# Performance of Optical OFDM in Ultralong-Haul WDM Lightwave Systems

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***Abstract*—We show, using simulations, that a combination of orthogonal frequency division multiplexing (OFDM) and optical single sideband modulation can be used to compensate for chromatic dispersion in ultralong-haul wavelength-division multiplexed (WDM) systems. OFDM provides a high spectral efficiency, does not require a reverse feedback path for compensation, and has a better sensitivity than nonreturn to zero. This paper provides design rules for 800–4000-km optical-OFDM systems. The effects of WDM channel number and spacing, fiber dispersion, and input power per channel on the received *Q* are studied using extensive numerical simulations. These effects are summarized as a set of design rules.**

***Index Terms*—Compensation, fiber dispersion, fiber nonlinearity, four-wave mixing (FWM), long haul, optical single sideband modulation (OSSB), orthogonal frequency division multiplexing (OFDM).**

## I. INTRODUCTION

ELECTRONIC dispersion compensation (EDC) [1]–[3] is an alternative to optical dispersion compensation techniques such as dispersion compensating fiber (DCF) [4], Bragg gratings [5], and optical resonators [6]. Although EDC normally requires separate electronics for each wavelength-division multiplexed (WDM) channel, whereas optical techniques can compensate multiple WDM channels simultaneously, it is attractive because 1) it can easily be made adaptive to compensate for temporal variations in dispersion; 2) its ability to self-adapt means it offers plug and play functionality (rather than requiring design of a dispersion map [7]); 3) self-adaptation is useful for optically switched networks where the physical path between the transmitter and receiver will depend how the wavelengths are routed; 4) EDC is usually located at the ends of the link, so that it requires less outside plant than for DCF; 5) if data rates are being upgraded from say 2.5 to 10 Gb/s, the outside plant may not require modification if EDC is used, whereas optical dispersion compensation may require DCF to be placed along the fiber spans; and 6) optical dispersion compensation incurs optical loss, so that it requires additional amplification. With all this being said, optical dispersion compensation still has many merits, most notable is its ability to compensate many tens of WDM channels simultaneously.

EDC falls into three categories: compensation at the receiver (post compensation), compensation at the transmitter (predistortion [8]), and use of electronic processing to substantially modify the transmitted waveform so that it can be equalized at the receiver using further signal processing.

Electronic post compensation (EPC) [9] is attractive for fibers that have rapidly varying characteristics. An EPC using feed-forward equalization and decision feedback equalization [10] is becoming standardized for multimode fibers [11] but can also be applied to single-mode fibers (SMFs) [12]. Another form of receiver equalization is maximum likelihood sequence estimation (MLSE). MLSE combined with optical duobinary modulation can compensate for dispersions up to 4500 ps/nm [13]. For longer distances, EDC at the receiver works well when combined with optical single sideband modulation (OSSB) [14], [15] because the optical phase is translated to an electrical phase signal by the photodiode, whereas in a double-sideband system, the two optical sidebands destroy this direct relationship.

Electronic predistortion (EPD) [16], [17] is a recent development where the transmitter's modulator creates an optical signal that has already propagated through a "virtual DCF" so that it arrives at the receiver undistorted, even after transmission through 5120 km of standard SMF (S-SMF) [18]. EPD can also compensate for intrachannel nonlinearity in WDM systems [19]. However, EPD requires a reverse feedback path from receiver to transmitter and a modulator with dual drives for the longer systems. The reverse feedback path means that rapid variations caused by thermal drift, vibration, optical network switching, and polarization rotation cannot be compensated for.

Orthogonal frequency division multiplexing (OFDM) [20] uses substantial electronic processing at the transmitter and receiver, so that it falls into the third category. OFDM has been rapidly and widely adopted in RF-wireless systems such as cell-networks and digital-audio and digital-video broadcasting, because it is resilient to multipath propagation and phase distortion and requires no reverse path (which would be impossible to provide for television broadcasting, for example). OFDM transmits on many narrow-frequency orthogonal carriers that are each equalized using a single complex multiplication.

In optical communications, optical OFDM has been demonstrated for multimode [21] and free-space links [22], which both suffer from multipath. However, standard optical OFDM requires a high dc-bias [23] to convert bipolar electrical to unipolar optical signals. The high bias degrades the receiver sensitivity by more than 5 dB. We recently presented a method

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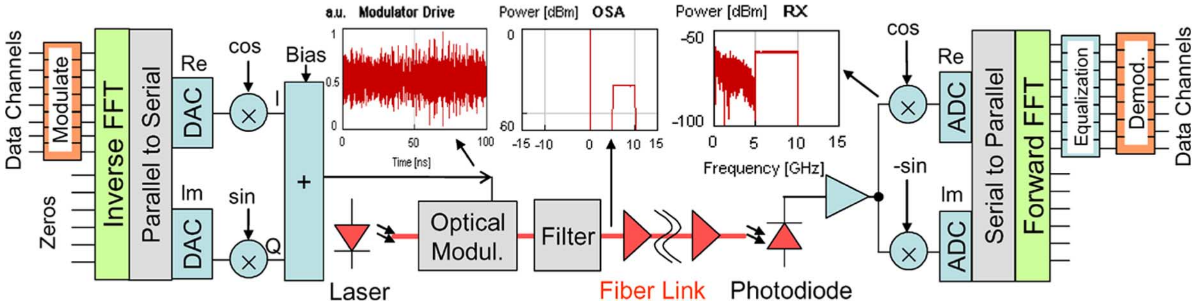

Fig. 1. Optical-OFDM system block diagram, including modulator drive waveform, optical spectrum after filter, and RF spectrum after the photoreceiver.

[24], [25] to overcome this limitation, giving optical OFDM a 1.8-dB sensitivity advantage over nonreturn to zero (NRZ) for links dominated by a thermal receiver noise.

Optical OFDM can also be used for single-mode links to compensate chromatic dispersion; however, a single optical sideband (that is, OSSB) must be used [26] so that optical phase distortion is mapped onto electrical phase at the receiver, which then can be compensated by electronic phase equalization. In a similar manner to Hui's subcarrier multiplexed systems [27], optical-OFDM subcarriers are each of sufficiently low bandwidth to tolerate large amounts of dispersion, although their phases need to be equalized before demodulation. We have previously shown by simulation that optical OFDM combined with OSSB can compensate for chromatic dispersion over an almost infinite distance if nonlinearities are not considered [26]: When nonlinearities are considered, we showed that transmission over 4000 km was possible [28]. Our systems did not require feedback paths and could take advantage of well-established OFDM techniques such as adaptive cyclic prefixes/guard-bands and adaptive channel rates [29] to self-optimize transmission capacity over a variety of fiber plant (such as a switched all-optical network). Our simulations demonstrated that suppressing the optical carrier gave OFDM receiver sensitivities better than for optimized NRZ, for optically amplified systems. In contrast, DCF for NRZ would require additional optical amplification, reducing the potential transmission distance. Other groups have since reported optical-OFDM systems for chromatic dispersion compensation: Djordjevic and Vasic [30] have shown that optical OFDM outperforms RZ for transmission distance and spectral efficiency in the presence of nonlinearities in a single-channel optically dispersion-compensated link, and Shieh and Athaudage [31] have simulated a single-channel coherent optical-OFDM system, assuming no fiber nonlinearities. The performance of optical-OFDM systems using multiple optical carriers (WDM) with fiber nonlinearity has not been studied.

This paper extends our previous work [28] by identifying the key design considerations of long-haul WDM systems using OFDM for dispersion compensation. We systematically examine the effect of fiber nonlinearity on transmission performance over different fibers and by using different WDM channel spacings. We show that optical OFDM can be combined with WDM with only a small increase in nonlinear penalty even with large channel counts. Transmission over several thousand kilometers of S-SMF is possible. Dispersion compensation is achieved entirely by OFDM, and there is an effectively zero dispersion penalty; indeed, we show that high dispersions are desirable as they reduce the nonlinear penalty.

This paper is organized as follows. Section II outlines the system. Section III reports the effects of modulation depth, carrier suppression, number of WDM channels, WDM channel spacing, and fiber dispersion. Section IV discusses the performance of our optical-OFDM system compared with the NRZ systems. Section V draws this paper to a conclusion.

## II. SYSTEM DESCRIPTION

Fig. 1 outlines our system [26] and shows the representative spectra and waveforms as insets. The system comprises the following subsystems.

### A. *Electrical OFDM Transmitter*

Data at 10 Gb/s are presented in 1024-bit blocks to 512 quadrature amplitude modulators (4-QAM). These modulators supply 512 inputs of an inverse fast Fourier-transform (IFFT). This transform generates a waveform that is a superposition of all the modulated subcarriers (each carrying 20 Mb/s). Zero padding of the IFFT inputs provides an interpolated waveform with a well-controlled spectrum, although this could also be obtained with analog filters after the digital-to-analog converters. We displace the OFDM sidebands from the optical carrier by modulating them onto a 7.5-GHz RF subcarrier to give an RF sideband from 5 to 10 GHz so that practical optical filters can be used for carrier and sideband suppression. Unlike our previous optical-OFDM designs [24], [25], the modulator drive and bias is adjusted to minimize the positive and negative clipping of the OFDM waveform (see left inset) by the modulator.

### B. *Optical Modulator and Filter*

The modulator is assumed to be linearized to provide an optical output power proportional to the electrical drive voltage. Recently, however, it has recently been shown that Mach–Zehnder modulators without linearization can be used in optical-OFDM systems [32]. After modulation, the lower optical sideband is removed using an optical filter. The optical carrier is suppressed to increase the electrical received power for a given optical power, and so, the receiver sensitivity is improved. This suppression can be used to compensate for a low modulation depth, which is one method of improving the nonlinearity of the modulator. Simulations showed that the best receiver sensitivity is when the power in the optical carrier equals the power in the OFDM sideband. Suppressing the carrier means that the intermixing of OFDM subcarriers upon photodetection gives significant distortion; however, because the OFDM band is displaced by 5 GHz from the optical carrier, the distortion products fall mostly outside the OFDM band (right-most inset of Fig. 1).

### *C. Fiber Plant*

The fiber link comprises 80-km spans of S-SMF with an optical amplifier before each span. The fiber has a dispersion of 16 ps/nm/km, a loss of 0.2 dB/km, a nonlinear coefficient of $2.6 \times 10^{-20}$ $\mathrm{m}^2/\mathrm{W}$, and an effective area of 80 $\mu\mathrm{m}^2$. The nonlinearity is modeled using the split-step method, as implemented in VPIsystems' VPItransmissionMakerWDM V6.5. The amplifiers have a 16-dB gain and a 6-dB noise figure. Noise was added into the signal polarization as a random optical field: This assumes that noise orthogonal to the signal has a little impact on performance. Each optical amplifier used a different random number seed to ensure that the noise was not coherent from span to span.

### *D. Receiver Model*

At the receiver, the photodiode produces a time-domain waveform proportional to the optical power. The photodiode has a responsivity of 1 A/W and is noiseless to show the noise and distortion due to the optical amplifiers and fiber nonlinearity. The photocurrent is converted to inphase $(I)$ and quadrature $(Q)$ components by mixing with a 0° and 90° phase of a 7.5-GHz local oscillator. The $I$ and $Q$ waveforms can then be converted to the frequency-domain using an FFT, which acts as a set of closely spaced narrowband filters if the transmitter and receiver blocks are synchronized. Once in the frequency-domain, each channel is equalized to compensate for phase and amplitude distortions due to the optical and electrical paths. This is easily achieved by using a separate complex multiplication for each QAM channel. After equalization, each QAM channel is demodulated to produce 512 parallel data channels. These can be converted into a single data channel by parallel to serial conversion. The $Q$ is extracted from the constellation. By assuming that the Cartesian axes are the decision thresholds, the $Q$ is defined as $Q_{(\mathrm{dB})} = 20 \cdot \log_{10}(q)$, where $q^2 = \mu_x^2/\sigma_x^2 = \mu_y^2/\sigma_y^2$, with $\mu$ being the mean value of a particular cluster from a decision threshold and $\sigma^2$ is its variance in that direction, as illustrated in Fig. 2. The bit error ratio (BER) can be estimated using $1/2\mathrm{erfc}(q/\sqrt{2})$. For simulations with multiple WDM channels, $q^2$ was averaged over all channels before conversion to $Q$(in decibels).

## III. RESULTS

### *A. Dispersion Compensation*

Fig. 2 illustrates a typical received constellation before and after the equalizer in the receiver. Before the equalizer, each constellation point is rotated around the origin to form a doughnut shape. The degree of rotation, which is due to fiber dispersion, is proportional to its frequency relative to the optical carrier squared. The equalizer is trained before each simulation run by transmitting a known set of bits. The expected phase is subtracted from the received phase to produce an error signal. This ideal training approximates to a practical equalizer that would be trained by averaging over many blocks of data to reduce uncertainty. Fig. 3 shows the phase error versus OFDM channel index; this has the expected quadratic characteristic. The error signal is then used to correct the received signals, giving distinct symbols within the constellation of Fig. 2. The symbols have some spread due to fiber nonlinearity and amplifier noise. If nonlinearity and noise are disabled in the simulations, the constellation reduces to four points, indicating that the dispersion compensation is perfect. At first sight, this would suggest a dispersion penalty of zero; however, a dispersive fiber will require a small overhead to be added to the OFDM symbol rate, as discussed in Section IV-A.

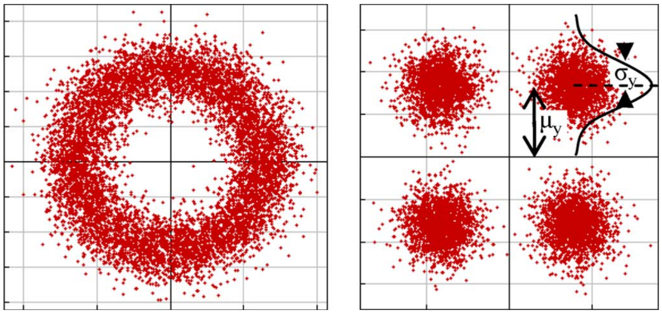

Fig. 2. Optical constellations (left) before and (right) after equalization for an eight-channel 4000-km system with a −8-dBm fiber input power per channel.

It is important to use different bit sequences for the training and actual simulations; otherwise, the error correction would also falsely compensate for nonlinearities. Also, training is done without an optical amplifier noise: This simulates a practical training scheme where the error estimates are averaged over a long time. Alternatively, the error estimates could be based on fitting a quadratic function to the error versus the channel index.

### *B. Quality versus Carrier Suppression*

Fig. 4 shows the received $Q$ for a back-to-back system versus carrier suppression for a number of modulation drive levels. The modulation depth is defined as a standard deviation of the electrical drive as a percentage of the voltage required to turn the modulator from 0% to 100% transmission. Optical amplifier noise was added to give a 12.9-dB optical signal-to-noise ratio (OSNR) and measured over a 12.5-GHz optical bandwidth. This OSNR gives a $Q$ of 15 dB for an NRZ system with an electrical receiver bandwidth of 75% of the bit rate. The optical bandwidth of the receivers was 10 GHz. For drive levels above 20%, the OFDM waveform will be clipped at 0% and 100% transmission. This clipping reduces the maximum $Q$ to below the noise-limited level.

It is not possible to achieve a reasonable $Q$ at the transmitter, without carrier suppression. Conversely, very low modulator

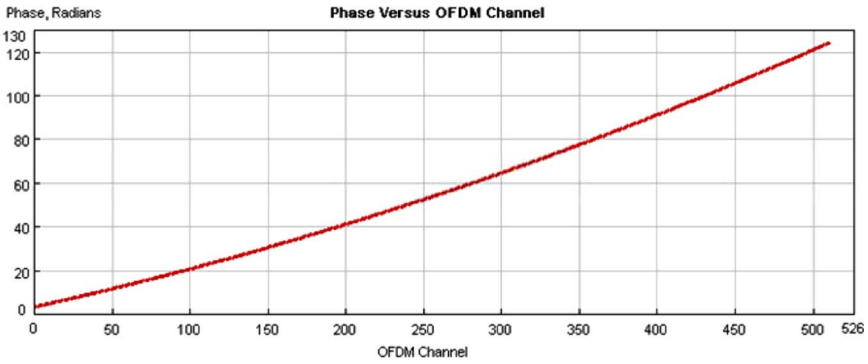

Fig. 3. Phase equalization versus OFDM channel (or subcarrier) index.

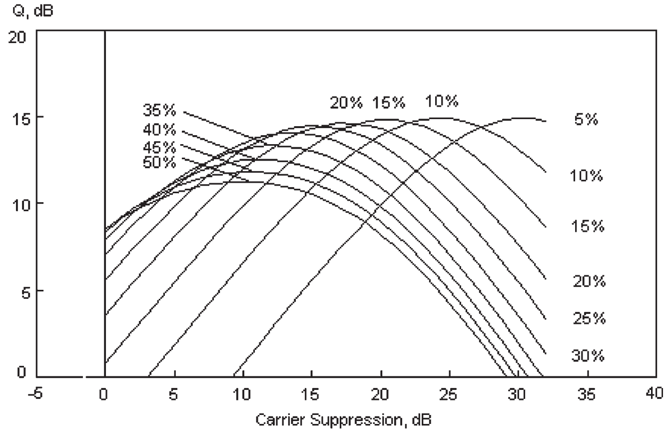

Fig. 4. Quality versus carrier suppression. Label is modulation depth.

drive levels ($< 10\%$) give very low optical sideband powers and so require strong attenuation of the optical carrier, which is also undesirable as a high gain optical amplifier will be required after the modulator to boost the signal into the fiber. In the following simulations, we used a modulation depth of 12%: This required a carrier suppression of 23.5 dB to maximize $Q$. Modulation depths between 10% and 20% would give similar results.

### C. Sensitivity versus NRZ Systems (Linear Systems)

The BERs of NRZ and OFDM systems subject to the same OSNR were estimated. The OFDM system used a 10-GHz bandwidth brickwall optical filter before the receiver: The NRZ system used a 20-GHz brickwall optical filter. The NRZ transmitter was a zero-linewidth laser with a perfect-extinction modulator driven by data with rise times of 25 ps. The NRZ receiver used a 7.5-GHz fourth-order electrical Bessel filter and optimum decision thresholding, which is close to zero because of the combination of perfect extinction and the dominant effect of signal-spontaneous noise. The optimization was achieved by sweeping the decision threshold to find a minimum BER. The optimum sampling instant was selected by eye from the eye diagram. The errors were counted by comparing the transmitted and received data bits. Up to 800 000 bits were used per point, enabling BERs $< 10^{-5}$ to be estimated.

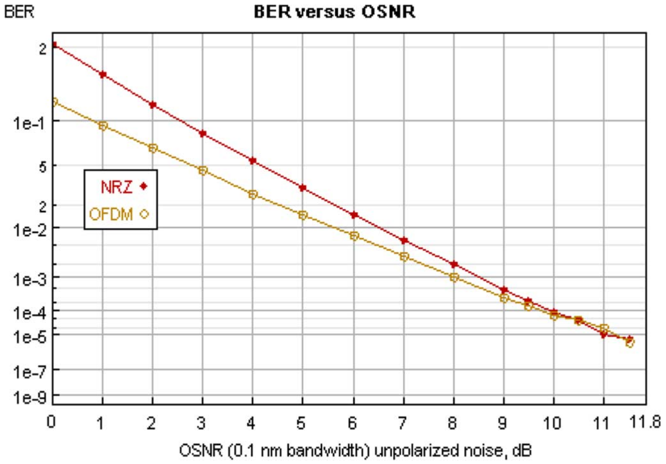

Fig. 5. BER versus OSNR for OFDM and NRZ systems.

Fig. 5 plots BER versus OSNR, measured over a 12.5-GHz bandwidth, which is equivalent to 0.1 nm at 1550 nm. NRZ requires a 0.5-dB better OSNR than OFDM for BER $= 10^{-3}$. This advantage of OFDM over NRZ reduces to zero for lower BERs. However, if the decision threshold of the NRZ system is set midway between one and zero levels, as would be required for poor extinction ratio modulators, OFDM has a 1.6-dB advantage for all OSNRs.

### D. Received Optical Spectrum

There has been much discussion about the impact of nonlinearities on EDC systems [33], [34]. The reason is that the signal peaks are likely to be strongly affected by fiber nonlinearity. Also, the subcarriers in the OFDM systems are closely spaced (10–100 MHz) so that they will not walk-off one another due to fiber dispersion [35]. This means that four-wave mixing (FWM) products could coherently add along the fiber's length, rather than adding incoherently. However, if multiple optical carriers are used (forming a WDM system where each channel is an optical carrier plus a band of OFDM subcarriers), then the WDM channels are likely to walk-off so that they will not affect one another.

Fig. 6 shows a typical optical spectrum for an eight-channel system just before the optical demultiplexer at the receiver. The signal has propagated over 4000 km with an input power per channel to fiber span of −7 dBm. Noise is included in each

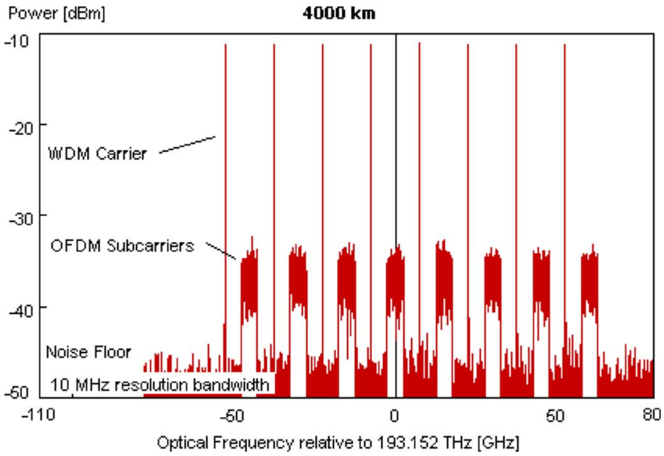

Fig. 6. Spectrum after propagation through 4000 km of fiber.

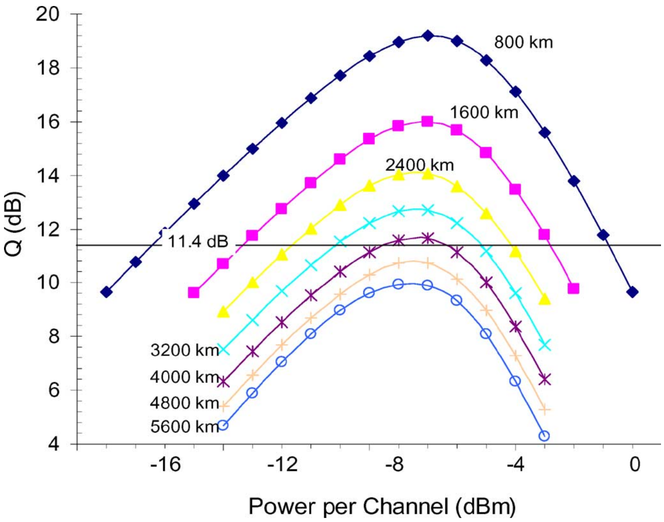

Fig. 7. $Q$ versus input power for a number of fiber lengths, showing the definition of the minimum and maximum $Q$-values and the optimum power for each length.

optical amplifier model and will mix with the signals due to fiber nonlinearity. The WDM carrier spacing is 15 GHz, which allows for 5-GHz guard bands between the channels to allow demultiplexing with practical optical filters.

The optical carriers have very small amplitude variations ($\ll 1$ dB) due to FWM between the carriers producing mixing tones that fall on top of the carriers. There is a far stronger variation in the amplitudes of the subcarriers, which should ideally be equal in amplitude for 4-QAM modulation. This variation will cause the QAM symbols within the constellations to have amplitude errors; however, the FWM also causes phase errors because the mixing tones have a phase dependence on the phases of the OFDM subcarriers from which they were created. This causes the constellation clusters to spread equally in all directions (see Fig. 2).

### *E. Effect of Nonlinearity on Quality*

To assess the performance limitations due to fiber nonlinearity, a large number of simulations were performed while sweeping parameters such as input power, fiber dispersion, and WDM channel spacing. Receivers were placed at intervals of 800 km along the system.

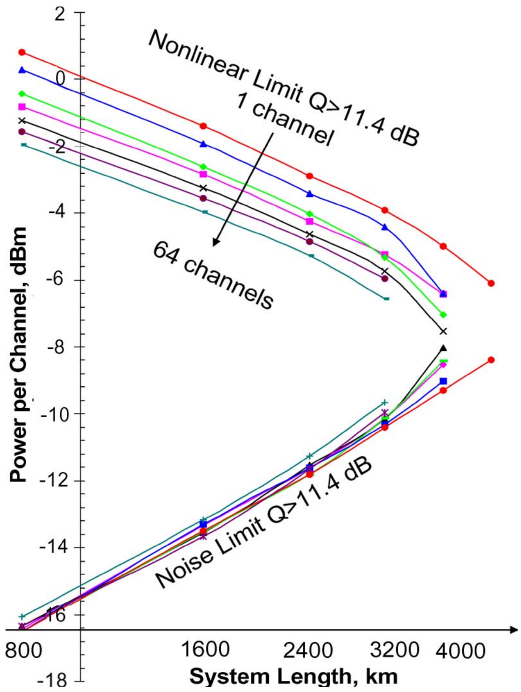

Fig. 8. Maximum and minimum powers per channel versus system length. The WDM channel spacing is 15 GHz.

Fig. 7 shows a typical result of a simulation run for eight WDM channels with a 15-GHz channel spacing with a swept input power. For each receiver position, there is an optimum input power which decreases only slightly with the system length ($< 1$ dB over 800–4000 km). Thus, the optimum performance is achieved with this input power for any add/drop point along the length of the link. For lower input powers, the $Q$ is limited by optical amplifier noise and increases decibel-for-decibel with power per channel; for high input powers, the $Q$ is limited by fiber nonlinearity and decreases approximately 2 dB/dB with power per channel. Systems longer than 4200 km cannot achieve $Q > 11.4$ dB.

The nonlinear threshold (NLT) is commonly defined as the power per channel that causes a 1-dB penalty for BER $= 10^{-4}$. This approximately corresponds to a power 0.5 dB above where the curves descend through the $Q = 11.4$ dB line.

Fig. 8 combines the data of Fig. 7 and of similar plots for different numbers of channels; the maximum and minimum powers per channel that gave $Q = 11.4$ dB are plotted against the system length. The noise limit (minimum power per channel) is independent of the number of WDM channels, except when the NLT is approached. As expected from the amplifier noise theory [36, eq. (2)], the required power per channel doubles with each doubling of the transmission length. The nonlinear limit is dependent on the number of WDM channels and reduces approximately 2 dB with each doubling of the system length; this is in contrast to the conventional systems which suffer a 3-dB reduction [37]. Doubling the number of channels reduces the nonlinear limit by about 0.43 dB. Fig. 8 predicts that a 3200-km system could be designed with 32 WDM channels.

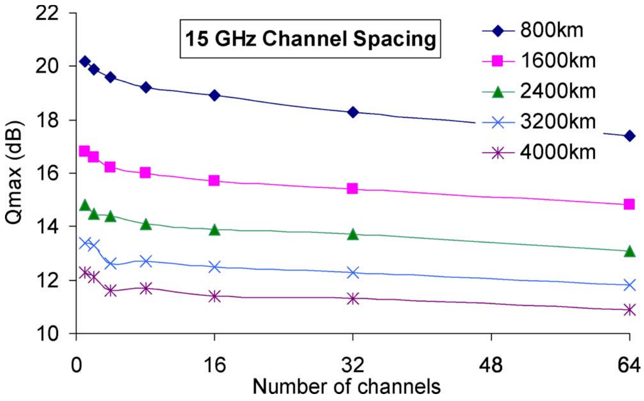

Fig. 9. Maximum $Q$ versus number of WDM channels for five lengths.

### F. Performance versus Number of WDM Channels

Fig. 9 plots the peak $Q$ for each system versus the number of WDM channels. When there are few channels, the $Q$ falls rapidly with an increasing channel count; however, for a large number of channels, the decrease is less rapid. This is because close neighbors of a particular WDM channel will affect its performance, but far-away channels are likely to have a reduced impact due to walk-off. There are, however, some resonance effects [38] due to the periodic amplification of the system, so that far away channels can sometimes affect a given WDM channel more strongly than expected.

### G. Performance versus WDM Channel Spacing

It is well known that increasing the frequency difference between WDM channels decreases their nonlinear interaction because of walk-off. However, the spectral efficiency of the system is sacrificed. Fig. 10 plots the nonlinear limit versus the WDM channel spacing for 8- and 16-channel systems. Increasing the channel spacing from 15 to 25 GHz allows the channel power to be increased by about 1 dB for all systems (but reduces the spectral efficiency from 66% to 40%). The poor performance of the 15-GHz system is due to the fact that the optical carriers facilitate power transfer between adjacent OFDM bands as the carriers lie exactly between the OFDM bands (Fig. 6). Increasing the carrier spacing to > 20 GHz means that the transferred power falls outside the neighboring OFDM band [39].

### H. Performance versus Fiber Dispersion

The systems work well with S-SMF because of the rapid walk-off between channels that reduces FWM. However, fiber with lower dispersion fiber has been installed to increase the dispersion-limited distance of the systems. Fig. 11 plots the difference between the maximum and minimum input powers (the power tolerance) for three lengths of eight-channel system with fibers with 0, 1, 6, and 16 ps/nm/km dispersion fibers. Clearly, the higher dispersion fibers offer the largest design tolerance, as these ensure the maximum walk-off between the WDM channels and the subcarriers within the WDM bands. The single-channel system is an interesting case as it improves with lower dispersion fiber. A close examination of the optical spectrum shows that strong coherent phase modulation along low-dispersion fibers causes large spectral broadening; however, this has little effect on the received signal but would be disastrous in the WDM systems.

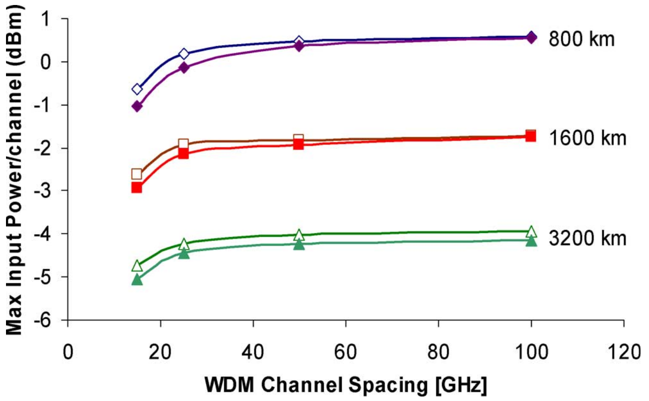

Fig. 10. Maximum input power versus WDM channel spacing. Open symbols are for eight channels. Closed symbols are for 16 channels.

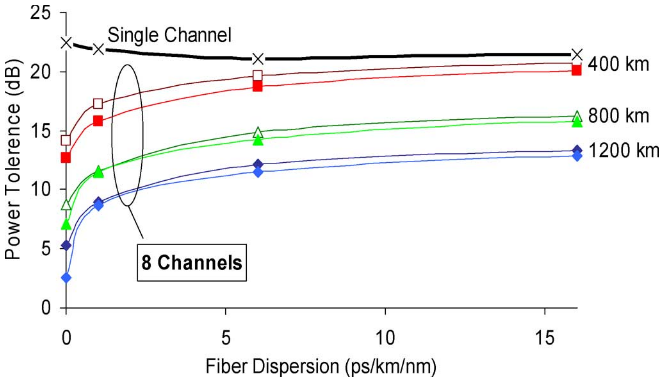

Fig. 11. Power tolerance versus fiber dispersion. Open symbols are 25-GHz spacing. Closed symbols are 15-GHz spacing.

## IV. DISCUSSION

### A. Maximum Dispersion

Optical OFDM can compensate for almost any practical accumulated dispersion that is either positive or negative without introducing a dispersion penalty. It is thus attractive as an adaptive method that will work in optical networks with continually changing path lengths. The effect of dispersion on optical OFDM is to create a time delay across an OFDM band of subcarriers. The solution is to add a cyclic prefix to the OFDM waveform [20] so that the end of the waveform block generated by the IFFT is copied and attached to the beginning of the block. If the prefix is sufficiently long, any time shift will not affect the received signal within the time window of the receiver's FFT, so the subcarriers will remain orthogonal. The cyclic prefix wastes transmission capacity; however, it only adds an overhead of a few percent for systems up to 4000 km if the FFT block length is 1024 data bits [26]. Shorter block lengths (fewer OFDM subcarriers) increase the overhead proportionally; however, they are faster to compute.

### *B. Nonlinear Thresholds*

EPD has been compared with DCF [33], [34] in terms of its NLT. These works have shown that EPD suffers from a much lower NLT than when the accumulated dispersion is kept within limits by periodic compensation. Essiambre and Winzer [33] predicted an NLT (the input power that requires a 1-dB increase of OSNR) of ~1 dBm for single-channel 10.7-Gb/s RZ transmission over 14 spans of 80 km, with EPD giving a BER of $10^{-3}$. Klekamp *et al.* [34] have also compared EPD to conventional DCF, for a 12-span 80-km per span system. The NLT for EPC was $-0.6$ dBm for a BER of $10^{-5}$, which was 9.2 dB less than an NRZ intensity-modulated system. Our single-channel system offers a BER of $10^{-4}$ at a power of $-0.4$ dBm over 14 spans, suggesting an NLT of approximately 1 dBm, which is very similar to EPD. This is not surprising as both EPD and OFDM use input waveforms with a higher peak to average power than other formats. However, in systems with several tens of WDM channels, the power per channel is limited by the saturation powers of the amplifiers rather than by nonlinearity.

Essiambre and Winzer [33] also show that EPD produces some events with a very large penalty (due to certain data sequences). Optical OFDM also has some adversely affected subcarriers, as shown in Fig. 6. However, OFDM's many subcarriers within a single WDM channel offers the possibility of applying coding over these subcarriers to provide an improved performance of each WDM channel.

### *C. Design Rules*

The results of the figures can be summarized as follows.

- The minimum power per channel follows the noise limit [36, eq. (2)] for multispan systems (Fig. 8).
- The optical OFDM can operate with a poorer OSNR than NRZ intensity-modulation (Fig. 5).
- The maximum power per channel for a single-channel 800-km system for $Q = 11.4$ dB is approximately $+0.8$ dBm (Fig. 7).
- The maximum power per channel decreases by 2 dB for each doubling in system length (Fig. 8).
- The maximum power per channel decreases approximately by 0.4 dB for each doubling of the number of WDM channels (Fig. 8).
- Increasing the WDM channel spacing from 15 to 25 GHz increases the maximum power by 1 dB (Fig. 10).
- Using lower dispersion fibers than S-SMF decreases performance, as shown in Fig. 11. This is obviously an area for improvement.

For all practical systems, the dispersion penalty is zero, although the addition of a cyclic prefix adds an overhead to transmission that could be treated as a (small) penalty.

## V. CONCLUSION

OFDM is a well-established technology that can compensate for all frequency-dependent amplitude and phase characteristics of a communications channel, so that it offers a robust and adaptive method of increasing system performance. This paper has shown that a combination of OFDM and suppressed-carrier OSSB transmission can compensate ultralong-haul optical links, with better receiver sensitivity than a back-to-back NRZ system. The simulations have explored the effects of fiber nonlinearity in detail and provided design rules for the maximum power per channel as a function of the system length, number of channels, WDM channel spacing, and fiber dispersion. Optical OFDM offers similar NLTs to EPD; however, it has the advantages of not requiring a feedback path because it can respond to rapid changes in fiber plant and support mid-span drops.

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