Long-Haul WDM Transmission Using No-Guard-Interval Coherent Optical OFDM

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Abstract

This paper reviews 100-Gb/s/ch long-haul WDM transmission techniques based on no-guard-interval coherent optical orthogonal frequency-division multiplexing.

Introduction

100-Gb/s-class transmission technologies are being extensively investigated for backbone optical transport networks (OTN) based on WDM transmission [1, 2]. In such high-speed long-haul WDM systems, excellent system resistance to chromatic dispersion (CD) and polarization-mode dispersion (PMD) is essential. Furthermore, future WDM systems are required to offer 10-Tb/s-class total capacity. In order to realize such high capacity WDM systems, improving the spectral efficiency (SE) is essential. Coherent detection with digital signal processing (DSP) is attractive for 100-Gb/s applications because of its powerful equalization of the linear distortion created by CD and PMD [3-6], and its improved tolerance to amplifier noise. Fig. 1 plots the transmission distance as a function of total capacity (a) and SE (b) of recent transmission experiments. We can confirm that coherent detection dramatically improved the transmission distance and total capacity. Record total capacity of 32 Tb/s has been demonstrated by using a 25-GHz spaced 114-Gb/s/ch single-carrier RZ 8-QAM format [4].

Optical orthogonal frequency-division multiplexing (OFDM) is also a promising candidate for 100-Gb/s modulation because it matches the advantages of single-carrier coherent reception with regard to CD and PMD tolerance [7-15]. Moreover, high SE is expected because of its compact signal spectra. We recently proposed the no-guard-interval (No-GI) coherent optical (CO-) OFDM scheme for 100-Gb/s-class long-haul transmission [10-15]. By using 111-Gb/s No-GI CO-OFDM, we have recently reported 135-channel transmission over 6,248 km with the record capacity-distance product of 84.3 Pb/s.km, and 10-channel transmission over 9,612 km with the record SE-distance product of 19.2 kb/s/Hz.km at the SE of 2 b/s/Hz [15](Fig. 1). In this paper, we review the No-GI CO-OFDM scheme focusing on system configuration and transmission performance.

System configuration

In optical OFDM transmission, the OFDM signal is usually synthesized by inverse fast Fourier transformation (IFFT) at the transmitter, and demodulated by FFT operation at the receiver. GI is introduced to avoid the inter-symbol interference (ISI) induced by CD and PMD. The length of GI, which introduces overhead into OFDM system, is determined by the maximum delay induced by CD and PMD. The conventional approach to reducing the overhead is to set a long symbol interval, namely use many subcarriers. However, the use of many subcarriers increases the peak-to-average power ratio (PAPR), and this degrades the tolerance to nonlinear effect in the transmission fiber. In particular, the transmission characteristics of periodically dispersion-compensated transmission lines [16] or low-dispersion transmission fibers such as non-zero dispersion-shifted fibers (NZDSF) or DSF over L-band are strongly affected.

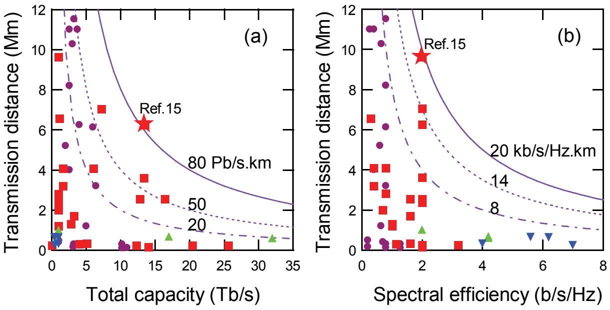

Fig. 1. Transmission distance as a function of total capacity (a) and spectral efficiency (b) of recent transmission experiments.

Optical OFDM with a small number of subcarriers is attractive for reducing PAPR and thus improving the nonlinear resistance. In this case, the use of GI to compensate CD- and PMD-induced distortion would result in excessive overhead or limited compensation capability. Therefore, to realize CO-OFDM with a small number of subcarriers, we adopted a linear compensation scheme based on digital filters instead using GI. Consequently, No-GI CO-OFDM minimizes the unnecessary overhead.

Fig. 2 shows the configuration of the transmitter (a) and the receiver (b), and the DSP block diagram (c). The transmitter configuration is based on optical multiplexing, where the baud rate of each subcarrier modulation equals the subcarrier spacing. The receiver consists of a DSP-based polarization-diversity intradyne coherent receiver, which is commonly used in single-carrier coherent reception. The frequency of the local oscillator (LO) is tuned to the center of the received

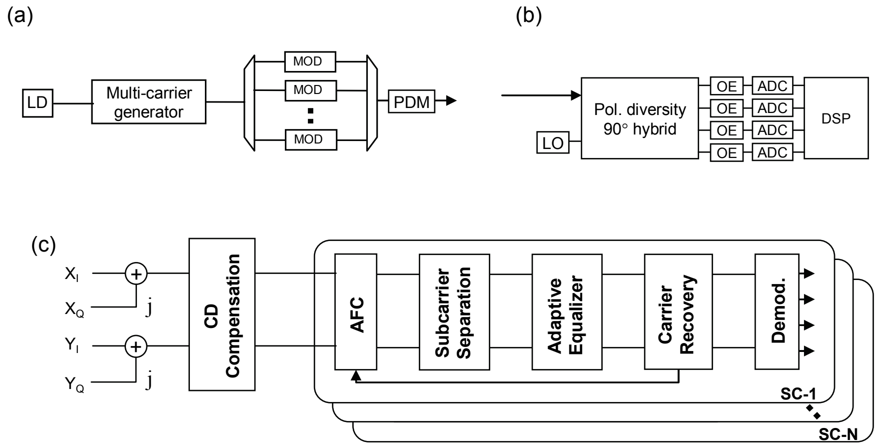

Fig. 2 Tx configuration (a), Rx configuration (b), and DSP block diagram (c) of No-GI CO-OFDM.

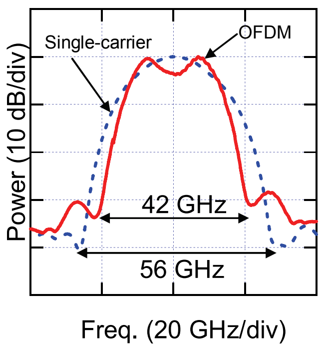

Fig. 3 Optical spectra

OFDM signal to reduce the required bandwidth of the electronic devices. A detailed block diagram of the DSP is shown in Fig. 2-c, which is similar to that for the single-carrier intradyne receiver except for the subcarrier separation part. First, CD is compensated by fixed-tap linear filters, where frequency-domain equalization is applied to reduce DSP complexity [17]. After shifting each subcarrier frequency to zero, each subcarrier is demultiplexed by discrete Fourier transformation, followed by carrier recovery and symbol demodulation.

Transmission characteristics

Hereafter we discuss the transmission characteristics of 2-subcarrier No-GI CO-OFDM. Fig. 3 shows the measured optical spectra of a 111-Gb/s polarization-division multiplexed (PDM) QPSK-modulated No-GI CO-OFDM signal. A single-carrier 111-Gb/s PDM QPSK signal is also shown for comparison. The spectral width measured at the first null point was 42 GHz, which was 75% of that of the single-carrier PDM QPSK signal. Because of this narrow spectral width, high tolerance to pass band narrowing is expected. Actually, we have confirmed that the concatenation of eighteen 50-GHz ROADM nodes is possible with less than 0.5 dB filtering penalty for 88-Gb/s 2-subcarrier CO-OFDM transmission [12].

2-subcarrier CO-OFDM holds the PAPR to only 4 dB, so good transmission characteristics can be expected even in low dispersion fiber. We demonstrated 111-Gb/s 2-subcarrier CO-OFDM transmission over DSF in the L-band. In this experiment, although the local dispersion was as low as 1.5 ps/nm/km, 2,100-km transmission was demonstrated using 50-GHz spaced 10-channel WDM signals [13]. We also confirmed that superior performance can be obtained in a periodically dispersion-compensated transmission line by using 2-subcarrier CO-OFDM [18].

In CO-OFDM transmission, it is known that no-inline compensation effectively reduces the nonlinear-induced degradation. By using this dispersion map, we have demonstrated large-capacity long-haul transmission [15]. The transmission line consists of pure silica core fiber (PSCF), and second-order distributed Raman amplification was employed to improve the received OSNR. Since the CD of the entire transmission line is compensated by a DSP at the receiver, frequency-domain equalization is used to ease DSP complexity [17]; CD of about 229 ns/nm was compensated. This effectively suppressed the nonlinear inter-channel interaction, and enabled 135-channel 6,248 km transmission which maximized the capacity-distance product and 10-channel 9,612 km transmission which maximized the capacity-distance product.

Conclusions

We reviewed long-haul WDM transmission techniques using No-GI CO-OFDM. This scheme is effective in improving nonlinear tolerance, and large-capacity long-haul transmission has been demonstrated with a record capacity-distance product and an SE-distance product. Our 100G OTN standardization activities are supported in part by the National Institute of Information and Communications Technology (NICT) of Japan under “Universal Link Project”.

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