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Invited Papers

Optical orthogonal division multiplexing for long haul optical communications: A review of the first five years

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ABSTRACT

Optical OFDM was proposed for dispersion compensation in long-haul optical communications systems in 2006 in two forms, one using direct-detection and the other using coherent detection. Since then there has been extensive innovation towards developing intermediate forms of optical OFDM that are more suited to specific applications. This review paper presents our view on the developments in optical OFDM for long-haul optical transmission applications. It covers the basic elements of radio OFDM before concentrating on direct detection optical OFDM and its development, followed by coherent optical OFDM. All-optical OFDM is then considered, together with optical methods of generating and separating the OFDM subcarriers. The paper then discusses the critical issue of nonlinear degradation due to the Kerr effect in optical fibers and reviews recent innovations to mitigate the effects of fiber nonlinearity. Finally some future research directions are discussed.

1. Introduction

Optical fiber communications is tremendously successful because of the near-perfect characteristics of optical fibers when compared with copper cables and metallic waveguides. The single-mode fiber allowed gigabit-rate non-return to zero (NRZ) pulses to be transmitted at gigabit rates with around a hundred kilometers between regenerators. The invention of the Erbium-doped fiber amplifiers (EDFAs) removed the issue of fiber loss, allowing transcontinental communications without electronic regeneration, and made wavelength-division multiplexing (WDM) cost-effective, multiplying the capacity of a single fiber by a factor of more than a hundred. Negative-dispersion fiber, used in Dispersion-Compensating Modules (DCMs) [1], removed the limitation on bit rate per wavelength-channel due to fiber chromatic dispersion (CD). Polarization-mode dispersion (PMD) imposed a higher limitation on rate [2], but spun optical fibers had sufficiently-low PMD for most system lengths. Fiber nonlinearity, which results in a phase-modulation of signals proportional to the instantaneous combined intensity of all signals in the Fiber (the Kerr effect), has become the current limit to the total (data) capacity–length–product of a fiber, resulting in the "nonlinear Shannon limit" [3,4].

There has been and continues to be a vibrant research community working on optical methods of improving fiber capacity and transmission distance using optical technologies. However, a major shift in thinking occurred throughout the engineering community after the introduction of commercial electronic pre-compensation of CD [5], followed by electronic postcompensation [6]. Such products used electronic digital processing to compensate for optical dispersion [7]; before this electronics was seen as the bottleneck in optical communications systems. An advantage of the electronic approach is that it greatly simplified the design and installation of a link, because the DCMs were removed [1]. This simplified the design process, decreased the cost of the initial roll-out of the link and reduced maintenance of the 'outside plant'. Another electronic approach to compensate dispersion at the receiver involved Maximum-Likelihood Sequence Estimation (MLSE). These early Electronic Dispersion Compensation (EDC) techniques operated at 10.7 Gbit/s [8]. Soon after, dispersion unmanaged 40 Gbit/s per wavelength, and more recently 100 Gbit/s, systems were demonstrated using coherent receivers and digital compensation [9–12]. These systems used polarization-multiplexed transmission [13]. The challenge of increasing bit rates per wavelength beyond 100 Gbit/s has led to a flurry of research and development activity across the world, with a goal in providing computationally efficient equalization techniques [14,15].

In 2006 two groups reported dispersion-compensation techniques based on digital-processing implementations of Orthogonal Frequency Division Multiplexing (OFDM) [16]. Lowery and Armstrong first proposed a direct detection solution in a postdeadline paper at OFC 2006 [17]. This was soon followed by an *Electronics Letter* from by Shieh and Athaudage [18]. Meanwhile, Djordjevic and Vasic were working on a direct-detection optical OFDM [19]. All groups included experts in OFDM applied to radio systems,

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and this seeded the question: "Why not use OFDM to compensate dispersion in optical systems?" An optical implementation of OFDM had been reported in 2002 [20], but had dismissed the use of electronics at high speeds. In some ways, OFDM was an extension to using multiple subcarriers to carry a high speed channel [21]; however, these earlier systems did not use the orthogonality property of OFDM, required bulky microwave components to generate and separate the subcarriers, and did not use digital equalization of optical subcarriers.

Lowery and Armstrong had earlier proposed power efficient methods using OFDM for multimode-fiber [22] and free-space systems [23,24], and the main challenge was to overcome the problem of mapping a bipolar OFDM system, with its strong negative-peaks, onto a positive-going optical intensity waveform. The traditional solution was to use a high bias, to ensure that all negative peaks mapped to a positive intensity [25–27]. Lowery and Armstrong proposed clipping the waveform at the zero voltage level, mapping all negative voltage values to zero optical power, which ensured the distortion falls into unwanted regions of the baseband spectrum. Multimode optical OFDM systems [28] will not be covered in this paper. However, Tang *et al.* have proposed considerable advances including adaptive modulation [29] and impressive real-time demonstrations using FPGAs for signal processing which have been recently extended to single-mode links [30,31].

A solution of making optical OFDM suitable for long-haul systems required further innovation as it must compensate for chromatic dispersion rather than multipath (or modal) dispersion [32]. Lowery and Armstrong proposed a system which only required a simple direct-detection receiver, together with single-sideband modulation [33,34] and a frequency gap between the optical carrier and OFDM sideband for intermodulation products to fall into. This technique is commonly referred to as direct detection optical OFDM (DDO-OFDM). Shieh and Athaudage proposed the use of a coherent receiver [18], which mapped the traditional OFDM voltage signal onto an optical field waveform. This is most commonly referred to as coherent optical OFDM (CO-OFDM). Soon after, Jansen et al. produced an experimental demonstration of coherent optical OFDM with an innovative solution to overcome laser phase noise [35].

It was very difficult to publish these early papers: the argument against Optical OFDM was sometimes that there would be huge problems with optical nonlinearity, due to the systems using hundreds of subcarriers which would all mix, giving millions of interference tones due to the Kerr effect. The early papers used simulation to show this concern to be overblown [36], because each subcarrier has a small power [37] and later that high-data rates in standard dispersion fibers offer significantly better performance over theoretical predictions for lower rates in low-dispersion fibers [38,39]. These first publications showed that OFDM could be used to transmit data over long-haul distances, leading to an acceptance of Optical OFDM followed by an intense interest from the research and development communities, and spurning multiple technical sessions at major conferences. OFDM is now considered a contender for >100 Gbit/s transmission with many off-line demonstrations of extremely high spectrally-efficient systems using concatenated bands to reach Tbit/s transmission rates with digital subcarrier generation [40,41] and multi-Tbit/s rates with optical-band multiplexing techniques [42,43].

This paper maps the developments in optical OFDM from these early years focusing mainly on long-haul systems. There have been many technical innovations, particularly in methods of generating optical OFDM signals, in compensating polarization-mode dispersion, in improving spectral efficiency, in increasing receiver sensitivity, and in compensating for Kerr nonlinearity. Many of these developments have led to new analytical theories to ascertain performance limits. Although this paper cannot cover each aspect in detail, a large number of references will be given to aid further exploration of each topic. There are a number of other excellent reviews concentrating on different aspects of optical OFDM [40,44–47] and high-speed long-haul optical transmission in general [3,12,13,47–51].

2. Theory of OFDM

2.1. Radio Frequency OFDM systems

OFDM is a multi-carrier modulation technique, where a data stream is encoded onto many subcarriers that are then transmitted together on a common path [52]. Fig. 1 illustrates the overlapping spectra of the subcarriers, together with the transmitted waveform, which comprises a sequence of OFDM symbols. An advantage of OFDM is that each subcarrier has a narrow bandwidth compared with the total data rate, so is relatively unaffected by multipath interference or phase distortion. Strictly, the subcarriers have a much wider bandwidth than their frequency spacing because the transitions between data symbols are fast compared with the symbol duration; each subcarrier is a sinc-function ($\sin(x)/x$) in the frequency domain upon modulation. Spectral efficiency is gained by overlapping the sinc functions so that the centre frequencies of all subcarriers other than the one of interest lie on the nulls of the subcarrier of interest. OFDM signals can either be transmitted at baseband (such as over ADSL networks) or up-converted onto a carrier with a mixer as shown in Fig. 2. To maximize power efficiency, no carrier is transmitted and a local oscillator is used at the receiver.

The received data is recovered using a matched filter for each subcarrier, which perfectly rejects interference from neighbors and also causes no distortion of the wanted channel. The matched filter usually has a rectangular impulse response; that is, it combines the samples of the received signal with equal-magnitude weights. The phase of the weights increases monotonically; the rate of increase of phase is a frequency offset and determines the subcarrier being received. In practice, the bank of matched filters receiving a number of subcarriers can be replaced by a discrete Fourier transform (DFT) [53], which can be implemented efficiently using the Fast Fourier Transform (FFT) algorithm [54].

Fig. 2 shows the signal flow in a radio OFDM system. Data is modulated in parallel using a bank of modulators, which converts, for example, pairs of bits into a complex number ($\pm 1, \pm j$) carrying Quadrature Phase-Shift-Keyed (QPSK) symbols. The outputs of the modulators feed some of the inputs of an inverse fast Fourier transform (IFFT), representing positive and negative frequencies close to DC. The highest frequency inputs are usually set to zero. This zeroing is useful to provide guard-bands in the spectrum, so that analog filters can be used to remove images from the transmitted spectrum. The output of the IFFT is a superposition of all of the modulated subcarriers. This is converted into a time-series by a parallel to serial converter. The real part of the time-series is fed to one Digital to Analog Converter (DAC), to provide an Inphase signal. This is upconverted to an RF carrier using a balanced mixer. The imaginary part of the time series becomes a quadrature waveform which is also upconverted and added (in quadrature) to the Inphase part. The carrier now has distinct information in its positive and negative sidebands. After transmission through the dispersive channel, which typically has multiple paths from transmitter to receiver, the modulated carrier is downconverted to baseband using mixers. A Serial to Parallel converter presents the data to a forward FFT, which provides a series of parallel outputs, each corresponding to a subcarrier. The amplitude and phase of the subcarrier can be calculated from its real and imaginary components. However, it is usually demodulated using

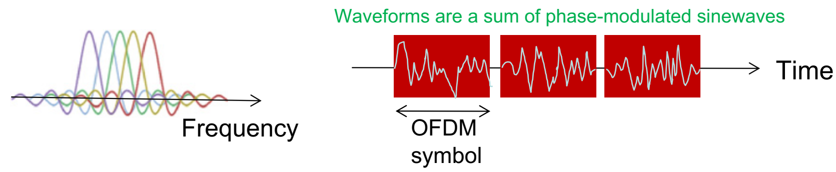

Fig. 1. OFDM spectrum (left) and time-waveform (right). The spectrum comprising overlapping subcarriers (sinc functions): the waveform in each OFDM symbol is a summation of phase- and amplitude-modulated subcarriers.

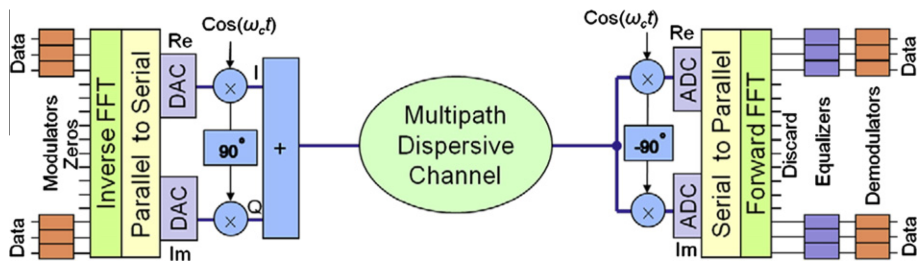

Fig. 2. Simplified radio-OFDM system implemented using Fourier Transforms. Using zeros at the inputs of the FFT gives a spectral guard-band around the OFDM band, which is critical in radio applications to avoid interference with neighboring channels.

thresholding about the *x* and *y* axis. Because the channel is dispersive, equalizers are required to adjust the amplitude and phase of each subcarrier before thresholding. They can also compensate for amplitude errors in a channel with fading. Since the equalization is a single multiplication, these are known as 1-tap equalizers. In contrast, most single-carrier systems require equalizers consisting of a weighted sum of delayed versions of the input signal, using 'multiple taps' of a delay line. This simplification is possible because the subcarriers are so narrow that each, within itself, is practically unaffected by dispersion.

The dispersive channel will cause a relative time delay between the subcarriers which will shift a subcarrier from one OFDM symbol to the adjacent symbols. This has two effects: firstly the subcarrier will become aperiodic within the desired symbol which causes its power will leak into neighboring subcarriers when Fourier transformed causing Inter-Carrier Interference (ICI); secondly, it will pollute adjacent OFDM symbols, causing Inter-Symbol Interference (ISI).

A solution to this problem is to add a Cyclic Prefix (CP) to each OFDM symbol [55]. As shown in Fig. 3, the CP simply copies the last part of an OFDM symbol, as produced by the inverse FFT, and attaches it to the start of the same OFDM symbol. The extended symbol is able to accommodate the relative time-shift of each subcarrier of up to the duration of the CP because a time-shifted version of the subcarrier (with CP) will remain periodic within the Fourier-Transform window of the receiver. The phase errors in each subcarrier generated by the channel can be corrected with a single complex multiplication in each subcarrier's equalizers.

A disadvantage of the CP is that the payload of the symbol must still be sent at the required rate. Because the CP part of the symbol does not carry additional information, the bandwidth of the signal must be increased.

2.2. Spectra in OFDM systems

The actual signal spectrum in an optical OFDM system is a source of confusion, as it can be measured at several different points in the system, in the optical, electrical or digital domains, using different methods. The spectrum also changes with the addition and stripping of the cyclic prefix.

The commonly accepted explanation of orthogonality is that each subcarrier has a sin(*x*)/*x* (a *sinc*) spectrum, whose nulls align

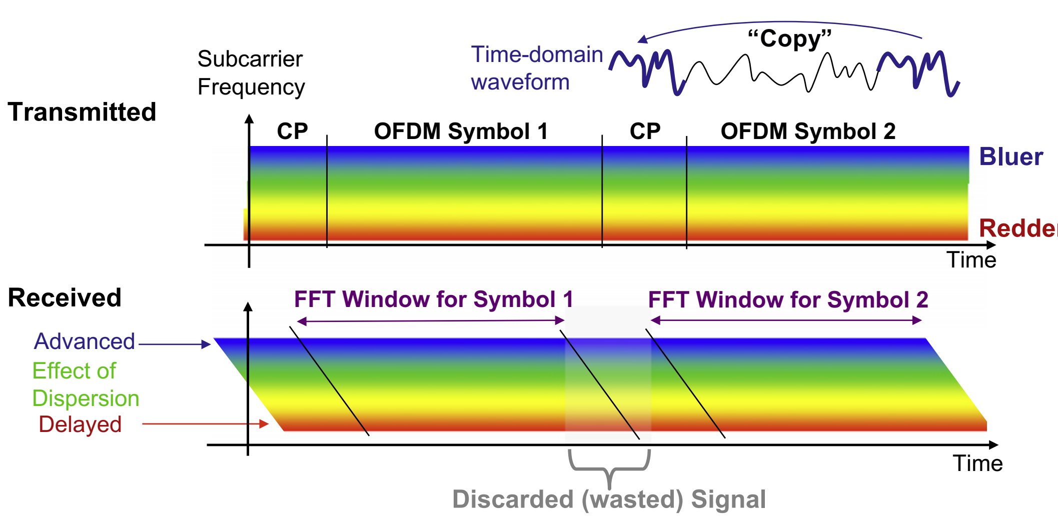

Fig. 3. Addition of a Cyclic Prefix (CP) to accommodate the spreading of the subcarriers in time, due to chromatic dispersion in an optical fiber, for example.

with the peaks of the sinc spectra of adjacent subcarriers, so cause no intersymbol interference. This is not universally true along the optical system, but is a reasonable explanation if applied at the correct point in the receiver. We will use a series of time-waveforms and their spectra to explain what could be expected along a system under certain conditions.

(i) *Continuous spectrum of a single rectangular pulse*. A rectangular pulse can represent the envelope of the modulation of one OFDM subcarrier. For example, it could have data encoded onto its amplitude and/or phase. A rectangular pulse of duration T_{pulse} in the continuous domain (not sampled) has an analytical transform yielding a sinc-baseband spectrum with $2/T_{pulse}$ between the first nulls in its spectrum.

(ii) *Spectrum of a sequence of adjacent pulses with random modulation*. The modulation of a sequence of pulses can be represented by a series of Dirac delta functions carrying, say, a different phase and/or amplitude, spaced at T_{pulse}. Because the pulses carry random phase and amplitude, their Auto-Correlation Function (ACF) is a delta function, and therefore their spectrum is flat (being the Fourier transform of the ACF, by the Weiner–Khinchin theorem [55]). The waveform of a continuous *sequence* of pulses will be a convolution of this Dirac-pulse sequence with the single rectangular pulse, in the time domain. Convolution in the time domain is equivalent to multiplication in the frequency domain. Therefore, the spectrum of a sequence of pulses with random modulation, when measured over a long time, tends towards the sinc spectrum of a single pulse.

(iii) *Spectrum of a sequence of pulses modulated onto an electrical carrier*. The inverse Fourier transform in an OFDM transmitter will produce a set of subcarriers, each modulated with a sequence of rectangular pulses (one transform produces one pulse in the sequence). The IFFT produces a complex-valued output waveform, which allows separate information to be encoded onto the positive and negative frequency components of the waveform. If only a single frequency-point is used at the input of the transform, then the Inphase and Quadrature components of the output waveform (corresponding to the real and imaginary parts of the complex-valued waveform) will be Hilbert transforms of one another. The electrical spectrum of this complex-valued single-subcarrier signal, measured over many pulse intervals, tends towards a sinc function in the limit of an infinite measurement interval.

(iv) *Spectrum of the pulses modulated onto an optical carrier*. The output of the FFT can be upconverted to an optical carrier frequency using a complex optical modulator. The spectrum of a single transmitted subcarrier will tend towards a sinc shape, as shown by the jagged spectrum in Fig. 4. This assumes the modulator is operated in linear-field mode and biased for a null output with no signal input.

Taken over an infinite duration, the spectrum of a band of subcarriers will have a flat top, with tails closely resembling the sinc-like tails of the outermost subcarriers. The edge of such a band is shown in Fig. 5. If a conventional optical modulator is used, a double-sideband spectrum will be produced. In both cases, there may be some leakage of the unmodulated optical carrier depending on the data sequence and also the biasing of the modulator.

(v) *Spectrum of the detected electrical signal*. Photodiode(s) are typically used to down-convert the optical signal to an electrical signal comprising of the original subcarriers. In a CO-OFDM system, a coherent receiver is used to linearly down-convert the optical signal to a complex electrical baseband signal comprising of Inphase and Quadrature components. Without noise or fiber dispersion, the spectrum of the recovered electrical signal should be identical to the spectrum driving the modulator. The single photodiode receiver of a DDO-OFDM system is a square-law detector so will produce signal × signal beat terms which will be discussed in Section 3. Both receiver topologies will down-convert optical noise (Amplified Spontaneous Emission, ASE, from optical amplifiers) into the electrical band [56].

(vi) *Spectrum of the sampled electrical spectrum*. The digital to analog converters will sample the received electrical waveform (or waveforms, if inphase and quadrature components are both detected), producing a sequence of discrete values, each quantized to a number of bits. The spectrum of this sequence can be analyzed using digital computation by a discrete Fourier transform. Depending on the duration (window) of the transform, the observed spectrum will have different characteristics. For example, if the transform observes exactly over a single pulse, then its outputs at frequencies of m/T_{pulse} will correspond to individual subcarriers, without

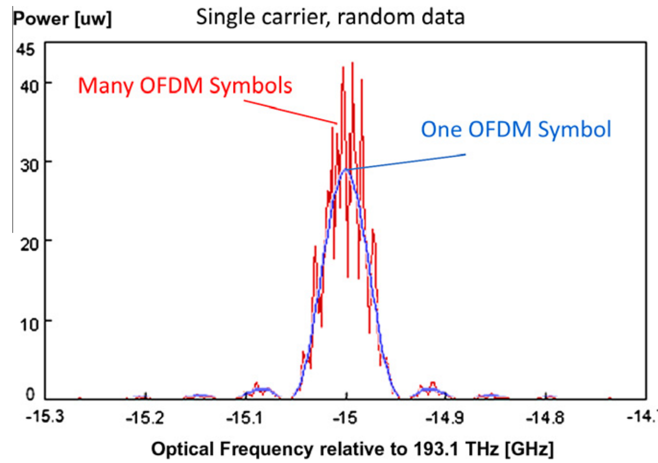

Fig. 4. Spectra of a single subcarrier at −15 GHz modulated onto an optical carrier at 193.1 THz. The smooth (blue) line is the spectrum with one single OFDM symbol; the jagged (red) line is the averaged spectrum over many hundreds for OFDM symbols, carrying random data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

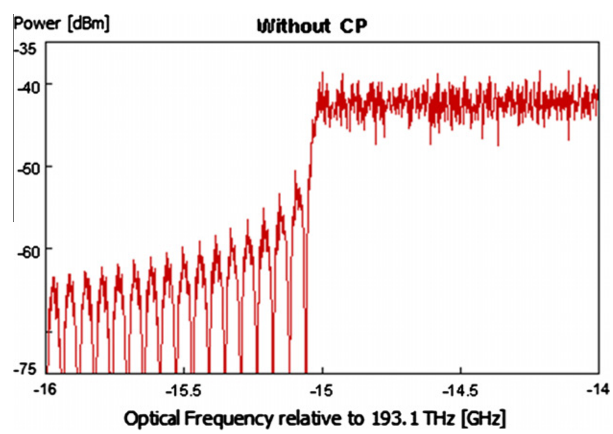

Fig. 5. Edge of a spectrum of a multiple subcarriers modulated onto an optical carrier at 193.1 THz. The signal band has a flat top if averaged over many more symbols: this shows that all portions of the passband are used to carry the same amount of data.

leakage. The output at frequencies between these points will contain a mixture of several subcarriers. If the transform observes many pulses, then its outputs will not uniquely map to either individual subcarriers, nor the data contained in each pulse. A Fast Fourier Transform allows efficient numerical computation of the DFT, produces outputs only at frequencies m/T_{pulse}, and is thus commonly used in optical OFDM receivers to recover the phase and amplitude of each subcarrier.

(vii) *Addition of cyclic prefix*. For a given OFDM symbol duration, $T_{OFDM} = T_{pulse}$, giving a subcarrier spacing $1/T_{OFDM}$. The CP reduces the data rate by a factor of $T_{OFDM}/(T_{OFDM} + T_{CP})$ because of the additional time required to transmit the CP. The effect on the spectrum, optical and electrical, is to produce nulls in the subcarrier band. For example, with $T_{CP} = T_{OFDM}$, every other subcarrier is nulled, as shown in Fig. 6. For a more reasonable CP, say $T_{CP} = T_{OFDM}/2$, the nulls will not be as deep (Fig. 7).

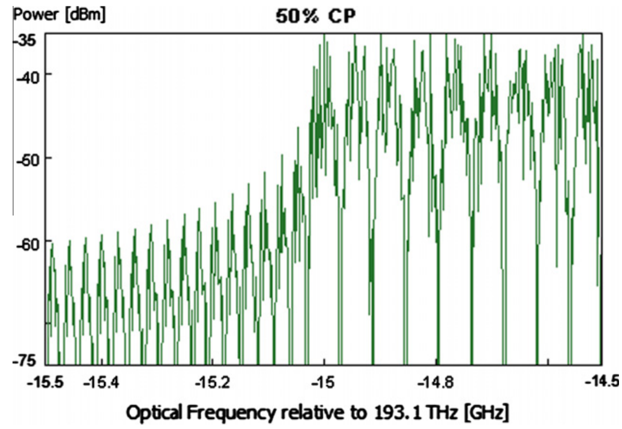

Fig. 7. Edge of a spectrum of a multiple subcarriers with a 50% CP added to each OFDM symbol.

2.3. Constellations

In on-off keyed systems, the traditional method of quickly assessing signal quality is the eye diagram, obtained with an oscilloscope triggered by the recovered clock signal on a high persistence setting, so that many portions of the received bit sequence are overlaid. The eye opening can be used as a measure of signal quality, and shows bandwidth and noise limitations, including dispersion and noise. For OFDM systems, the received eye, obtained by overlaying subsequent OFDM symbols, reveals little, except for the distribution of signal levels. This is because the signal is a superposition of sinusoids at the subcarrier frequencies, and each sinusoid is phase modulated. Thus, no particular peaks or openings can be discerned. The constellation, obtained just before the thresholder in the OFDM receiver, is thus used to assess signal quality. This plots the imaginary (Q) coefficient of the FFT output against the real (I) part, usually for all subcarriers in an OFDM symbol, and possibly over multiple OFDM symbols.

One of the simplest constellations is for 4-QAM (which is also known as QPSK). This has four clusters of points, each lying in one quadrant of a Cartesian plot. With little noise, the clusters have a small spread compared with their separation. The optimal threshold is at the axes which makes it easy to recover the data. Fig. 8 shows a 4-QAM constellation for a DDO-OFDM system carrying 60 Gbit/s with added ASE. The optical signal to noise ratio (OSNR) was 15.8 dB (12.5 GHz measurement bandwidth) with an optical noise filter bandwidth of 60 GHz to allow the carrier and subcarrier-band to pass.

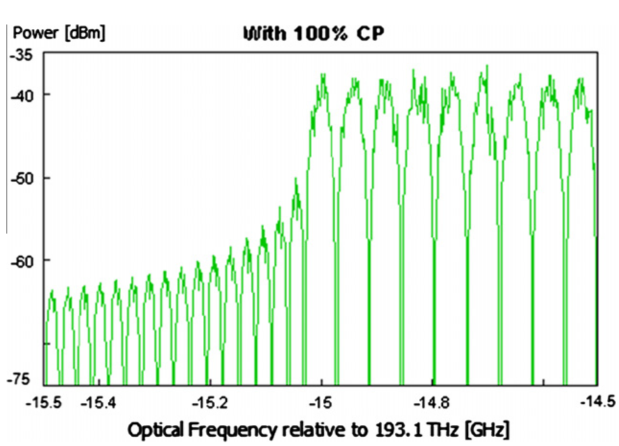

Fig. 6. Edge of a spectrum of a multiple subcarriers with a 100% CP added to each OFDM symbol. The CP produces nulls in the OFDM spectrum.

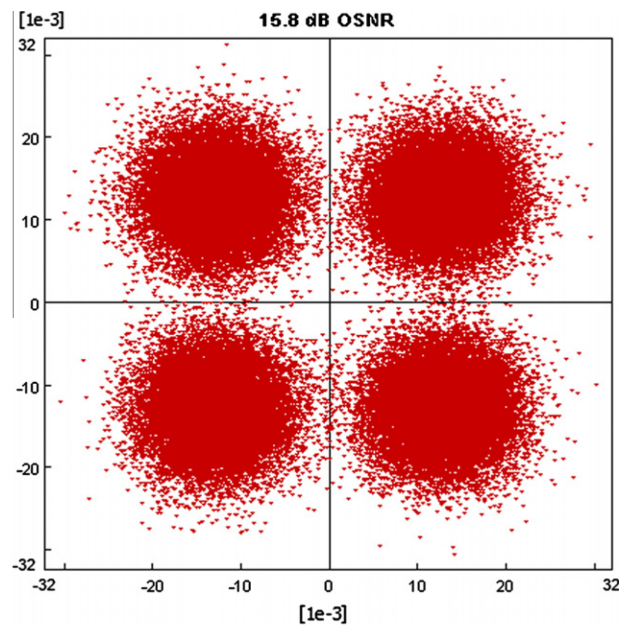

Fig. 8. Constellation for a 30-Gbit/s 4-QAM DDO-OFDM system with a 15.8-dB Optical Signal to Noise Ratio and a 60 GHz noise bandwidth, which is the minimum possible bandwidth to pass both the carrier and subcarrier.

The average quality, q, was calculated for this constellation using the means, μ, and the variances, σ^2, of the distributions of the clusters, rotated into the first quadrant, in the Cartesian coordinates:

$$q^2 = \frac{((\mu_x + \mu_y)/2)^2}{(\sigma_x^2 + \sigma_y^2)/2} \tag{1.1}$$

Usually the quality is quoted in dB, where $Q(\text{dB}) = 20\log_{10}(q)$. For a 15.8-dB OSNR, as used in Fig. 8, the average Q over 320 OFDM symbols, over all 512 subcarriers (around 320,000 bits), was 10.08 dB.

2.4. Bit Error Ratio

The Bit Error Ratio, BER, can be approximately calculated from the constellation-derived signal quality, q, using

$$\text{BER} \approx \frac{1}{2}\text{erfc}\left(\frac{q}{\sqrt{2}}\right) \tag{1.2}$$

Using this equation, a Q of 9.8 dB is required for a BER of 10^{-3}. In Fig. 8 an average Q, over all subcarriers, of 10.01 dB was required to obtain a BER (by counting errors) of 10^{-3}. This is because in DDO OFDM each subcarrier has a different signal quality which causes this method to underestimate BER. A better method is to calculate the BER for each subcarrier (using an average of many OFDM symbols), average the BERs, and back-calculate the signal quality, of required [57].

2.5. Early optical OFDM systems

For more than 10 years there has been research in transmitting OFDM signals over optical fibers, in "radio-over-fiber" (RoF) systems [58]. These used intensity modulation, where the OFDM signal's voltage was mapped to optical intensity, as shown in Fig. 9 [26], using a laser driven with a current proportional to the OFDM signal voltage, plus a DC bias to ensure that the laser never turned off by being driven below its threshold current [26]. At the receiver, the photodiode converts intensity back into photocurrent, and then a transimpedance amplifier (TIA) converts photocurrent into a signal voltage. Such a system is linear from end to end, providing that there is no fiber dispersion and also that the optical bandwidth is not restricted. This is because the optical spectrum is considerably wider than the RF spectrum. Firstly, the optical signal is a double-sideband signal, so has sidebands above and below the laser carrier. Secondly, the optical field is proportional to the square-root of the drive voltage (plus bias, minus the laser threshold current), meaning the optical signal has harmonics and mixing products of the original OFDM signal. A disadvantage of the system is the large intensity bias required to prevent negative peaks clipping [59], causing a performance degradation [60]. This means that more optical power is allocated to sending a large optical carrier than is allocated to signal-bearing sidebands. A partial solution has been the use of symmetrical clipping followed by windowing [61]. More recently, analytical methods of determining the optimum clipping ratio have been developed [62].

It should be noted that optical systems using multiple subcarriers had been developed before optical OFDM had been proposed for dispersion compensation [21,63]. These provided an N^2-fold gain in the dispersion-limited length of a system, for N-subcarriers, but did not embrace the orthogonality of the subcarriers, which were generated by microwave mixing techniques rather than digital computation. Note that the acronym OFDM in Ref. [63] meant *Optical* Frequency Division Multiplexing.

2.6. Power efficient intensity-modulated optical OFDM

Armstrong and Lowery provided solutions to the large intensity bias based on clipping the signal about its mean value [23], known as Asymmetrically-Clipped Optical OFDM (ACO-OFDM). This provided a sweet-spot in operation, where the received (electrical) signal quality was maximized and the DC bias minimized. Clipping about the mean value (removing all negative-going signals) caused a large amount of intermodulation distortion between the subcarriers. Two solutions were proposed: (1) displacing the OFDM upwards in frequency which produces a 'gap' was left between the optical carrier and the OFDM sidebands [22] allows most of the intermodulation products to fall into this gap and (2) using only the odd subcarriers, so that *all* intermodulation distortion falls on the even subcarriers, to be rejected by the receiver's Fourier transform [64]. Both methods reduce the spectral efficiency of the system, but both give thermal-noise-limited receiver sensitivities close to or better than On–Off Keying (OOK) systems using Non-Return to Zero (NRZ) modulation. Early papers showed that these solutions could be used to compensate multipath dispersion as occurs in multi-mode fiber and free-space optical systems.

3. Direct detection optical OFDM for long-haul systems

3.1. Compensating for CD

An issue with intensity-modulated optical systems is that the fiber's chromatic dispersion will cause the signals of the two sidebands to rotate, which converts amplitude modulation into phase modulation. This produces nulls at certain frequencies when the sidebands mix with the carrier upon photodetection [65]. A solution to this issue is single-sideband modulation [34,66], where one of the sidebands is removed by optical filtering (made easier by the frequency gap). Alternatively, a single sideband optical modulator with one drive the Hilbert transform of the other can be used [67], as shown in Fig. 10.

In order to utilize a CP to compensate for CD, the mapping from electrical to optical and back to electrical domains must be linear for the subcarrier band. At the transmitter, this can be achieved by biasing the MZM in the linear-field region, close to a transmission null. A single-sideband 'field modulated' optical signal will have an optical OFDM single of equal bandwidth to the electrical OFDM signal. The photodiode used at the receiver for the optical to electrical conversion is a square-law detector. Therefore, a guard band of equal bandwidth as the OFDM signal must be left between the OFDM signal and the optical carrier [32]. A CP of equal duration to the time-shift from lowest-to highest-frequency subcarrier will prevent any degradation from inter-symbol interference. Such 'Field Modulation' was used by Schmidt et al. [68] to achieve higher-order modulation (32-QAM); without Field Modulation, the received constellations had a residual error in the presence of fiber dispersion.

This single-sideband field modulated optical OFDM system is commonly referred to as 'Direct Detection Optical OFDM', although technically intensity-modulated optical OFDM systems are also 'direct detected'.

3.2. Improving sensitivity

When field modulation is used in conjunction with a guard band, it is not required to keep the optical field positive allowing an arbitrary carrier power to be used. It has been shown that the

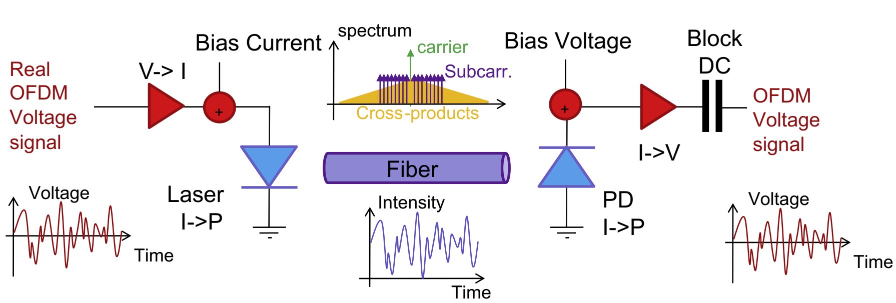

Fig. 9. Intensity modulated optical OFDM (IM-OOFDM) system.

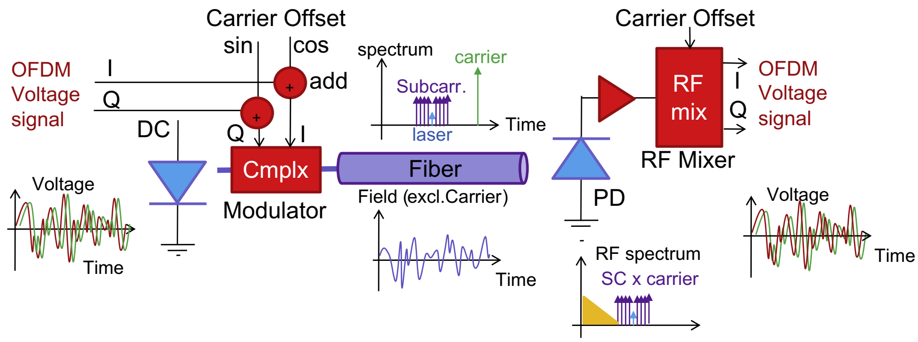

Fig. 10. Direct-detection optical OFDM system with a virtual carrier generated by frequency-shifting the laser's frequency.

optimal carrier-to-signal ratio for a simple photodiode receiver is close to one-to-one for most reasonable optical signal to noise ratios [69].

The single-photodiode receiver in DDO-OFDM suffers from poor noise performance. This is because there are many ways in which the carrier, subcarrier and optical noise can mix due to the square-law of the photodiode to produce electrical noise [56]. This becomes apparent when compared with a coherent receiver. One method of reducing the noise mixing is to use a balanced pair of photodiodes; for example, if one receives (ASE + Carrier + Signal) and the other only (ASE + Signal), then noise and interference terms due to $(\text{ASE} + \text{Signal})^2$ will cancel [70]. A simpler, though less effective, method is to boost the carrier with respect to the subcarriers just before the receiver [71].

3.3. Polarization-mode dispersion (PMD) compensation

PMD is a result of a single-mode fiber supporting multiple polarization states, which can be decomposed into two orthogonal modes, or principal states of Polarization (PSPs). Due to manufacturing tolerances, the two PSPs are likely to have slightly different group velocities; thus, if a signal is launched into both PSPs (which is almost always the case, as the PSPs are unknown to the transmitter PSP), it will have a fast and a slow component. These components will interfere at the receiver causing frequency nulls in the spectrum. This results in the Signal to Noise Ratios (SNRs) of some subcarriers to become unacceptably poor [72]. In a direct-detection optical OFDM system, where the carrier is displaced away from the subcarriers, the carrier and subcarriers may suffer different polarization rotations, so the carrier will no longer mix with the subcarriers at the photodiode. This could cause a majority of the subcarriers to fade in power.

Some solutions to PMD have been proposed. The simplest is to split the sideband signal into two orthogonal components at the receiver, and detect each with a separate photodiode [73]. The carrier's polarization should be controlled before the splitter, so that equal amounts of carrier reach each photodiode. In this way, the signal is guaranteed to be detected by one or other photodiode. A more-complex solution is to use a multi-stage PMD compensator to ensure that the sideband's subcarriers all align with the carrier before photodetection.

3.4. Polarization multiplexing

Polarization multiplexing (PolMux) doubles the spectral efficiency of a system by transmitting separate data on orthogonal polarizations [74]. The advent of digital signal processing combined with polarization-diverse coherent receivers has made it easier to undo the scrambling of the channels due to polarization-mode dispersion along the optical fiber and track changes in the PSPs [75]. While PolMux is relatively simple for coherent optical OFDM systems (see next section), the 'remote' carrier used in DDO-OFDM systems makes it more difficult to control the carrier's polarization at the receiver. Therefore, PolMux in DDO-OFDM has proven to be challenging. Xie developed a polarization diverse receiver using a Faraday rotator to detect PolMux DDO-OFDM signals [76]. Unfortunately the Faraday rotator only provides an orthogonal polarization for certain input polarization states. An alternative polarization diverse receiver was developed by Schmidt et al. [72].This is similar to a coherent receiver, except that the local oscillator is derived from an optical carrier sent along the fiber link and extracted with an optical filter. This is also known as a self-coherent receiver, and has advantages in terms of phase noise, though the spectral efficiency is not as high as a coherent receiver. Note, however, that the frequency gap used in DDO-OFDM can be reduced, though must be sufficient to allow optical filtering to separate the carrier from the signal. 120 Gbit/s transmission has been demonstrated experimentally using this technique [77].

Feng et al. [78] also proposed a self-coherent receiver, but using two separate fibers: one to carry the subcarrier and carriers, and one to transport the carrier and alone. Another alternative was to time-multiplex the carrier and subcarrier [79] which also gives some advantage in noise performance.

Qian et al. proposed to use two optical carriers at orthogonal polarizations placed either side of the signal band [80]. This method was experimentally demonstrated at 108 Gbit/s. The signal can be separated into the original polarization states provided the two carriers remain in orthogonal polarization states. However, because there is a large frequency difference between the two carriers, it is possible for PMD to cause the carriers to be no longer orthogonal. This will result in a sensitivity penalty.

3.5. Laser linewidth

Although the carrier and sideband are derived from the same laser in DDO-OFDM systems, these systems are not immune to phase noise. Chromatic dispersion causes walk-off between the carrier and subcarriers which decorrelates their phases [81,82]. The relative phase error between the subcarriers and carrier results in baseband phase errors and intra-carrier interference [83]. The pilot tone compensator could compensate this error [83] and re-aligning the carrier to the subcarrier with a delay line also improved performance [84]. A digital form of pilot tone extraction has also been applied to DDO-OFDM, which is able to significantly increase the transmission distance for a given linewidth [85]. The fiber's chromatic dispersion also converts laser phase noise to intensity noise [86,87], which may affect the system depending on the modulation format.

3.6. Efficient use of DAC bandwidth

The sampling-rate limitations of commercial Arbitrary Waveform Generators (AWGs), and Digital to Analog Converters (DACs) in general, have produced innovative solutions to maximize the transmitted data rate. Early DDO-OFDM systems used the AWG to convert the whole OFDM symbol, including carrier, into a single-sideband optical signal with the subcarriers centered on the laser, as shown in Fig. 11.

This was wasteful because the subcarrier-band and carrier were displaced by a frequency gap which was created by setting the inputs to the inverse Fourier Transform to zero. Therefore, half the positive-frequency range of the FFT was wasted and so was half the DAC bandwidth. The single sidebanding was created using an optical filter in these systems which filtered out the lower side-band.

Alternatively, the single sideband could be created by driving a 'Single Sideband' (or complex/IQ) modulator with two drive signals, representing the complex outputs of the IFFT, as shown in Fig. 12. If the negative frequency coefficients of the IFFT were set to zero, then a single-sideband optical signal would be obtained. This requires two DACs, effectively halving their utilization. For example, a 10 Gbit/s 4-QAM system would require two 20-GS/s DACs to transmit an upper sideband 5-GHz away from the optical carrier at DC.

Peng et al. [88] introduced the concept of a virtual carrier, generated by shifting the laser source to the negative edge of the modulated band, while the whole positive half of the DAC band was used for the subcarriers. This halved the required DAC rate for a given subcarrier bandwidth as illustrated in Fig. 13. Note that the Inphase and Quadrature signals are shown as single-sided spectra, so the tones that generate the VC are shown as a positive frequency; however, the relative phases of these tones are such that the complex optical modulator shifts the laser downwards in frequency.

Fig. 14 shows an ultimate solution that uses the AWGs only for the sideband generation, and use a separate oscillator to generate the virtual carrier [89]. Two 20 GS/s DACs could then generate a band almost 20-GHz wide, centered on the laser line. A virtual subcarrier could then be generated by adding 30-GHz sine and cosine waves to the modulator drives, to produce a frequency-shifted version of the carrier 20-GHz away from the sideband. This could support almost 40 Gbit/s with 4-QAM modulation: 8-QAM could support 60 Gbit/s, 16-QAM 80 Gbit/s and 32-QAM 100 Gbit/s. Pol-Mux could be used to double these rates once again. Practically, the obtainable optical bandwidths (double-sideband, using a complex modulator are around 80% of the sampling rates) and the QAM modulation is limited by the effective number of bits of the DACs. That said, 120 Gbit/s has been demonstrated using single-band DDO-OFDM with a self-coherent receiver [77].

3.7. Increasing the spectral efficiency in DDO-OFDM

Compatible single-sideband (SSB) optical OFDM is a method to increase the spectral efficiency of DDO-OFDM systems, by reducing the frequency gap between the transmitted carrier and the subcarriers [90]. This gap is to accommodate *subcarrier* × *subcarrier* intermodulation products, which when detected extend up to the bandwidth of the subcarrier band. The word *compatible* comes from broadcast radio, where Compatible Single-Sideband transmitters were developed to replace Amplitude-Modulated transmitters without changing the receivers. Compatible optical OFDM reduces the gap to zero by modulating the envelope of the optical signal rather than the field, and also using signal transformations and phase modulation to obtain a single-sideband optical signal. CD induces an OSNR penalty in compatible SSB optical OFDM because there is no longer 1:1 mapping between the optical spectrum and the received subcarriers. This penalty increases with the amount of residual CD at the receiver and decreases with the size of the FFT/IFFT used. Compatible OFDM has recently been demonstrated experimentally and showed an optimum carrier level around 10-dB higher than the subcarrier band's power [91].

Alternatively, to reduce the gap, the intermodulation products can be partially cancelled by a multi-step process where the *carrier* × *subcarrier* signals (unfortunately polluted by the modulation products) are used to estimate the *subcarrier* × *subcarrier* intermodulation products [92]; so the estimate can be subtracted from the polluted *carrier* × *subcarrier* signals. This is not a perfect process since the estimates are themselves polluted, but it does allow the spectral efficiency to be traded against the required OSNR for a given bit rate.

A recently proposed alternative method for increasing the spectral efficiency is frequency-interleaving [93]. This uses periodic optical filters to interleave two signals, so that a subcarrier band of one signal fits between the carrier and the subcarrier band of the other signal.

3.8. Direct-detection optical OFDM for Passive Optical Networks (PON)

The tight spectral control available in OFDM signals has led to proposals for DDO-OFDM to be used in passive optical networks, because the well-confined downstream signal can also contain unmodulated laser lines that can be modulated at the user end (the, Optical Network Unit, ONU) to send upstream data [94]. A 108 Gbit/s downstream transmission has been demonstrated over 20 km using 16-QAM polarization-division multiplexing and a polarization-diverse receiver based on a polarization beam splitter and two direct-detection photodiodes [80]. The two polarizations each had a separate carrier; one displaced upwards in frequency relative to its subcarrier band, and the other downwards. This meant that although the subcarrier bands for both polarizations spectrally overlapped, the carriers did not. If the two carriers (of two orthogonal polarizations) were at the same frequency, they would simply add to form a single carrier in the new PSP. This would clearly not provide the polarization diversity needed in a receiver of a polarization multiplexed signal. The receiver was

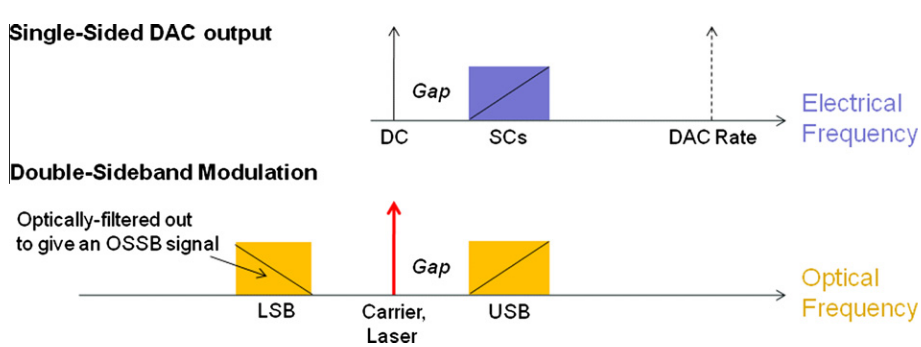

Fig. 11. A single DAC can be used to modulate a single-drive MZI to obtain a double-sideband optical spectrum, which can then be filleted to give an optical single-sideband (OSSB) spectrum with an optical carrier centered on the source laser frequency.

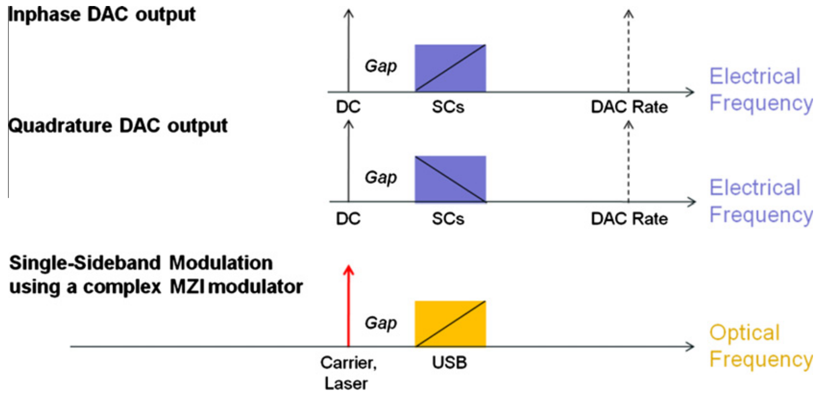

Fig. 12. Two DACs can be used to drive the I and Q inputs of a complex MZI modulator to obtain a single-sideband optical spectrum.

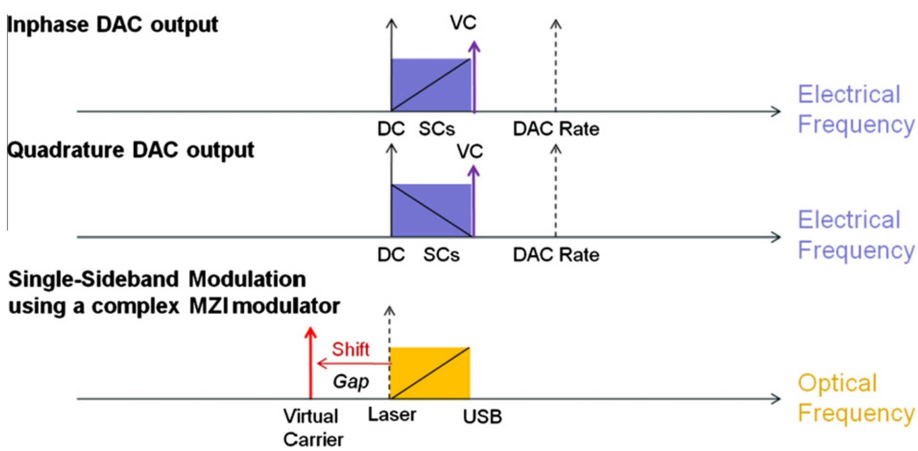

Fig. 13. Two DACs can be used to drive the I and Q inputs of a complex MZI modulator to obtain a single-sideband optical spectrum and a virtual carrier.

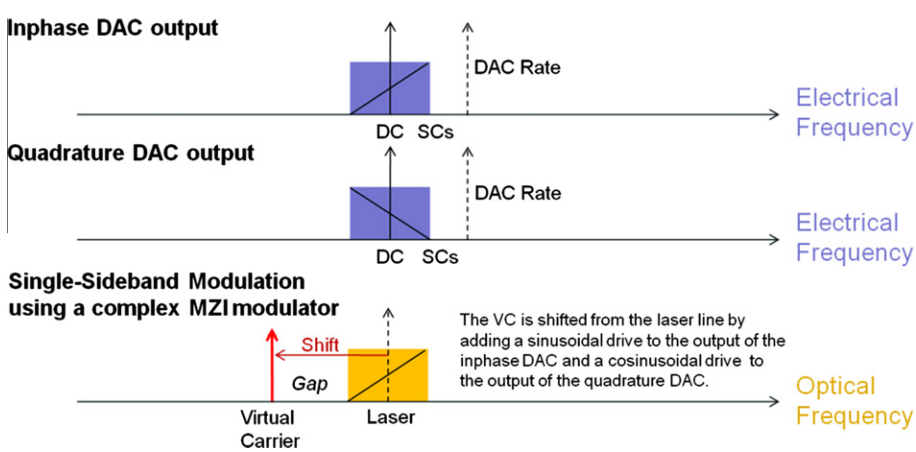

Fig. 14. Two DACs can be used to drive the I and Q inputs of a complex MZI modulator, with a separate drive to give the virtual carrier.

similar to the receiver proposed by Mayrock and Haunstein [73] but without the polarization controller so an OSNR penalty would result if higher order PMD in the link caused the two carriers to no longer be in orthogonal PSPs. Real-time processing of 44 Gbit/s upstream signals [80,95] has been demonstrated recently with real-time processing at the receiver, using a novel scheme where the I and Q components of a baseband OFDM signal were transmitted on separate wavelengths, then recombined using appropriate delays to compensate for chromatic dispersion. [94]. Direct-detection optical OFDM may excel in these short-haul links, due to its simplicity and compatibility with wireless-based access signals. This is leading to world-wide research effort in this area using advanced multiplexing schemes [96] and low-cost components [97].

4. Coherent optical OFDM

4.1. Theory

One method to reduce the transmitted power is not to send the carrier, which gives rise to coherent optical OFDM (CO-OFDM)

[18,45]. This method is very similar to typical RF OFDM systems except the RF carrier is replaced with an optical carrier. Because the carrier is fully removed at the transmitter, a carrier must be regenerated at the receiver. A coherent receiver is then used to map the optical subcarriers 1:1 with electrical subcarriers. A typical coherent optical OFDM system is shown in Fig. 15. An OFDM voltage signal is mapped onto an optical-field waveform using a complex optical modulator, as in the direct detection system. The optical spectrum is as wide as the spectrum of the voltage signal. At the receiver, a local oscillator is tuned to the frequency of the transmitter laser. The coherent receiver is able to provide Inphase (I) and Quadrature (Q) components that reproduce the input signal to the transmitter. Phase-offsets between the transmitter laser and the local oscillator can be compensated digitally, as discussed in Section 4.3.

CO-OFDM requires around 7–9 dB less OSNR than DDO-OFDM for a given error rate because CO-OFDM a carrier is not transmitted, and coherent receivers suppress electrical noise generated by subcarrier × ASE mixing and ASE × ASE mixing [56]. All linear channel degradations, such as CD, can also be compensated with a single complex multiplication because the optical modulation and demodulation are linear with respect to the optical field [98].

4.2. Effect of laser linewidth

One of the major optical effects that restricts CO-OFDM systems is laser phase noise. The duration of each symbol places a restriction on the linewidths of the lasers used in coherent systems – longer OFDM symbols require narrower-linewidth lasers [99]. This is because the phase wander associated with linewidth will cause the subcarriers to become aperiodic during an OFDM symbol, leading to Intra-Carrier Interference (ICI) – essentially a loss of orthogonality. For this reason, experimental demonstrations of CO-OFDM systems have typically used shorter symbols than DDO-OFDM systems. Unfortunately shorter OFDM symbols suffer from a greater proportion of their duration being used for a cyclic-prefix, so a compromise is necessary. One solution is to stagger the transmission times of groups of subcarriers [100,101], so that they arrive in synchronism at the receiver, after suffering the differential group delays imposed by CD. This means that short, or even zero, cyclic prefixes can be used.

An elegant solution to the issue of laser linewidth in CO-OFDM systems is to use a pilot tone that has sufficient guard bandwidth around it in order to be able to detect the phase difference between the transmitter's laser and the local oscillator. This pilot can be extracted with a microwave filter or using DSP [102], as shown in Fig. 16. Once extracted, the pilot tone is mixed with the subcarrier band to downconvert the band to baseband. This mixing extracts the relative phase between the pilot and the subcarriers and cancels phase errors between the local oscillator and the transmitted laser. This technique has successfully supported system demonstrations with very-high QAM modulation, giving high spectral efficiencies, and large FFT/IFFT sizes which require extremely good phase stability [103].

4.3. Equalizer training

Many methods have been used to train the equalizer. For slowly-varying effects, such as CD, it is sufficient to periodically send a training symbol instead of data [68]. This has known data, so that the received symbols can be compared with the transmitted symbols at the receiver, to give a set of phase errors, one for each subcarrier. For CD, these are likely to have a quadratic dependence on frequency. This property could be used to improve the estimate of errors so that the noise during the training sequence becomes less important. Alternatively, the errors collected during several training sequences could be averaged for each subcarrier [35,45]. For fast-evolving phase errors, such as caused by the evolution of the laser phase difference between the transmitter's laser and the receiver's laser in a coherent system, some of the subcarriers can be used as pilot tones to give an estimate of the mean phase error of all subcarriers for that particular symbol. Increasingly sophisticated techniques of phase estimation are currently being developed [104]. These include using the information within each symbol to update the channel estimation [105] and using Maximum Likelihood (ML) techniques [106].

4.4. Polarization multiplexing

The PSP of the local oscillator is easy to control; this makes the implementation PolMux much easier for coherent optical systems. Fig. 17 shows a typical coherent PolMux system. The Polarization Beam Combiner (PBC) at the transmitter ensures that the channels are transmitted on orthogonal polarizations. A polarization-diverse coherent receiver, which is effectively two coherent receivers, one for each polarization, provides suitable outputs to four Analog to Digital Convertors (ADCs) [13]. The digital data can then be digitally equalized to undo the effects of PMD in the fiber [49]. Because of PMD, the each frequency of the received signal will be transposed onto a new polarization, though the two signals can be demultiplexed without loss if there is no polarization-dependent loss in the system [107]. When added to optical OFDM systems, PolMux provides 100 Gbit/s with high spectral efficiencies [43,77,103,108].

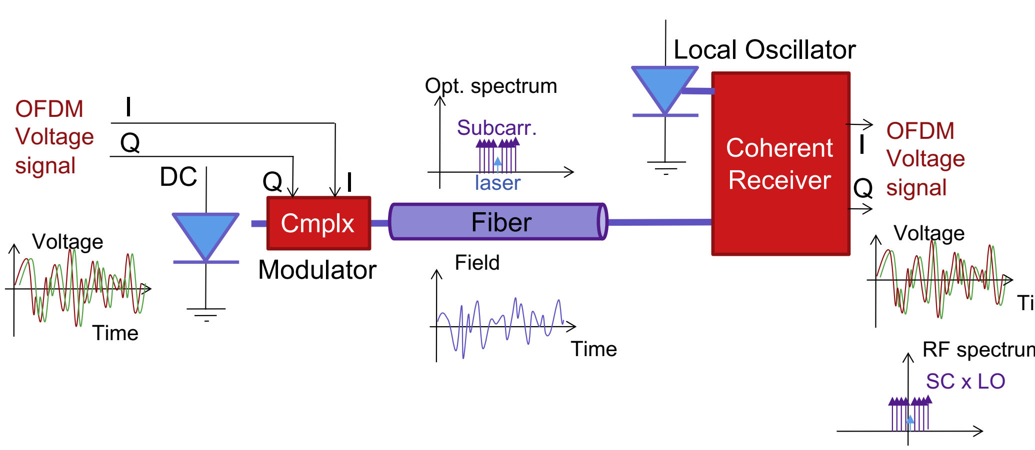

Fig. 15. Coherent optical OFDM system using a local oscillator at the receiver to regenerate a carrier.

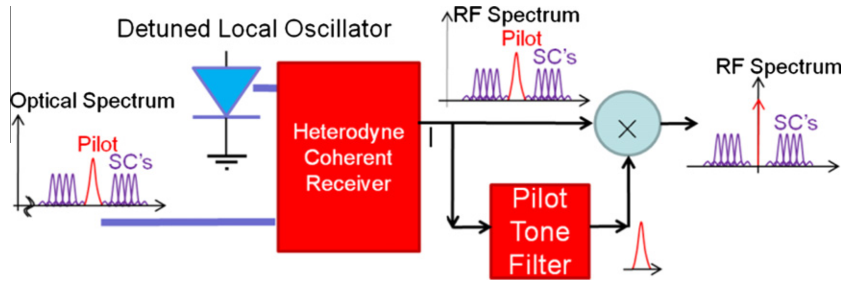

Fig. 16. Use of a pilot tone to remove phase noise from all subcarriers.

5. All-optical OFDM

Although each subcarrier of an optical OFDM signal has a sinc-shaped optical spectrum, which has power extending beyond its Nyquist bandwidth, OFDM obtains spectral efficiency by overlapping these spectra. An OFDM band is most easily generated by an IFFT, and converted to an optical spectrum containing hundreds of subcarriers; however, optical OFDM signals can also be generated by a bank of parallel optical modulators, each generating a single optical subcarrier [109]. The outputs of the modulators can also be arranged to be orthogonal, provided that the drive waveforms are aligned [110] (or more accurately, arranged to be aligned when they reach the receiver). The orthogonality means that the subcarriers from each modulator can also be packed together tightly. Fig. 18 shows a typical all-optical OFDM system. Note that only a few subcarriers are generally used, though each subcarrier can be modulated with OFDM itself.

In a real system, each modulator would be driven by unique waveforms, each carrying different data. In laboratory environments, the cost of AWGs precludes this, so generally 'even' bands are driven from one AWG, and odd bands from another. Further savings can be obtained by using one AWG and delaying its outputs by a few OFDM symbols. This still requires several optical modulators, so a common arrangement is to use one modulator fed with several laser lines, so it generates all of the 'even' bands simultaneously, with another modulator generating all of the odd bands. Most experimental demonstrations of PolMux systems use similar techniques to save hardware: the orthogonal polarizations are generated by the same modulators, but the signal is split into two polarizations one of which is delayed, before they are recombined. Extremely impressive experimental results have been obtained in this way, with data rates above 13 Tbit/s [111].

5.1. Coherent WDM

A forerunner to the development to optical OFDM is coherent WDM [112,113]. Here a number of intensity modulated channels are combined with phase-locked carrier phases. This is achieved by generating the carriers from one laser. The frequency-comb of carriers is then split into individual carriers, modulated, then recombined. It was found that optimizing the relative phases of the modulated carriers has a significant effect on the received signal waveform [114]. This is because the coherent interference between the modulated carriers can be moved away from the sampling time if their relative phases are adjusted. In 2005, 1.5 Tbit/s transmission was demonstrated using five wavelengths each carrying 298 Gbit/s [115]. This necessity to align phases precludes the use of phase modulation, such as QPSK.

5.2. Concatenation of OFDM bands

The capacity of optical OFDM systems can be increased by combining many optical OFDM bands, however generated, into one optical fiber. The simplest method is using traditional Wavelength Division Multiplexing (WDM) techniques, where each optical OFDM signal comes from a separate laser. Sufficient optical guard bands are required so optical filters can be used to separate the wavelengths before each channel is detected with a separate optical OFDM receiver. However, the guard bands reduced the spectral efficiency. Fundamentally, the optical filters must be wide enough to allow the tails of the sinc spectra to pass to prevent the subcarriers within the OFDM band from losing their orthogonality [116]. Shieh et al. have introduced the concept of orthogonal band multiplexing [117], where bands of optical OFDM subcarriers are combined coherently in the optical domain to form a super band of subcarriers without a guard band. This has similarities with the coherent combination of single-carrier signals [109,111], but instead combines bands of OFDM subcarriers each generated electronically. As with orthogonal combination of single-carriers, the key is that all of the frequency bands share a common frequency grid [118], so that all subcarriers from all bands are orthogonal. As with other OFDM systems, the OFDM symbols from each band will also have to arrive *at the receiver* in synchronism [100,110], within one CP, so that the receiver's Fourier transform can separate

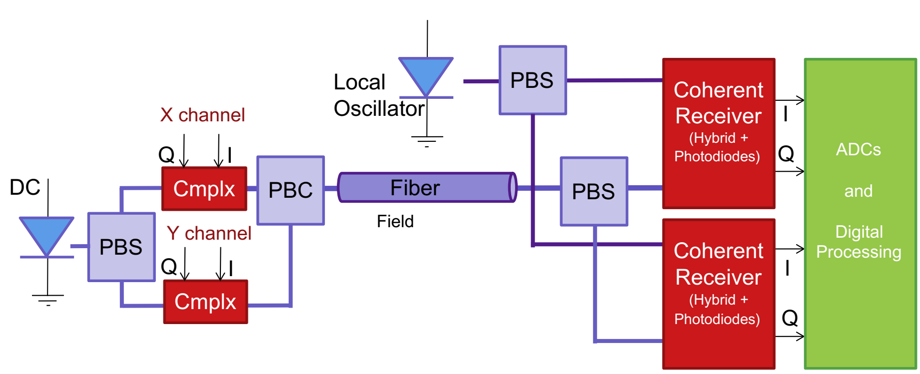

Fig. 17. Polarization-multiplexed coherent optical OFDM system. PBS = Polarization Beam Splitter; PBC = Polarization Beam Combiner.

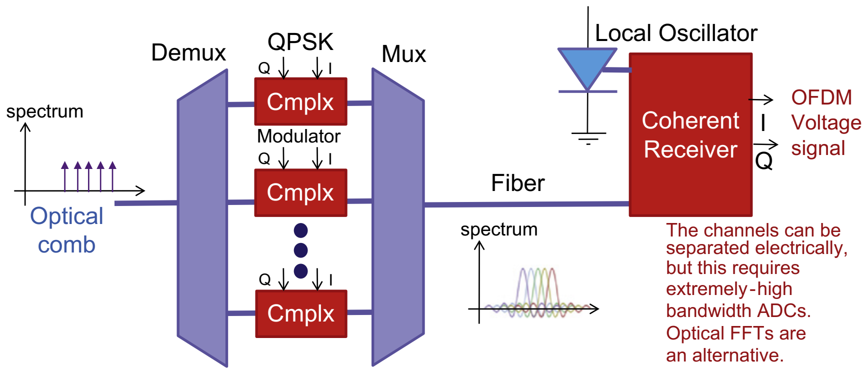

Fig. 18. Use of multiple modulators to construct a wide-bandwidth OFDM signal by modulating lines of an optical comb with individual modulators.

them without crosstalk [100]. The earlier demonstrations of banding used an laser tone, intensity modulated then phase modulated, to generate a comb of carrier frequencies locked to the OFDM symbol generators [117]; later work used a serrodyne comb generator based on a complex optical modulator within a recirculating loop [119]. An interesting feature of these systems is that the receiver can pick out any set of subcarriers to obtain a lower data-rate service.

5.3. Optical receivers

Because optical sampling oscilloscopes are available with sample rates two to four times greater than the sampling rates of the AWGs, it is possible for one sampling scope to capture enough optical bandwidth to decode the outputs of several AWG bands. For example, a 30-GHz bandwidth sampling oscilloscope with inphase and quadrature outputs from a homodyne coherent receiver could capture 60-GHz of optical bandwidth. This could potentially carry 120 Gbit/s using 4-QAM in a single polarization, which could be doubled with a polarization-diverse receiver to 240 Gbit/s. Using 16-QAM modulation could double this to 480 Gbit/s per wavelength.

However, if higher rates are required, it would be useful to optically pre-process the received signal to split it between lower-rate receivers. Optical Fourier Transforms have been implemented by several groups, with pioneering work by Sanjoh et al. [20]. These generally comprise a network of optical splitters, delays, phase shifters and couplers, followed by electrical or optical sampling gates [120]. The array of splitters and delays generally form a serial-to-parallel converter, which is followed by phase delays and couplers to form a weighted sum of the parallel samples (which were time-consecutive samples, before the serial to parallel conversion). Because the optical Fourier transform provides a continuous (rather than sampled) output, it gives a continuously-varying output as the Fourier transform window rolls across the received waveform. Its output is only valid if the rolling window coincides with a received OFDM symbol. Thus the output of the optical network needs to be sampled once per OFDM symbol [20]. This can be achieved using optical switches (modulators), nonlinear gates, with a coherent receiver with a pulsed local oscillator. These developments are reviewed in Ref. [116].

6. Fiber nonlinearity and compensation

6.1. Fiber nonlinearity in optical OFDM systems

The Kerr effect in optical fibers describes the dependence of the instantaneous refractive index of a fiber on the instantaneous optical power carried in the fiber. This causes phase retardation proportional to the instantaneous intensity. Because there are many subcarriers in an optical OFDM system, their combined optical field causes a complicated optical intensity waveform, which can produce wide-bandwidth phase modulation at any point in the Fiber. Another way of looking at this time-domain effect is to treat it as any two subcarriers causing an intensity beat, which phase modulates another subcarrier to give new sidebands. These new sidebands fall upon other subcarriers, causing phase errors, as shown in Fig. 19. This is known as Four-Wave Mixing (FWM), which is a manifestation of the Kerr effect. It has been shown, with both numerical simulation [38] and analytically [121], that FWM alone can accurately predict the performance of CO-OFDM systems.

Given that there could be hundreds of subcarriers, there are many pairs of subcarriers that produce an intensity beat, and many subcarriers that are phase modulated. Therefore, there are order N-cubed sideband products falling upon N subcarriers [37], thus the problem should scale with N-squared. Fortunately the signal power is shared between N subcarriers, and the strength of FWM products scales with power-cubed, so the total power of FWM products generated is independent of N. This analysis leads to the simple expression for the nonlinearity-limited signal quality, Q_{nl}, dispersion-free systems [37]:

$$Q_{nl}(\mathrm{dB}) \approx -20\log_{10}(\gamma L_e P_{total}) - 3.01 \tag{1.2}$$

where γ is nonlinearity coefficient of the fiber (usually around 1.3 $\mathrm{W}^{-1}\,\mathrm{km}^{-1}$), L_e is the effective length the fiber (usually around 20 km) and P_{total} is the total power in the OFDM band (W). In systems with guard bands, some FWM products fall outside the received bandwidth, so this estimate is pessimistic [37].

In dispersive links, this limit is further increased [122] because the nonlinear products do not add coherently along the link [38]. This benefit increases with the signal's bandwidth. More detailed analyses showed that higher CD values resulted in higher nonlinearity limited signal qualities [39] and higher maximum signal qualities in the presence of noise [121].

6.2. Intensity-driven fiber nonlinearity compensator

A simple way to undo the phase modulation due to the Kerr effect is to drive a phase modulator from with the intensity waveform [123], as shown in Fig. 20. Phase modulation can be placed at the transmitter or receiver [124]. Fiber dispersion causes the intensity waveform to evolve along the fiber because the relative phases of the subcarriers change. Thus the transmitted or received waveforms are only approximately like the average waveform along the fiber. Significant benefits were shown to be possible for CO-OFDM systems [123,124]. For DDO-OFDM systems, filtering the intensity waveform significantly increased the improvement gained by compensation [125]. For PolMux systems, further

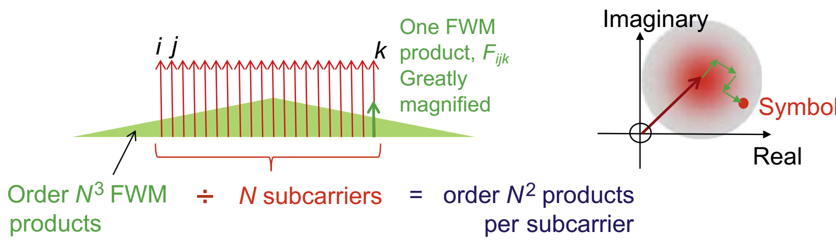

Fig. 19. Nonlinear mixing of subcarriers (red arrows) produces FWM products (green triangle). The FWM fields add randomly to cause an error to a received constellation point (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

improvements in nonlinearity compensation can be gained by processing both polarizations jointly [126]. An improvement can be gained by applying compensation at both the transmitter and receiver. This works well because the waveform at the middle of the link is somewhat between the transmitted and received waveforms [124].

Fiber dispersion reduces FWM because the high-frequency parts of a waveform evolve faster along a fiber than lower-frequency parts. Thus, the high-frequency phase modulation experienced in one part of the fiber will not add coherently with the phase modulation in another part of the fiber; whereas the lower-frequency modulation products will. This insight suggests that nonlinearity compensators only have to deal with the lower-frequency parts of the intensity waveform; indeed, trying to compensate for higher-frequency intensity fluctuations is fruitless and even damaging [38]. Band-limiting the intensity fluctuations before applying the phase modulation was shown to improve the benefit from intensity driving nonlinearity compensation for 100-Gb/s CO-OFDM systems [127].

Recently, the compensation of the effects of Kerr nonlinearity across several wavelength channels, commonly referred to as cross-phase modulation (XPM), has been demonstrated using digital processing to compensate for the low-frequency phase modulation [128]. Fig. 21 shows an XPM compensator. By detecting the intensity waveform before the optical demultiplexer, the intensity fluctuations generated by a band of WDM channels is received with only a single photodiode. Although the intensity fluctuations contain very high frequencies, only the low-frequency intensity fluctuations (<1-GHz) are required when compensating for XPM. Interestingly, this means that low-frequency (few-GHz bandwidth) components and circuits could compensate for effects occurring over optical ranges of hundreds of GHz. This technique also works for mixtures of signal formats [129], as would be expected during a gradual upgrade of a legacy link.

6.3. Split-step nonlinearity compensation

At data-rates of 100-Gb/s or above, a single-stage intensity-driven fiber nonlinearity compensator will only be effective in dispersion managed links [38]. In "Greenfield" links, removing the inline dispersion compensation can greatly reduce the cost and design effort for a link.

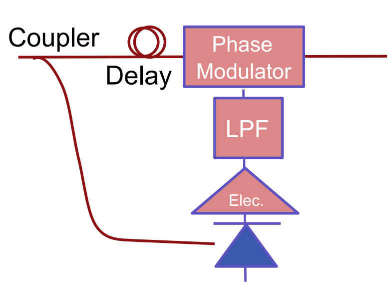

Fig. 20. A simple FWM compensator based on undoing the Kerr-effect's phase-modulation using an optical modulator driven by the received intensity waveform.

It is well known that fiber can be numerically modeled using split-step Fourier methods [130]. In 2005, Roberts et al. [131] showed that by digitally propagating the signal through an inverse model of the link, fiber nonlinearity generated by the signal can be almost completely mitigated. However, this method is very computationally intensive and requires the transmitter to have an accurate model of the link. With a coherent receiver, it is also possible to use an inverse fiber model at the receiver [132,133]; this is often referred to as backpropagation. Offline experimental demonstrations have shown digital backpropagation to be beneficial for optical OFDM [129].

The problem with all split-step methods is the computational requirement. It was estimated that a practical implementation of a 25-span link would require over 100-times more computational power as a linear chromatic dispersion compensator [133]. Whilst methods of reducing the computational requirement of digital backpropagation have been proposed [134], the computational power required is over 10 times that of linear chromatic dispersion compensators. This makes it very difficult to realize in real-time systems.

It is possible to compensate for inter-channel nonlinearities with split-step methods if multiple channels are received with a single receiver [135] or if multiple channels are reconstructed into a single channel digitally [132]. However, the wider bandwidth and higher sampling rates further increase the computational complexity. There is, however, a limit to the maximum signal quality that can be achieved in a given link because ASE will also induce intensity fluctuations. Since ASE is a random process, the fiber nonlinearity caused by ASE will also be random and cannot be compensated [136].

6.4. Peak to average power ratio

Nonlinearity in optical fibers is usually associated with high peak powers, as the instantaneous phase shift is proportional to the instantaneous power. OFDM is known to have high peak powers, because the sinusoids of the subcarriers can add to produce a large peak, depending on their relative phases [137]. Thus optical OFDM signals are thought to interact strongly with the fiber's nonlinearity so reducing the peak-to-average power ratio (PAPR) has been the goal of many researchers. Goebel et al. [122] plotted the correlation between PAPR and received signal quality and showed that a selective mapping technique adjusting the phases of the subcarriers symbol-by-symbol increased the nonlinear tolerance of optical OFDM. Although the PAPR can be reduced at the start of the link, the PAPR will quickly regrow due to fiber dispersion altering the relative phases of the subcarriers. In multi-subcarrier systems, it is possible to reserve some subcarriers for inclusion or exclusion from the transmitted waveform to reduce the PAPR [138]. A novel approach to PAPR reduction is to move the outer

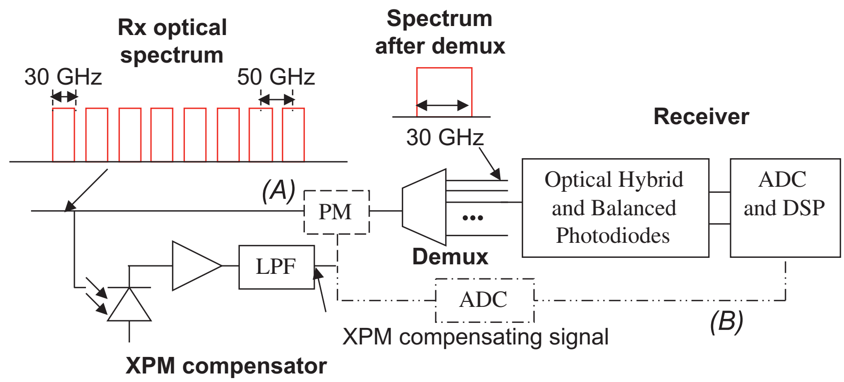

Fig. 21. Receiver with a XPM compensator before the optical demultiplexer.

constellation points away from origin. This does not affect the slicing of the received signal, to recover the bits, because there are no slices beyond the outer ring of points [139].

Single-carrier frequency domain equalization (SC-FDE) is a concept developed for wireless, where the transmitted signal is a single carrier, but is converted to a frequency-domain signal at the receiver for equalization in the frequency domain. The signal is separated into blocks, each with a CP, which allows a similar equalizer to conventional OFDM systems. SC-FDE gives better nonlinear performance than OFDM because its PAPR is small in the initial span of a multi-span system [140].

It is also possible to 'wrap' a DFT around the IFFT/FFT of a conventional OFDM system. By using an outer transform with a smaller block size, the amount of data-carrying frequencies is reduced, thus reducing the PAPR. A larger inner transform is typically used as the overhead associated with the CP is inversely related to the size of the inner transform. Numerical simulations have shown that these DFT spread-OFDM systems perform better than conventional optical OFDM and single carrier system in links without DCF [141].

7. Experimental progress of optical OFDM

The first forms of optical OFDM suitable for long-haul transmission, now referred to as DDO-OFDM [17,32] and CO-OFDM [18] were proposed in 2006. The first successful experimental demonstrations were presented at OFC 2007 using offline digital signal processing. In 2009, the first real-time optical OFDM systems were demonstrated. Table 1 shows a list of some of the experimental demonstrations of optical OFDM in its various forms. Optical OFDM is now seen as a potential candidate for next-generation optical systems in both long-haul and shorter reach applications. However, the development of optical OFDM has been constantly limited by the availability of the components needed. As a result, real-time demonstrations, at the time of writing, are still limited to low data-rates.

7.1. Off-Line processing

Early experimental demonstrations were all conducted using offline digital signal processing. Repeated blocks of data were transmitted; one or more blocks were captured at the receiver and processed using a Personal Computer (PC). As the PC processes far slower than the data is transmitted along the link, then only a small fraction of the data is actually processed. However, results obtained using offline-processing have become acceptable for proof-of-concept publications.

A key to offline processing is the use of real-time sampling oscilloscopes at the receiver. These are able to process chunks of a waveform by converting consecutive samples of the waveform into a sequence of digital numbers. The sampling, and hence conversion, rate is extremely fast: rates of 80 GSample/s are now available, but much of the earlier work was done at 50 GSample/s. The limitation is the depth of memory used to store the sequential samples and ultimately the bus speed required to feed these into a processor. Thus the oscilloscope must 'rest' between chunks of data.

The second enabler to prototyping OFDM systems has been the development of high-speed Digital-to-Analog Convertors (DACs), available with memory and control circuits as an Arbitrary Waveform Generator. These are used at the transmitters to convert a stored digital waveform into a series of analogue samples. Unfortunately the sampling rates are not as high as available for oscilloscopes. Thus the performance of the AWG is the limit to the amount of data that can be modulated onto a single wavelength. In contrast, transmitters that only have two output levels can use far higher-rates, as 56 Gbit/s test generators are available. One way of generating higher data rate signals is to use multiple optical bands. As is shown by Table 1, experimental demonstrations exceeding 1-Tb/s have been possible with multiple optical bands.

7.2. Real-time systems

Real-time demonstrations of optical OFDM systems have predominantly been limited to low data rates. The rates of real-time systems are limited by the DAC and ADC. Until recently, there were no commercially available data converters beyond a few GSample/s. This has limited the data rate of most real-time demonstrations. Although DACs at 26 GSample/s (Micram, GmbH) and ADCs at 56 GSample/s (Fujitsu) are now available, custom circuits are required to stream data to and from the ADCs and DACs. This is an expensive proposition for most research laboratories.

For systems operating at high data rates, like 100 Gb/s, the DSP becomes another major barrier. The extremely high line rates means the processes must be highly parallelized, leading to a large amount of interconnect logic being needed. Real-time demonstrations of coherent single carrier systems have used over 40 high performance FPGAs [142]. An optical OFDM system would need a similar amount of hardware [113–115].

8. Conclusions

Optical OFDM for long-haul optical transmission systems has been the subject of intense research interest since its inception in 2006. Initially it was disregarded as being too susceptible to

Table 1
Experimental demonstrations of optical OFDM.

Author	Publication	Paper	Year	Format	Rate (GHz)	Ub-bands	λs	Intra-chan SE	Intra-chan SE	Distance (km)	PolMux?	Real time/offline
Jansen	OFC	pdpl5	2007	CO	20	2	1	1.56	–	4160	No	Offline
Schmidt	OFC	9dpl8	2007	DDO	20	1	1	2	–	320	No	Offline
Jansen	OFC	pdp2	2008	CO	121.9	4	10	5.35	2.44	1000	Yes	Offline
Yang	OFC	pdp7	2008	CO	107	5	1	3.34	–	1000	Yes	Offline
Yamada	OFC	pdpS	2008	NoGI	88.8	2	50	3	1.78	800	Yes	Offline
Masuda	OFC	pdpb5	2009	NoGI	111	2	135	2.78	2.22	6248	Yes	Offline
Takahashi	OFC	pdpb7	2009	CO	65.1	1	8	9.72	7	240	Yes	Offline
Ma	OFC	pdpcl	2009	CO	1080	36	1	3.37	–	600	Yes	Offline
Dischler	OFC	pdpc2	2009	CO	1200	50	1	3.33	–	400	Yes	Offline
Schmidt	OFC	pdpc3	2009	DDO	100	1	1	3.57	–	500	Yes	Offline
Qian	OFC	pdpd5	2009	DDO	108	2	1	–	–	20	Yes	Offline
Yang	OFC	pdpc5	2009	CO	3.6	15×3.6	15	1.2	–	–	Yes	Real time
Giddings	Opt. Exp.	vol 17	2009	IM	3	1	1	–	–	0.5	No	Real time
Buchali	ECOC	pd2.1	2009	CO	12.1	9×12.1	9	1.6	–	12.1	No	Real time T_x
Benlachte	ECOC	pd2.4	2009	DDO	8.36	1	1	1.045	–	1600	No	Real time T_x
Chandrasef	ECOC	pd2.6	2009	NoGI	1200	24	1	3.7	–	7200	Yes	Offline
Giddings	Opt. Exp.	vol 18	2010	IM	11.25	1	1	–	–	25	No	Real time
Hillerkuss	OFC	pdpcl	2010	All opt	10,800	75	1	5.76	–	–	No	No DSP
Dischler	OFC	pdpd2	2010	CO	253	15	3	2.81	2.53	764	Yes	Offline, field trial
Qian	OFC	pdpd9	2010	IM	41.25	1	2	–	–	20	No	Real time
Takiguchi	ECOC	pdl.4	2010	All opt	100	10	1	1	–	–	No	No DSP
Peng	ECOC	pd2.5	2010	DDO	213.7	9	1	2.67	–	720	No	Offline
Liu	ECOC	pd2.6	2010	CO	606	10	1	7.76	–	1600	Yes	Offline
Brahim	ECOC	pd3.4	2010	fast	14.348	1	1	1	–	–	No	Offline

degradation by fiber nonlinearities. However, it has achieved similar performance to single-carrier systems in many situations; any differences in performance will decrease as the data rate increases and as new techniques for mitigating nonlinearity are developed. OFDM offers tight spectral control of the transmitter's output, with little out-of-band energy. This means that OFDM bands can be tightly packed into the available bandwidth, with the bands being orthogonal to one another if they share the same frequency grid. This could improve spectral efficiency by around 50%, compared with WDM systems using 32-GHz channels on a 50-GHz grid. OFDM can also maximize the use of the receiver's sampling rate, as fractional oversampling can be accommodated simply by choosing the number of zeroed subcarriers at the transmitter. All-optical OFDM and combinations of optical and electronic OFDM signal generation will allow almost continuous signal bands across the optical spectrum. OFDM's ability to support fine-grained channel equalization and modulation-format adaptation will allow the last bit/s to be squeezed through optical fibers. Doubtless there are many more innovations in the pipeline, and the story of optical OFDM will become ever more complex as new combinations of optical and electronic technologies are introduced.

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