DAC Generated Multi-Channel Nyquist WDM

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Paper Summary

We experimentally demonstrate 16.77-Tb/s multi-channel Nyquist WDM using multiple subchannels per modulator to allow optimization of baud rate and nonlinear performance. After 400-km transmission, the 257×65.3-Gb/s bands had an average BER of 2.3×10^{-3}.

Introduction

Nyquist wavelength division multiplexing (N-WDM) systems modulate each optical carrier with near-sinc-shaped pulses to give square-spectra, allowing subchannels to be densely packed [1]. Numerical simulations suggest that the optimal baud rate for multi-subchannel systems is around 5 Gbaud for typical long-haul links without inline chromatic dispersion (CD) compensation [2-4]. Therefore, it is more cost effective to generate several subchannels with each optical modulator, as recently demonstrated for coherent optical orthogonal frequency division multiplexing (CO-OFDM) [3, 5].

Previously we have generated several N-WDM subchannels with a single optical modulator in a 31-Gb/s system [6]. In this paper, we extend this idea by modulating 257 wavelengths, each carrying two 4.08-Gbaud 16-QAM Nyquist-shaped subchannels. The average BER was 2.3×10^{-3} after 400-km of standard single mode fiber.The total data rate is now 16.77 Tbit/s.

Subcarrier Generation and Detection

Fig. 1 shows the transmitter and receiver digital signal processing (DSP) structure for a two-subchannel N-WDM band. Two groups of QAM symbols are generated and converted into the frequency domain (FD) using DFTs. The outputs of both DFTs are passed into a larger IDFT. Zeros can be inserted between the subchannels to add narrow spectral guard-bands, which enable the subchannels to be demultiplexed without crosstalk. The DFT/IDFT structure up-samples the original streams using Nyquist interpolation; each subchannel's frequency is determined by its IDFT input index. Data pulses are allowed to spread across the block boundaries of each IDFT because overlap-add processing is used to create a continuous signal.

At the receiver, a large DFT transforms the signal into the FD. FD equalization (FDE) is then used to compensate for both CD and polarization mode dispersion (PMD) using adaptive multiple-input-multiple-output (MIMO) FDE. Each subchannel is an independent channel so the overlap duration only needs to be as long as the impulse response of each subchannel. After FDE, multiple smaller IDFTs are used to recover the symbols in each subchannel stream. Alternatively, the FDE can be reduced to a CD compensator and fractionally spaced TD equalizers (FS-TDE) can also be used to compensate for PMD [6, 7]. Because overlap-add processing reconstructs the continuous streams from the IDFT outputs, the DFT/IDFT operations at the transmitter and receiver are transparent to the data modulation and equalization processes of the individual subchannels. This enables separate time-domain equalizers for each subchannel, which makes processing more efficient.

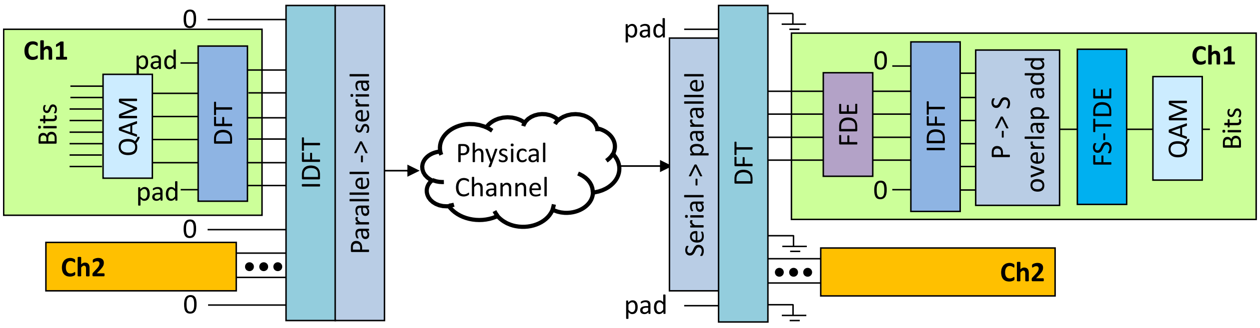

Fig. 1. Generation and demultiplexing of subcarriers using digital signal processing.

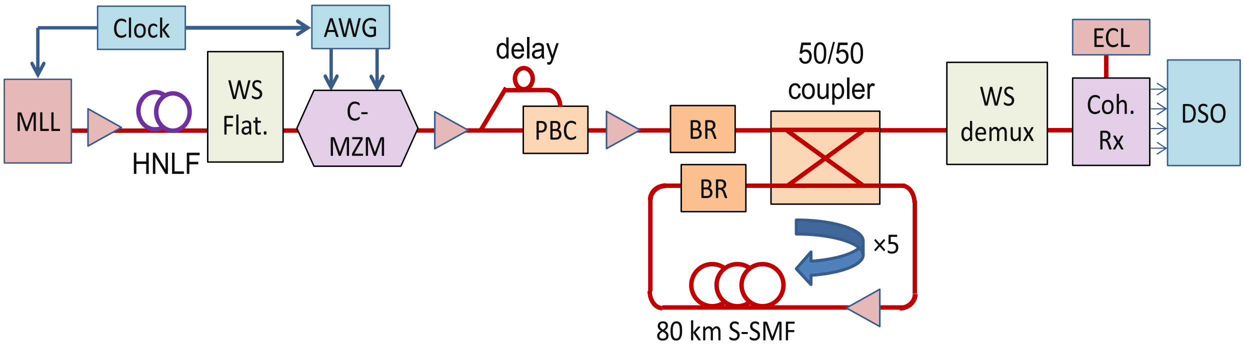

Fig. 2. Experimental setup. MLL – mode locked laser. AWG – Arbitrary waveform generator. PBC – polarisation beam combiner. WS – Waveshaper. HNLF – Highly nonlinear fiber. C-MZM – complex Mach-Zehnder modulator. BR – Brimrose optical switch for recirculating loop. Coh. Rx – coherent receiver. DSO – digital sampling oscilloscope.

To generate the near-Nyquist pulses required in regular N-WDM, finite impulse response (FIR) filters with hundreds of taps are required at the transmitter; these can be implemented efficiently using DFTs/IDFTs. Therefore, generating multiple subchannels does not add computational complexity. In real-time systems, it may be more efficient to generate the pulses using a look-up table to avoid multiplies [8] – a multi-channel signal can be generated by incorporating a subchannel's carrier frequency in the look-up table.

Our structure is very similar to that in DFT-spread-OFDM (DFT-S-OFDM) [4, 5], except that overlap-add processing is used to avoid the CP overhead and allow mature equalization algorithms developed for single-carrier systems [6] to be used. Therefore, our system can also be thought of as continuous DFT-S-OFDM.

Experimental Details

The experimental setup is shown in Fig. 2. An Ergo 10-GHz mode-locked laser (MLL) produces 2-ps pulses, which are amplified using a 2-W Lightwaves2020 erbium doped fiber amplifier (EDFA) and transmitted through 250 m of OFS highly nonlinear fiber to broaden the spectrum. The spectrum is flattened and band-limited to ~20 nm (2.57 THz) using a Finisar Waveshaper; 257 comb lines are selected. All comb lines are modulated using a Sumitomo complex Mach-Zehnder optical modulator, driven with a Tektronix 10-GS/s 2-channel arbitrary waveform generator (AWG) and SHF 807 microwave amplifiers. The AWG is programmed to produce two 16-QAM 4.08-Gbaud subchannels spaced 4.13 GHz apart. This generates 504 subchannels with a total bitrate of 16.77 Gb/s, neglecting the forward error correction (FEC) and training overheads. Each frame contained 20×160-sample training symbols and 198,400 data constellations for each subchannel.

The output of the modulator is re-amplified using a polarization maintaining EDFA, fed through a polarization division multiplexing emulator and switched into a recirculation loop with a single 80-km span of standard single-mode fiber (S-SMF) and a Lightwaves2020 gain-flattened EDFA. The loop loss was ~4 dB more than the loss in the S-SMF because of the 50/50 coupler in the loop and the optical switches. +19 dBm launch power was used, which was the maximum of our EDFA. The performance at +19 dBm was slightly better than +18 dBm, showing that this modulation format is resilient against fiber nonlinearity. After 5 re-circulations, the signal is switched out of the loop to another Waveshaper, which selects two wavelength channels.

These channels are received using a polarization-diverse coherent receiver constructed with a Kylia optical hybrid and four U^2T balanced photodiode pairs. The local oscillator is an Agilent external cavity laser (ECL). The output of the receiver is digitized at 40 GS/s using a 4-channel Agilent DSO-X 92804 real-time digital oscilloscope (DSO). The LO is placed between the two selected wavelength bands to receive both wavelength bands simultaneously; DSP is used to recover the two wavelength bands, which contains four subchannels. A single-stage training-aided MIMO FDE is used between the DFT and IDFT to compensate for both CD and PMD [9], which is the most computationally efficient equalizer [10].

Experimental Results

Fig. 3 shows the BERs of four subchannels every 100 GHz; this is one-fifth of the total subchannels transmitted. The BERs of all but two of the detected subchannels are below the hard FEC limit of 3.8×10^{-3}. The fluctuations are mainly caused by variations in power of the initial comb lines before modulation, which causes the optical signal to noise ratio (OSNR) of each band of subchannels to be different. Higher-power bands have very low BERs and lower-power bands have higher BERs. Because one comb line is used to produce two subchannels, the pairs of subchannels (triangles, dots) always perform similarly. Additionally, the lower frequencies (longer wavelengths) received slightly more gain from the EDFA inside the loop so the OSNR was slightly higher.

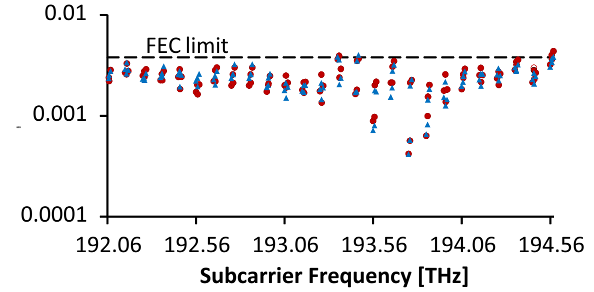

Fig. 3. BER versus channel frequency.

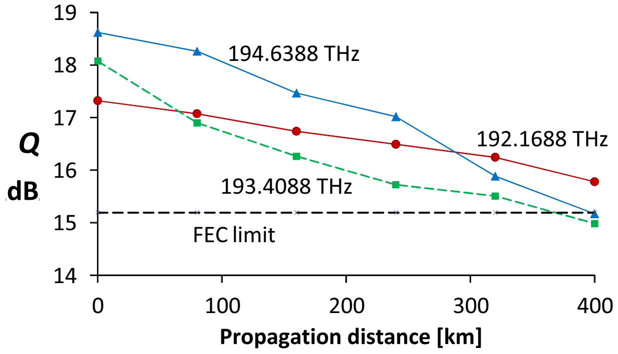

Fig. 4. *Q* versus propagation distance.

Fig. 4 plots the signal quality, *Q*, against the propagation length for four subchannels at the highest, lowest, and central frequencies. The *Q* is calculated from the counted BER and represents the required SNR for the received BER, assuming a Gaussian distribution. The subchannels at 192.07 THz had the lowest power at the start of the link and hence slightly poorer back-to-back performance.

Conclusions

We have proposed and experimentally demonstrated a multi-subchannel N-WDM system, where multiple subchannels are generated with each optical modulator and received with each coherent optical receiver, by using DFTs/IDFTs and overlap-add processing. This system structure allows the optimum subchannel rate for nonlinear transmission without wasting the bandwidth of typical commercial modulators and coherent receivers. This is especially useful in longer links because the optimum baud rate is lower. Overlap-add processing allows continuous data streams to be created, which avoids CP overheads. Either FS-TDEs or FDEs can be used for channel compensation.

We have experimentally demonstrated a 16.77-Tb/s multi-subchannel N-WDM using 257 wavelength bands; each band contains two subchannels. The two subchannels are generated using a single optical modulator. FDE is used between the DFT and IDFT at the receiver to minimize computational complexity. After 400 km, the average BER was 2.3×10^{-3}, well below the hard FEC limit of 3.8×10^{-3}.

Acknowledegements

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