Folded Orthogonal Frequency Division Multiplexing for Super-Channel Sub-Banding

Bill Corcoran(1,2), Chen Zhu(1), Binhuang Song(1), Arthur Lowery(1,2)

(1) Electro-Photonics Laboratory, Dept. Electrical and Computer Systems Engineering, Monash University, VIC 3800, Australia, bill.corcoran@monash.edu
(2) Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), Australia

Abstract *Orthogonal, periodic-sinc-shaped sub-carrier spectra allow multi-carrier bands with the precise, rectangular frequency definition of Nyquist-WDM. Experimental demonstration of these 'folded' OFDM bands shows a 0.5-1.7-dB implementation penalty, allowing 520-Gb/s super-channel transmission over 4160 km.*

Introduction

Multiplexing optical signals into super-channels with narrow or no guard-band allows maximum utilization of the available transmission spectrum in fiber optic communication systems [1,2]. Coherent optical orthogonal frequency division multiplexing (CO-OFDM)[1] and Nyquist wavelength division multiplexing (N-WDM)[2] both use sinc functions as a basis, either in the frequency domain as the subcarrier spectral distribution (i.e OFDM) or as a pulse shape in the time domain (i.e. N-WDM). However, there are other basis functions that are orthogonal, and so can be explored for super-channel generation. Discrete Fourier transform shifted OFDM (DFTS-OFDM) provides an additional super-channel multiplexing option[3], and uses a truncated, periodic sinc pulse shape as a time-domain basis[4]. In this case the long, sinc function tails are effectively folded back, allowing truncation to a single repetition period, while maintaining orthogonality between pulses.

Here we propose and demonstrate the use of truncated, periodic-sinc shapes in the *frequency* domain for the sub-carriers, forming well-confined, rectangular-shaped bands of what we call 'folded' OFDM (fOFDM). In experiment, we show that these bands can be generated and received with a low implementation penalty, and multiplexed into super-channels. We show an OSNR penalty of 0.6-dB for a single fOFDM band encoded with four QPSK subcarriers, and a 1.7-dB penalty when multiplexed into a 520-Gb/s, 14-band super-channel. Additionally, we show successful transmission over a 4160-km long (52×80km), EDFA amplified link.

Optical super-channels and folded OFDM

To illustrate the sinc-shaped basis functions for OFDM, N-WDM, DFTS-OFDM and fOFDM, Fig. 1a shows a sketch of single bands of each multiplexing format with only four sub-carriers. Practically, OFDM and DFTS-OFDM will use far more sub-carriers, however, the principle remains the same. As shown, OFDM can be considered a Fourier-transformed dual of N-WDM, as OFDM has a sinc shape in the frequency domain and a rectangular basis in time, while N-WDM has a rectangular spectrum and sinc-shaped temporal basis.

As the sinc shapes used for OFDM and N-WDM are infinite in extent, any truncation will lead to a loss of orthogonally, causing inter-carrier interference (ICI) in OFDM, or inter-symbol interference (ISI) in N-WDM. Practically, this effect can be made negligible by using large (inverse) discrete Fourier transform ((I)DFT) sizes (for OFDM) or a large filter with many taps (N-WDM). In both cases, care is normally taken that at the transmitter digital-to-analogue converter (DAC), images of the frequency bands from aliasing should be removed using a combination of low-pass filtering and some oversampling. In OFDM, this is generally

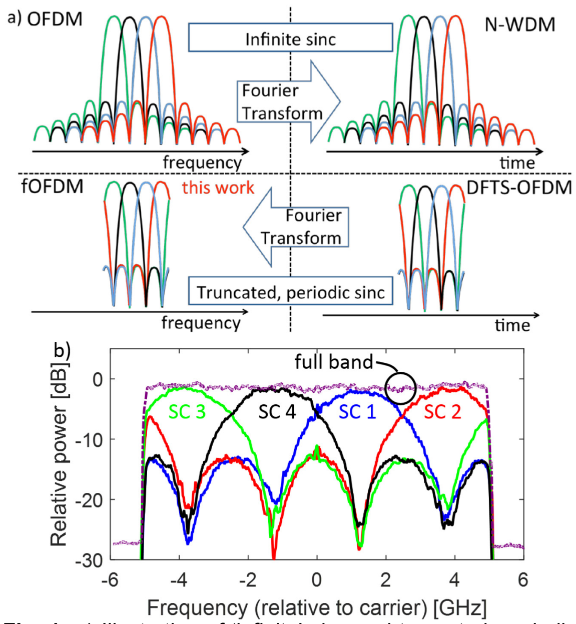

Fig. 1: a) Illustration of 'infinite' sinc and truncated, periodic sinc fOFDM power waveforms/spectra in N-WDM, OFDM, DFTS-OFDM, for single band signals with four sub-carriers only; b) Measured spectra for each subcarrier and full band of a four sub-carrier fOFDM band.

ISBN 978-3-8007-4274-5

achieved in the (I)DFT stage by zero padding the high frequency components, with parallel-to-serial outputs running at an effective rate > 1-Sa/symbol, separating the main signal band and projected alias images. DFTS-OFDM uses a two-stage DFT/IDFT process to generate signals. The initial DFT stage fully occupies the N-point DFT[3]. If the outputs of this DFT were to be considered independently, they form periodic sincs, which then give rise to the truncated periodic-sinc-shaped time domain basis for DFTS-OFDM at the output of the following IDFT stage. As with OFDM, aliasing is avoided by using zero padding in the IDFT stage.

In this work we use truncated, periodic-sinc shapes in the frequency domain for sub-carrier multiplexing for fOFDM. Similarly to the initial DFT stage for DFTS-OFDM, we fully occupy an N-point IDFT with N inputs. This folds the long sinc 'tails' typically associated with OFDM back into the main signal band, allowing truncation to generate periodic-sinc-shaped subcarriers in frequency. We the signal bandwidth by passing the signal through a root-raised cosine (RRC) filter, minimizing the out-of-band alias components. This results in the separate subcarrier spectra shown in Fig. 1b, as measured using a 15-MHz resolution optical spectrum analyser. To generate the sub-carrier spectra separately, the other three sub-carriers are set to zero (no data carried), while the full band spectrum shown is for all bands carrying independent data. The occupied signal bandwidth can be close to the aggregate baud rate of the sub-carriers, producing a signal spectrum very similar to a single N-WDM band. This then allows multiple fOFDM bands to be multiplexed into a single super-channel, again similarly to N-WDM. At the receiver side, the remaining alias components within the RRC filter bandwidth can be minimized by adaptive equalization, which can be used simultaneously to demultiplex sub-carriers from the fOFDM band.

Experiment and discussion

The transmitter and receiver are configured as follows. Incoming data is aggregated by the IDFT, which then shapes the sub-carriers. In this experiment, 4×2.5-Gbd QPSK tributaries are aggregated into a 10-Gbd fOFDM band. After serial-to-parallel conversion, a short synchronization header is added, then the signal is up-sampled to 2-Sa/symbol, filtered with a 1% roll-off RRC (25-dB stop-band attenuation), pre-emphasized to equalize the component frequency responses, and resampled to the transmitter DAC rate. At the receiver, the signal is resampled to 2-Sa/symbol, then frequency offset estimated by measuring residual carrier, dispersion compensated using overlap-add, RRC filtered, and synchronized. Each subcarrier is multiplexed and equalized separately using a training-aided least-mean-squares (LMS) algorithm followed by a constant modulus algorithm (CMA), both with 81 taps. A maximum-likelihood phase estimator corrects phase drift before de-modulation and bit-error counting.

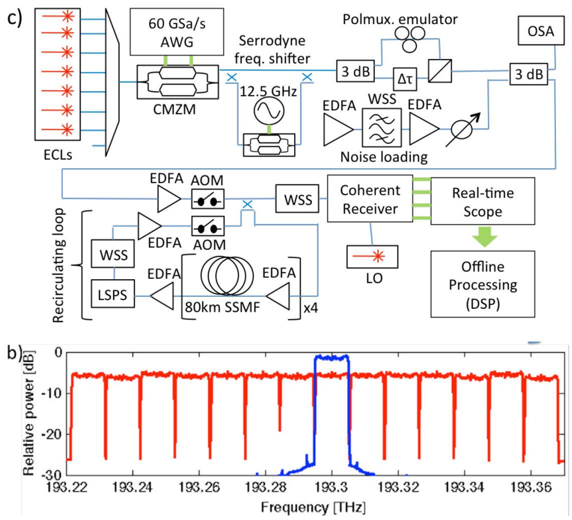

Fig. 2 –a) Measured spectrum of the generated 14-band fOFDM superchannel; b) Experimental set-up. ECL: External cavity laser, LSPS: Loop synchronous polarization scrambler, OSA: Optical spectrum analyser, AOM: Acousto-optic modulator, WSS: Wavelength selective switch, CMZM: Complex Mach-Zehnder modulator.

The experimental set-up is shown in Fig. 2a. At the transmitter, the generated 10-GHz-wide fOFDM band is modulated onto 7 separate, 20.1-GHz spaced free-running ECL lasers using a 20-GHz bandwidth I/Q modulator, via a 60-GSa/s arbitrary waveform generator (AWG). The bands are split into two arms, with one arm delayed and serrodyne frequency shifted by 10.5-GHz, then recombined with the original signal, to generate a 5% guard-band, 147-GHz-wide super-channel with odd/even channel structure (fig. 2b). Polarization multiplexing is emulated similarly by power splitting, with one arm delay de-correlated and polarization rotated by 90° before recombination. The super-channel is then either noise loaded with a variable amount of ASE, or passed into a recirculating loop incorporating 4×80km SSMF spans, with erbium-doped fiber amplifiers (EDFAs, 5-dB NF specified). The receiver is an integrated, polarization diverse hybrid with 25-GHz bandwidth balanced photodiodes, the output of which is digitized with an 80-GSa/s, 33-GHz bandwidth real-time oscilloscope. The collected samples are processed offline.

Fig. 3a shows the noise loaded performance of a single fOFDM band, without neighbouring bands present. Here Q is extracted from the mean (μ) and variance (σ^2) of the constellation points as

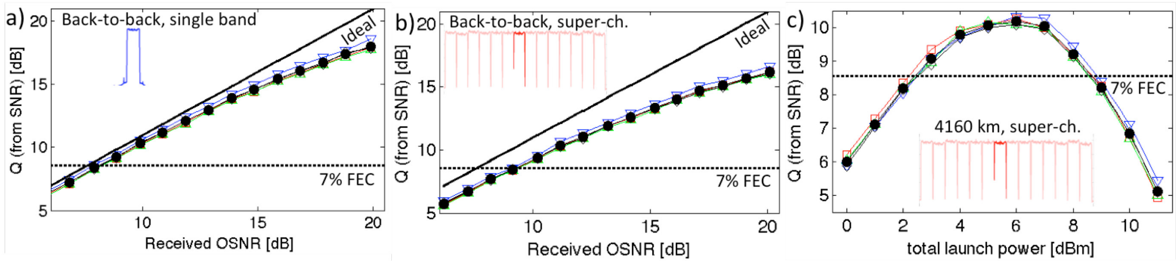

Fig. 3: Performance under noise loading of an fOFDM band as a) a single band and as b) the centre band within a super-channel. c) Performance of the fOFDM band after 4160-km super-channel transmission at varied launch powers. Solid black lines give ideal performance, open markers individual sub-carrier values and solid markers the mean values for the measured band. Dashed lines: 7% hard-FEC threshold.

$Q=10\log_{10}[\sqrt{(\mu^2/\sigma^2)}]$, to enable measurements where bit-errors were rarely observed. Individual values for each sub-carrier are plotted with open symbols, and their mean (from mean variance) plotted as sold circles. At low OSNRs, Q extracted from BER (as $Q=20\log_{10}[\sqrt{2}\text{erfc}^{-1}(2BER)]$) closely follows the values derived from μ & σ^2 (to within ±0.1-dB). At the 7% hard-FEC threshold (dashed line, BER=3.8x10^{-3}, Q=8.56), we find a 0.6-dB implementation penalty in required OSNR. This is extrapolated from the mean values, compared to ideal performance (solid line), where $Q=10\log_{10}(OSNR\text{x}10/12.5)$, indicating that we are able to accurately generate and receive fOFDM bands. Fig. 3b shows the noise-loaded performance of the centre fOFDM band within the super-channel. Compared to the single band, performance at high OSNR asymptotes to a lower value, and a larger penalty (1.7-dB in required OSNR) is observed compared to the ideal case. We suspect that inter-band interference arising from the serrodyne frequency shifting stage is likely the cause of this penalty, as the 5% guard-band should mitigate the effects of laser frequency drift.

Additionally, we transmitted over 4160-km of SSMF, in order to test the performance of fOFDM after propagation in a fibre channel. The signal performance against launch power, shown in Fig. 3c, behaves as expected. At low launch powers, we note a typical 1:1 performance increase with launch power due to ASE. The performance peaks at around 10.2-dB Q at 6-dBm launch power, well above the 7% FEC limit, before falling off due to nonlinear effects at high power.

The fOFDM system we show here may provide a simple method for aggregating a moderate number of low-baud-rate tributaries into a high bandwidth channel, with the LMS equalizer at the receiver allowing self-tuning to the sub-carrier of interest[5]. Thorough analysis is needed to assess complexity versus other multiplexing schemes.

In the context of all-optical generation of super-channels[4,6], fOFDM may provide some advantages over other schemes. Periodic-sinc filter functions are relatively simple to generate in LCoS based devices, and have indeed been predicted to allow for bandwidth limited reception[6]. Additionally, low complexity optical DFT circuits provide periodic-sinc filter functions, which may help practical implementation. Although sharp optical filters approaching 1% roll-off (as used in this demonstration) at rates compatible with available ADC bandwidths have not yet been achieved, lower roll-off filtering may allow fOFDM to be compatible with current ROADM/WSS filtering – whereas bandwidth limiting can cause major issues for all-optically generated OFDM[6].

Conclusions

We have shown an alternate super-channel multiplexing scheme based on using orthogonal truncated, periodic-sinc-shaped spectra from sub-carriers. Measurements of 10Gbd, PM-QPSK encoded fOFDM bands show a small (0.5-dB) implementation penalty for a single band, 1.7-dB penalty in a 5% guard-band super-channel, and the ability to transmit over submarine (4160-km) distances.

Acknowledgements

We gratefully acknowledge support from Australian Research Council grants FL130100041 and CE110001018.

References

[1] W. Sheih & C. Athaudage, "Coherent optical orthogonal frequency division multiplexing," Electron. Lett. 42, 587 (2006).

[2] G. Bosco *et al*., "Performance limits of Nyquist-WDM and CO-OFDM in high-speed PM-QPSK systems", Photon. Tech. Lett., 22, 1129 (2010).

[3] W. Sheih & Y. Tang, "Ultrahigh-speed signal transmission over nonlinear and dispersive fiber optic channel: The multicarrier advantage", Photonics J., 2, 276 (2010).

[4] A.J. Lowery *et al*., "All-optical generation of DFT-S-OFDM super-channels using periodic sinc pulses", Opt. Express, 22, 27026 (2014).

[5] L.B. Du & A. J. Lowery "No-guard-interval coherent optical OFDM with self-tuning receiver", Opt. Express, 19, 2181 (2011)

[6] J. Schroeder *et al*., "All-Optical OFDM with cyclic prefix insertion using flexible wavelength selective switch optical processing", 32, 752 (2014)

