Field-Trial of Layered/Enhanced ACO-OFDM

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Abstract *L/E-ACO-OFDM and DCO-OFDM are compared in a 20-km field fibre transmission experiment with high-order QAM. L/E-ACO-OFDM can provide a 0.7-dB benefit in maximum achievable Q-factor over DCO-OFDM using 3.5-GBaud 16QAM without dispersion. Sources of signal distortion are also analysed.*

Introduction

Direct modulation transmitters and direct detection receivers are compact technologies suitable for pluggable transceivers for short-haul links. Unfortunately, directly modulated lasers have limited bandwidths, so the electrical spectral efficiency (SE) of the modulation format is important. Pulse amplitude modulation (PAM-4) provides twice the electrical SE of on-off keying [1]. Discrete multi-tone (DMT), carrier-less amplitude and phase modulation (CAP) and optical OFDM are able to support m-QAM formats [1-3]. However, DMT (also known as DC-offset (DCO) OFDM) requires a larger bias to map a bipolar signal onto a unipolar optical intensity modulated signal. Asymmetrically clipped OFDM (ACO-OFDM) can save the bias but sacrifices half of the spectral efficiency [4]. L/E-ACO-OFDM [5-8] partly gains this capacity back, and theoretically requires the lowest optical power for high-order modulation schemes, such as 64-QAM [5]. The benefits of L/E-ACO come from its positive-skewed distribution of the drive signal, pushing the signal mean level to lower levels. However, because low bias reduces the laser bandwidth and introduces more laser distortion such as chirp and turn-on jitter, lowering the mean drive level can have detrimental implications for signal quality and achievable bit-rate. We have recently shown that L/E-ACO requires a lower bias than DCO for a given AC electrical drive signal, reducing the optical mean power for a given signal quality [9]. However, to enable a high system margin, lasers should be run at high bias, so a fairer comparison is to use the same bias and so the same mean optical output power.

In this paper, we compare L/E-ACO against DCO through a 20-km field link, and compare their relative performances with 16- and 64-QAM. We show a ~0.7dB Q-factor advantage for L/E-ACO over DCO using 16QAM in a power-loss link. However, we also observe that the interaction of laser chirp with fibre chromatic dispersion (CD), and error propagation in higher order QAM degrade L/E-ACO's predicted benefit.

Direct modulation process

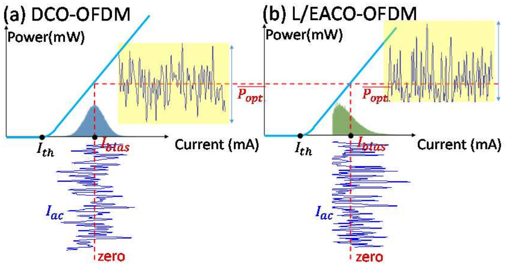

Fig. 1: E/O conversion by directly modulating a laser

Figure 1 shows the E/O intensity modulation process by directly modulating a laser. The modulated optical power can be expressed as:

$$P(t)=\eta(I_L(t)-I_{th})$$

where: $I_L(t) = I_{ac}(t) + I_{bias}$, I_{ac} is the AC part of the drive signal, I_{bias} is the laser bias current and I_{th} is the laser threshold. As shown in Fig. 1, when L/E-ACO and DCO use the same peak-to-peak AC drive amplitude, L/E-ACO has a lower mean value due to its positive-skewed signal distribution property. This then means that when the same bias is applied to the laser, L/E-ACO can provide a larger driving current margin above threshold (I_{margin} = minimum (I_{ac}) + I_{bias} – I_{th}), avoiding clipping at the laser threshold current. This lager margin translates to a larger AC drive signal (I_{ac}) without clipping for L/E-ACO compared to DCO, increasing the output optical signal amplitude. The increased optical signal swing range supports a higher link attenuation budget for direct detection (where thermal noise dominates) before considering any laser dynamic penalties. This indicates that when the laser is limited by the mean output optical power ($\overline{P_{opt.}}$), L/E-ACO can have a better received signal quality than DCO. We compare L/E-ACO against DCO experimentally using direct modulation, to see if this predicted benefit holds.

Experimental investigation

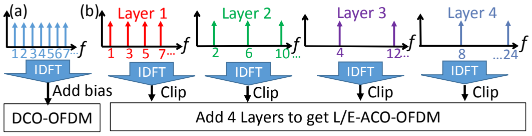

Fig. 2: SC arrangement for (a) DCO and (b) L/E-ACO

Both OFDM signal types were generated in MATLAB. The DCO signal (Fig. 2(a)) has 59 data sub-carriers with the 1st sub-carrier (0 position in frequency axes) left unmodulated for DC bias. The complex data's Hermitian conjugate value is allocated to negative frequency sub-carriers before inverse discrete Fourier transforms (IDFT) generate real-valued signals. The FFT size was 1024 to match the sample rate of the arbitrary waveform generator (AWG - see Fig. 3(a)). For L/E-ACO (Fig. 2(b)), we stacked 4 layers with the same FFT size and oversampling ratio, carrying 30, 15, 7 and 4 sub-carriers for the 1st, 2nd, 3rd and 4th layers. With such a sub-carrier arrangement in Fig. 2(b), the clipping distortion from layer *n* only falls upon the specific frequencies of layer (*n* + 1), enabling the received signal to be iteratively decoded, starting with layer 1 [5]. In MATLAB, both the L/E-ACO and DCO signals were normalized, so that their per-sub-carrier AC electrical powers are identical. Before the parallel-to-serial conversion, a cyclic prefix of 32 points was added, giving 32/1024 = 3.13% data rate loss.

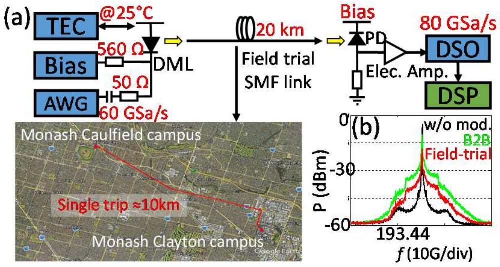

Fig. 3: (a) Experimental setup. (b) Measured spectra. (c) Measured laser frequency response.

Figure 3 (a) shows the experimental setup for ~3.5-Gbaud 16 QAM and 64 QAM transmission using DCO and L/E-ACO. After generating the DCO and L/E-ACO drive signals offline in MATLAB, a Keysight M9505A arbitrary waveform generator was used to drive the laser. Because of the 50-Ω impedance of the laser and series resistor, the amplitudes of both drive signals can be simply calculated as: V*pp* (in volts)/50 (A). With a DC-block at the AWG output and a bias-T, the mean laser output power is proportional to the bias current minus the threshold current. The AWG was set to 60 Gsample/s, giving ~3.5 (60/1024×59) GBaud. The laser is a Gooch & Housego AA0701 DFB, biased at 23 mA and controlled to 25℃. The link is a 20-km standard single-mode fibre connecting Monash Clayton and Caulfield campuses in South-East Melbourne, Australia, which gives ~6 dB power loss. The output of a 40-GHz photodiode (Finisar XPRV2021A) was sampled by a 28-GHz real-time digital oscilloscope (Agilent DSO-X92804A) at 80 GSample/s. Figure 2(b) shows the measured spectra. At the receiver DSP, a simple one-tap frequency domain equalizer was used to recover the data and then the iterative decoder is used for L/E-ACO.

We measured Q-factor (calculated from measured signal error vector magnitude (EVM)) versus drive signal amplitudes for L/E-ACO and DCO in three different scenarios: optical back-to-back transmission, 20-km field fibre transmission and 6-dB optical loss link transmission (which is the same loss as the 20-km field fibre). We test these signals with a 23 mA laser bias current, and vary the driving signal current from 12 mA to 32 mA. The effect on performance of clipping from the laser threshold is also modelled with a simple MATLAB simulation, where the laser's transfer function is modelled as a linear current to optical power transfer function with hard clipping at the laser threshold. In these simulations we limit the received SNR by adding in noise, where the noise power was determined from measured Q-factors when using a low drive signal (12 mA) in the optical back-to-back measurements. For the four scenarios described above (i.e. one simulated and three experimental), signal quality is plotted against drive current (Fig. 4-5 (a)), and the bar graphs in Fig. 4-5 (b) show the maximum achievable signal qualities.

We first investigate the performance of OFDM signals carrying 16QAM. For each of the scenarios shown in Fig. 4, a higher drive current increase the signal, and as thermal receiver noise dominates, the Q-factor is increased for low drive levels. For higher drive levels, the signal becomes clipped when the drive current drops below the lasing threshold. As illustrated in Fig. 1, at the same bias L/E-ACO should display greater tolerance to clipping distortion than DCO. This is reflected in Fig. 4(a), where L/E-ACO outperforms DCO at high drive currents in every scenario. However, this advantage does not always translate to an improvement in peak Q-factor performance. As shown in Fig. 4(b), using 16QAM, in optical back-to-back transmission, L/E-ACO has almost the same maximum Q-factor (0.1 dB less) as DCO. When a 6-dB optical loss limits received SNR, L/E-ACO has a 0.7-dB higher maximum achievable Q-factor than DCO. We attribute this to distortion from clipping at the laser threshold outweighing receiver-side noise, as L/E-ACO achieves peak Q at higher drive current than DCO. There is a marginal advantage in peak Q-factor for L/E-ACO and DCO after 20-km field fibre transmission, indicating the laser chirp interacting with fibre CD dominates the distortion for both formats.

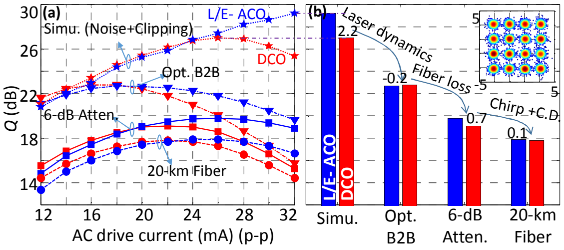

Fig. 4: (a) *Q*-factor vs. different driving currents. (b) Max. achievable Q. Inset: B2B received symbols at 20-mA.

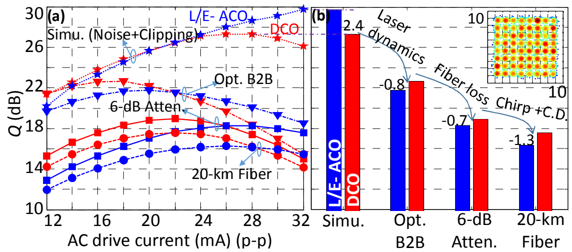

Fig. 5: (a) *Q*-factor vs. different driving currents. (b) Max. achievable Q. Inset: B2B received symbols in at 20-mA.

We further increase the modulation order to 64QAM. Inspecting the experimental scenarios, Q-factor is lower for all drive currents and the optimal drive current is shifted to a higher value when compared to the 16QAM case. This indicates that in directly modulated links, the performance benefit expected of L/E-ACO over DCO is limited by the effects of the nonlinear modulation transfer function of the laser and further distortions from the interaction of laser chirp with CD. To investigate the lowered peak Q, we further look at the performance for DCO and L/E-ACO in back-to-back transmission at a low drive current level of 12 mA, as shown in the Fig. 6. Slight Q-factor differences among DCO and layers in L/E-ACO can be observed in Fig. 6(a) where 16QAM is encoded. However, using 64QAM in Fig. 6(b), the first layer of the L/E-ACO signal has similar performance to DCO, while Layers 2, 3 and 4 degrade by ~2dB per layer. This is due to the error propagation in iteratively decoding L/E-ACO layers, where the inaccurate clipping estimation induced by error bits will accumulate and propagate to next layers, degrading the overall performance. Furthermore, the higher index sub-carriers' error will also transfer to low index sub-carriers in next layer by intermodulation in the nonlinear clipping noise estimating process.

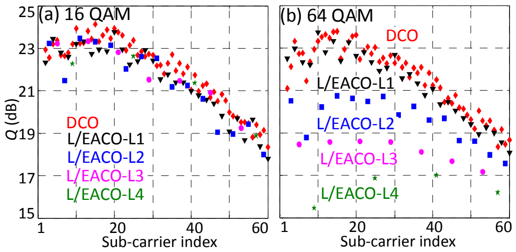

Fig. 6: B2B Q-factors for all sub-carriers in DCO and L/E-ACO for (a) 16QAM and (b) 64QAM.

Conclusions

Through this experimental investigation, we have shown that with the same laser bias (mean optical power), L/E-ACO-OFDM can support higher driving signal than DCO-OFDM before laser clipping and has a higher maximum achievable Q-factor in a lossy link. However, in 20-km field fibre transmission, we find that laser chirp interacts with fibre CD to reverse the previously predicted advantages of this format.

Acknowledgements

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