Transmission experiment of multi-gigabit coherent optical OFDM systems over 1000 km SSMF fibre

W. Shieh, X. Yi and Y. Tang

The first proof-of-concept experimental demonstration of coherent optical OFDM systems is reported. 128 OFDM subcarriers with a nominal data-rate of 8 Gbit/s are successfully processed and recovered after 1000 km transmission through SSMF fibre without optical dispersion compensation.

Introduction: Orthogonal-frequency-division-multiplexing (OFDM) is a special form of multicarrier modulation where a single data stream is transmitted over a number of lower rate orthogonal subcarriers [1]. Such a format has been widely implemented in various digital communication standards. Recently we proposed an equivalent optical multicarrier modulation format, called coherent optical OFDM (CO-OFDM) to combat chromatic dispersion (CD) [2]. It has been shown that CO-OFDM is insensitive to PDM in the fibre and in fact the system margin is improved in high PMD fibre owing to improved polarisation diversity against PDL-induced fading [3]. In this Letter we show the first experimental demonstration of CO-OFDM systems in which 128 OFDM subcarriers with a nominal data-rate of 8 Gbit/s are successfully processed and recovered after 1000 km transmission through SSMF fibre. The experimental work focuses on the proof-of-concept study on the feasibility of CO-OFDM signal processing, including OFDM window timing synchronisation, software RF downconversion, OFDM subcarrier and phase recovery, and I/Q detection for optical transmission. Our work serves to substantiate the suitability of the CO-OFDM format for optical transmission without a need for CD compensation.

Experimental setup: Fig. 1 shows the experimental setup for CO-OFDM systems. The OFDM signal is generated using a Tektronix arbitrary waveform generator (AWG7102B) as an OFDM transmitter. The time domain waveform is first generated with a MatLab program including mapping 2^8 − 1 PRBS into corresponding 128 QPSK-encoded subcarriers within multiple OFDM symbols, which are subsequently converted into time domain using IFFT, and inserted with guard interval (GI). The digital waveform is then uploaded into the Tektronix AWG operated at 4 GS/s to produce a real-time analogue RF OFDM signal. In theory, an optical I/Q modulator should be used for direct upconversion to optical domain, with the real/imaginary part of the OFDM signal feeding into the real/imaginary arm of the optical modulator. However, the Tektronix AWG has only one output, equivalent of only the real part of the OFDM signal. As a result, a single JDSU MZM modulator biased at zero output is used for RF-to-optical upconversion. This is equivalent to that only one modulation is filled in the optical I/Q modulator. Such waveform generation still produces 128 OFDM subcarriers, but with the constraint expressed as

\[ a_k + a_{256-k} = 0, \quad a_k \in \{0, 11\} \]

\[ a_k + a_{256-k} = 1, \quad a_k \in \{0, 10\} \]

where \( a_k \in \{01, 01, 10, 11\} \) is the two-bit symbol mapped onto k\textsuperscript{th} subcarrier \((k = 0, 1, \ldots, 127)\) with QPSK encoding. Such a constraint has insignificant impact on the nonlinearity and does not alter the algorithm in any aspects of the signal processing we study in this Letter. The MZM modulator is fed optically with a tunable laser (HP8168C). The optical OFDM signal is then input into a recirculation loop which includes one span of 80 km SSMF fibre and an EDFA to compensate the loss. The output optical signal from the loop is fed into an OFDM optical-to-RF downconverter that includes a balanced receiver from Discovery Semiconductor (DSC-R405-39) and a local laser (HP8168C). The RF signal is then input into a Tektronix time-domain-sampling (TDS) scope (TDS6154). The RF signal traces corresponding to 1000 km transmission are acquired at a sample rate of 20 GS/s and processed with a Matlab program as an OFDM receiver. The OFDM receiver signal processing involves (i) software downconversion of the OFDM RF signal to baseband by using either a residual main carrier tone, or a pilot subcarrier tone, (ii) window synchronising using Schmidl format to identify the start of the OFDM symbol [1], (iii) phase estimation for each OFDM symbol, and (iv) constellation construction for each carrier and BER computation.

Measurement results and discussion: Figs. 2a and b show equivalent optical domain OFDM spectra for 64 subcarriers (4 Gbit/s) and 128 subcarriers (8 Gbit/s) after 1000 km transmission, respectively. The spectra are obtained by performing FFT on the signal traces from the coherent detector acquired with the sampling scope. It can be seen from Fig. 2a that OFDM spectrum is tightly bounded at 4 Gbit/s with the outband signal falling off very quickly as predicted by the theory [1]. However, for a higher data-rate of 8 Gbit/s owing to the bandwidth limitation of the AWG, there is still a significant amount of residual outband signal (Fig. 2b). This does not present a problem for optical transmission, unlike the RF counterpart. In the remainder of this Letter, we focus on the nominal 8 Gbit/s OFDM transmission consisting of 128 subcarriers (Fig. 2b) with an observation period of 32 ns and a cyclic prefix of 4 ns.

Fig. 2 Equivalent optical domain spectra for 64- and 128-subcarrier CO-OFDM system

a 64-subcarrier
b 128-subcarrier

The recovery of OFDM symbols requires OFDM I/Q detection. It can be performed in optical domain using optical I/Q detection. In this Letter we elect to perform the I/Q detection in RF domain where the optical OFDM signal is first heterodyned and downconverted into an RF OFDM signal around 6 GHz (Fig. 2). In particular, the RF OFDM signal (as shown in Fig. 2b) is then downconverted to baseband by simply multiplying a complex residual carrier tone in software, eliminating a need for a hardware RF LO. The downconverted baseband signal is segmented into blocks of 200 OFDM symbols with the cyclic prefix removed, and the individual subcarrier symbol within each OFDM symbol is recovered using FFT.

The estimation of phase noise for each OFDM symbol is the most critical part of the receiver signal processing. The contributing noise sources for the OFDM phase estimation are white frequency noise of transmitter and receiver lasers, their laser frequency drift, and ASE noise induced phase noise. We have used two approaches for the phase noise estimation: (i) data-assisted phase estimation (12), equation 9), and (ii) frequency domain pilot-assisted synchronisation where 12 subcarriers cross the OFDM spectrum are allocated for phase estimation [1]. In the pilot-assisted phase estimation, the phase noise for the k\textsuperscript{th} OFDM symbol \( \phi_k \) is given by

\[ \phi_k = E(\arg(y_k) - \arg(y_0)), \quad k = 1, \ldots, N_p \]
where $y_{ki}/y_{ki}$ is the received/transmitted $k$th pilot subcarrier in the $i$th OFDM symbol, $\arg(- \cdot)$ is the phase angle of the information symbol, $E(- \cdot)$ the mathematic mean, and $N_p$ the number of pilot subcarriers.

Fig. 3 OFDM symbol phase against OFDM symbol sequence
Time unit of OFDM sequence equals OFDM symbol length of 36 ns; nominal OFDM data-rate is 8 Gbit/s

Fig. 4 BER performance of CO-OFDM signal at nominal data-rate of 8 Gbit/s

Conclusion: We have shown the first experimental demonstration of coherent optical OFDM systems (CO-OFDM). 128 OFDM subcarriers with nominal data-rate of 8 Gbit/s have been successfully processed and recovered after 1000 km transmission through SSMF fibre without optical dispersion compensation.

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References
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