitions can occur [16]; however, the CP will reduce the spectral efficiency of the system.

Alternately and beneficially the system can be rearranged so that each modulator (CMZI) is fed with identical pulses from the comb source (Fig. 3). Spectral shaping of the modulated pulses streams creates a band of OFDM subcarriers [17].

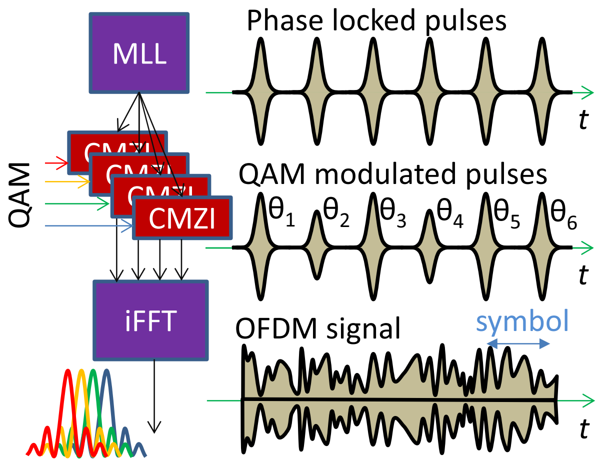

Fig. 3: Generation of an OFDM signal using modulator fed with mode-locked laser (MLL) pulses. The shading represents the high frequency carrier within the signal envelope.

The advantage here is that the modulators require a much lower bandwidth [18], as they only have to have the correct transmission state when a pulse is passing through them. Interestingly, the subcarrier frequencies need *not* lie on the original frequency comb. This allows a CP to be added, simply by retuning the centre frequencies of the spectral shaper, and makes the wavelength stability of the MLL unimportant [8].

Transmission of OFDM signals

The fiber link must deliver the symbols so that they are aligned in time, have little intermodulation caused by the nonlinearity (NL) of the fiber, and have a time spread due to chromatic dispersion (CD) that can be accommodated by the CP without a significant penalty.

The time spread between subcarriers due to CD can be reduced by fiber-based dispersion compensation modules, or by electronically dispersion compensating before the implementation of Eq. 1. Alternatively, the bands of subcarriers can be transmitted staggered in time, so they arrive in near synchronism [19].

Fiber nonlinearity

The effect of fiber nonlinearity is cited as a weakness of OFDM, particularly electrically-generated OFDM with many subcarriers. For N subcarriers, therefore there are order N^3 Four Wave Mixing (FWM) products falling upon each subcarrier; however, because the power in each subcarrier is $1/N$, the power of a FWM products scales with $1/N^3$, making the performance independent of N [20]. When CD is considered, the number of subcarriers becomes important when optimising NL performance, as it affects the granularity of the channel; justifying the use of all-optical OFDM with around 5-GHz subcarrier spacing. A key consideration is the overlap of the intensity spectrum (RF) propagating signal and the FWM efficiency function [6], because low-frequency intensity fluctuations cause stronger FWM products in a dispersive link [21].

Compensating the effects of fiber nonlinearity

There is a growing interest in compensating for nonlinearity for all types of fiber system, and this may be beneficial for all-optical OFDM. Generally, these methods undo the intensity-dependent phase modulation induced by fiber nonlinearity – the Kerr effect. For optical OFDM, this can be achieved using efficient digital processing for single [22] and multiple wavelengths [23]. Mid-span spectral inversion (MSSI) also provides a moderate benefit [24].

Due to CD, the phases of the FWM products evolve along the link, beneficially reducing the accumulated FWM [25, 26], but also making a 1-step (or lumped) compensator less effective unless modified [27]. Multi-stage digital back-propagation (DBP) [28] is a solution, but can be computationally expensive. We have shown DBP may be tractable for OFDM [29], especially if the bandwidth of the FWM processes is considered [30]. Because the subcarrier spacings in all-optical OFDM and WDM are similar, it is likely that the same benefits could be obtained by using similar NL compensation schemes for both types of system.

Conclusions

Optical subcarriers can be generated for 'orthogonal' reception with zero ICI using all-optical processing. Fiber nonlinearity causes degradation as in WDM systems, but can be mitigated. With these developments all-optical OFDM becomes suitable for long-haul transmission networks as it offers near-zero ICI, enabling spectrally efficient high-order modulation.

Acknowledgements

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