Coherent optical orthogonal frequency division multiplexing

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Coherent optical orthogonal frequency division multiplexing is proposed to combat dispersion in optical media. It is shown that optical-signal-to-noise ratio penalty at 10 Gbit/s is maintained below 2 dB for 3000 km transmission of standard-singlemode fibre without dispersion compensation.

Introduction: Orthogonal frequency division multiplexing (OFDM) has been extensively investigated to combat RF microwave multipath fading, and has been widely implemented in various digital communication standards such as wireless local area network standards (WIFI IEEE 802.11a) [1]. In this Letter, we propose an optical equivalent of the RF OFDM called coherent optical OFDM (CO-OFDM) to combat dispersion in fibre media. We show that with CO-OFDM the optical-signal-to-noise ratio (OSNR) penalty can be maintained below 2 dB for 3000 km transmission through standard-singlemode fibre (SSMF) without chromatic dispersion compensation. As such, CO-OFDM may be an alternative solution for electrical predistortion [2], but with the additional advantage that the optical signal can be dropped at any point within 3000 km.

CO-OFDM principle: The principle of OFDM is to transmit the data through a large number of multiple orthogonal subcarriers [1]. Fig. 1 shows the time and frequency structure of the OFDM signal. The OFDM signal in time domain consists of a continuous stream of OFDM symbols with a regular period T_s. The OFDM baseband signal $s(t)$ is written as

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{N_{sc}} c_{ki} \exp(j2\pi f_k (t - iT_s)) f(t - iT_s) \tag{1}$$

$$f_k = \frac{k-1}{t_s}, \Delta f = \frac{1}{t_s} \tag{2}$$

$$f(t) = \begin{cases} 1, (-\Delta_G < t \leq t_s) \\ 0, (t \leq -\Delta_G, t > t_s) \end{cases} \tag{3}$$

where c_{ki} is the ith information symbol at the kth subcarrier, $f(t)$ is the pulse waveform of the symbol, f_k is the frequency of the subcarrier, and Δf is the subcarrier spacing, T_s, Δ_G and t_s are the OFDM symbol period, guard interval length and observation period, respectively. A cyclic prefix associated with the guard interval is appended by cyclically extending the OFDM symbol into the guard interval (Fig. 1). It can be easily shown that, if the maximum delay spread of multipath fading is smaller than the guard time Δ_G, the cyclic prefix can perfectly eliminate the intersymbol interference (ISI) [1]. In the context of optical transmission, the delay spread due to the chromatic dispersion among the subcarriers should not exceed the guard time, and the fundamental condition for complete elimination of ISI in optical medium is thus given by:

$$\frac{c}{f^2} |D_t| \cdot N_{sc} \cdot \Delta f \leq \Delta_G \tag{4}$$

where f is the frequency of the optical carrier, c the speed of light, D_t the total accumulated chromatic dispersion in units of ps/pm, and N_{sc} the number of subcarriers.

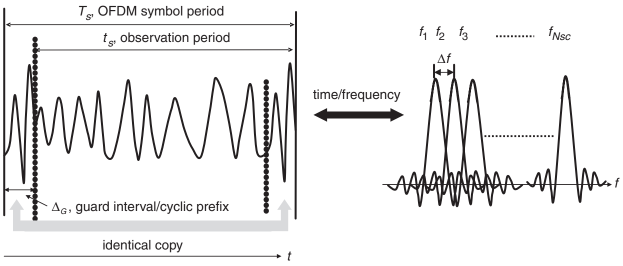

Fig. 1 *OFDM symbol in time and frequency domain*

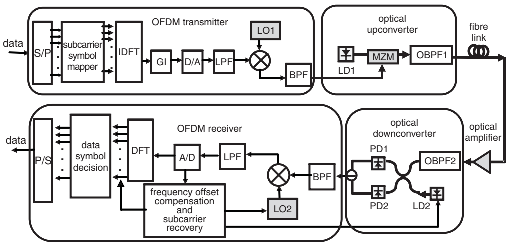

Fig. 2 *Conceptual diagram for complete CO-OFDM system*

S/P: serial-to-parallel; GI: guard interval insertion; D/A: digital-to-analogue; (I)DFT: (inverse) discrete Fourier transform; LPF: lowpass filter; BPF: bandpass filter; MZM: Mach-Zehnder modulator, OBPF: optical bandpass filter; PD: photodiode; LD: laser diode

Fig. 2 shows a conceptual diagram of a complete CO-OFDM system. The function of the OFDM transmitter is to map the data bits into each OFDM symbol, and generate the time series by inverse discrete Fourier transform (IDFT) expressed in (1), including insertion of the guard interval, and then upconvert to an appropriate RF frequency to be fed into an optical upconverter. The function of the optical upconverter is to linearly shift the OFDM spectrum from the RF domain to the optical domain. Fig. 2 shows an approach using a single optical Mach-Zehnder modulator. For instance, assuming LO1 of 15 GHz, and the OFDM baseband spectrum (f_1 to f_{Nsc}) spanning from 0 Hz to 10 GHz, two sidebands from 15 to 25 GHz away from the optical carrier will be generated. The modulation index can be as high as 0.5 without incurring significant penalty when the modulator is based at the zero output point. One of the two sidebands, for instance, the higher sideband, can be conveniently selected with an optical bandpass filter (OBPF1 in Fig. 2) and all other sidebands plus the optical carrier are rejected. The field at the output of the optical upconverter is given by

$$E_S = e^{j\{2\pi(f_{LD1}+f_{LO1})t+\phi_{LD1}\}} \cdot \sum_{k=1}^{N_{sc}} c_k e^{j2\pi f_k t} \tag{5}$$

where f_{LD1}/f_{LO1} are the frequencies for optical carrier/local oscillator 1 (LO1), ϕ_{LD1} is the phase noise of the laser diode 1 (LD1). For simplicity, only one OFDM symbol is shown in (5). The received optical signal after traversing through total chromatic dispersion of D_t, can be approximated as

$$E_S \simeq e^{j\{2\pi(f_{LD1}+f_{LO1})t+\phi_{LD1}\}} \cdot \sum_{k=1}^{N_{sc}} c_k e^{j2\pi f_k t} e^{j\Phi_D(k)},$$
$$\Phi_D(k) = \frac{\pi \cdot c}{f_{LD1}^2} D_t \cdot f_k^2 \tag{6}$$

where $\Phi_D(k)$ is the phase dispersion of each subcarrier owing to the fibre chromatic dispersion. The signal then passes through an optical downconverter, which consists of a pair of balanced photodetectors [3]. It is very critical to use an OBPF before the photodetectors to eliminate interference and optical noise from the image frequency to the OFDM spectrum. The detected signal at the output of the balanced receiver can be easily shown to be

$$P_S \propto e^{j\{2\pi(f_{LO}+f_{LD1}-f_{LD2})t+\phi_{LD1}-\phi_{LD2}\}} \cdot \sum_{k=1}^{N_{sc}} c_k e^{j2\pi f_k t} e^{j\Phi_D(k)} \tag{7}$$

where f_{LD2}/ϕ_{LD2} is the frequency/phase noise of LD2. The signal enters the OFDM receiver, is further downconverted to baseband with RF I/Q demodulation, sampled with sampling rate of N_{sc}/t_s in the observation period, and the received information symbol c_k' for each subcarrier k is then extracted by performing a DFT and is given by

$$c_k' = e^{j(\phi_{LD1}-\phi_{LD2})} \cdot c_k \cdot e^{j\Phi_D(k)} \tag{8}$$

The advantage of the coherent detection becomes obvious in (8): the system is simply a linear channel with a constant phase shift $\Phi_D(k)$ as far as each individual subcarrier k is concerned. This constant phase will be automatically included in symbol decision on the individual subcarrier basis, resulting in superior dispersion tolerance for CO-OFDM format.

Simulation model and results: The OFDM system parameters used for the Monte Carlo simulation are symbol period of 25.6 ns, guard time of 3.2 ns, and number of subcarriers of 256. BPSK encoding is used for each subcarrier resulting in total bit rate of 10 Gbit/s. The linewidths of LD1 and LD2 are assumed to be 100 kHz each, which is close to the value achieved with commercially available semiconductor lasers [3]. The link optical noise from the optical amplifiers is assumed to be white Gaussian noise and the phase noise of the laser is modelled as white frequency noise characterised by its linewidth. A total number of 800 OFDM symbols are used for each BER simulation, with the signal spanning 20.5 µs in time and containing 204 800 pseudorandom bits. The fibre nonlinearity is not considered in this Letter and optical filters are ideal in rejecting outband interference. The nonlinearity impact on CO-OFDM is system-specific, and a detailed study will be made known in an ensuing submission.

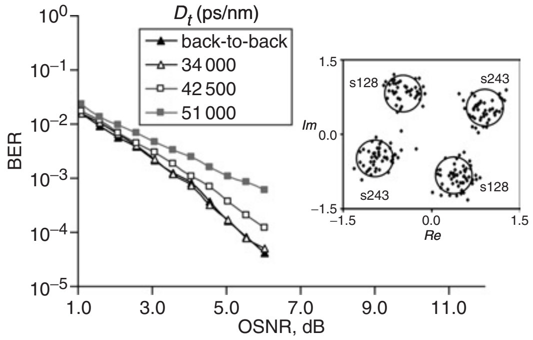

Fig. 3 *BER performance against OSNR with resolution bandwidth 0.1 nm*
Inset: Phase constellations for subcarrier 128 (s128) and subcarrier 243 (s243)

We have assumed that OFDM window synchronisation is achieved, the method of which has been extensively studied [1]. The simulation focuses on random phase walk from the laser phase noise characterised by the linewidth. The phase noise plus some constant offset for *i*th OFDM symbol ϕ_i is estimated by averaging over the phases of 256 subcarriers given by

$$\phi_i = \langle 0.5 \cdot \mathrm{mod}(2^* \arg(c_{ik}), 2\pi)\rangle \qquad (9)$$

where $\arg(c_{ik})$ is the phase of the complex coefficient for subcarrier k. The modular operation in (9) is to remove the '0' and 'π' phase modulation out of the phase estimation. The phase noise is estimated using (9) and removed from the receiving symbol in (8). A moving window of 100 OFDM symbols is used to estimate the position of '1' and '0' for each subcarrier for decision making. An error occurs when the transmitted '1'/'0' symbol in the particular subcarrier is closer to '0'/'1' at the receiver. OSNR penalty at 10^{-3} is used in expectation of strong inner and outer error-correction code being used in the CO-OFDM system. Fig. 3 shows the BER performance of the CO-OFDM for various cumulative chromatic dispersions D_t. For the back-to-back performance, a BER of 10^{-3} can be achieved at an OSNR of 3.8 dB, which gives CO-OFDM of about 5 and 2.5 dB advantage over NRZ/ASK and NRZ/DPSK formats, respectively. The OSNR penalty at a chromatic dispersion of 34 000 ps/nm is not measurable and the penalty at 51 000 ps/nm is below 2 dB. The inset in Fig. 3 shows the phase diagrams for subcarrier 128 (s128) and subcarrier 243 (s243). As can be seen, even though chromatic dispersion displaces the phase constellations among subcarriers, system performance is not affected because the bit decision is carried out separately on an individual subcarrier basis.

Conclusion: We have proposed coherent optical orthogonal frequency division multiplexing (CO-OFDM) for optical transmission. We have shown that with CO-OFDM OSNR penalty at 10 Gbit/s is maintained below 2 dB for total chromatic dispersion up to 51 000 ps/nm.

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