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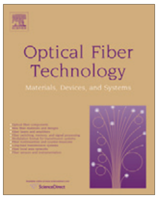

Invited Papers

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