Homodyne OFDM using Simple Optical Carrier Recovery

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Abstract: We demonstrate a novel optical injection locking approach to carrier recovery in RF-pilot aided OFDM. Any need for optical pre-filtering is eliminated and only very narrow guard bands are required. Improved system performance with respect to heterodyne OFDM detection is demonstrated.
OCIS codes: (060.0060) Fiber optics and optical communications; (060.2920) Homodyning

1. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) represents a promising technology for mitigating linear transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) [1]. A further attraction is that it allows software-defined bandwidth allocation and is therefore considered an enabling technology for flexible high-speed optical networks [2]. Despite these advantages sensitivity to carrier frequency offset (CFO) and phase noise remain issues for any practical implementation. Extensive research has been carried out on estimating and compensating the CFO and phase noise through Digital Signal Processing (DSP)[3]. Although DSP can successfully provide such compensation, the computing resources required add cost and consume a considerable amount of power. Homodyne detection with carrier obtained via optical means would overcome these issues and could potentially also improve performance. However, to be practical, any scheme should rely on largely the same optical hardware as the DSP-based approaches.

Among the optical OFDM variants, RF-pilot aided OFDM attracts a lot of attention due to relative ease of phase noise estimation and effective fibre nonlinearity compensation [3]-[4]. RF-pilot aided OFDM incorporates a carrier tone inserted in the middle of the OFDM spectrum (blue curve in Fig.1) and the carrier tone is extracted at the receiver side for DSP.

A promising all-optical method of extracting the carrier tone has recently been published [5]. It is based on all optical carrier recovery by injection locking a semiconductor laser diode. However, a large protection guard band (reducing transmission capacity by ~20-30%) and a narrow band optical filter for pre-filtering were required, which compromises the attraction of this method for practical application.

In this paper, we propose a modification of the recently-presented-method [5], mitigating its two main drawbacks – the severe reduction of transmission capacity and the need for an ultra-narrow optical filter. We demonstrate that the optical carrier can be cleanly recovered by direct (without any optical pre-filtering) injection locking of a single semiconductor laser leading to minimal loss of bandwidth for the carrier tone protection. We show that our injection locking based carrier recovery (ILCR) technology enables homodyne detection which reduces DSP computational complexity and avoids the penalty induced by non-ideal DSP-based CFO estimation. Moreover, by injection locking a large linewidth local oscillator (LO) with a narrow linewidth carrier tone, a narrow linewidth LO can be cost-effectively realized. As we show, this results in lower phase noise and better performance. Note that the technique has a similar component count as the popular DSP-based coherent receiver.

2. Injection Locking for Carrier Recovery

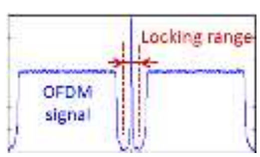


Fig. 1: Principle of injection locking based carrier recovery. Note the significant protection guard bands.

The principle of ILCR is schematized in Fig. 1. In RF-pilot aided OFDM, there is a guard band around the centre carrier tone to ensure clear tone extraction for DSP-based phase noise estimation. Optical injection locking can simultaneously filter and amplify the injected frequency tone, which makes it a perfect candidate for optical carrier recovery [6]. The key is to set the bandwidth of the injection locking to be smaller than the guard band. When the locking range is narrow enough, the centre carrier tone will be amplified with suppressed amplitude noise (an inherent feature of optical injection locking) while the subcarriers will be suppressed. Obviously, a smaller guard band means better bandwidth utilization and thus also higher transmission capacity: consequently the smaller the necessary injection locking bandwidth the better. The locking bandwidth depends mainly on the amount of power injected into the laser relative to the output power (injection ratio) – the lower the injected power, the narrower the locking range [7]. We have previously demonstrated that an injection ratio as small as -63 dB is possible enabling sub-100 MHz locking bandwidth and good long-term stability if supported with slow (and thus cheap and low power consumption) stabilisation electronics.

3. Experimental Setup

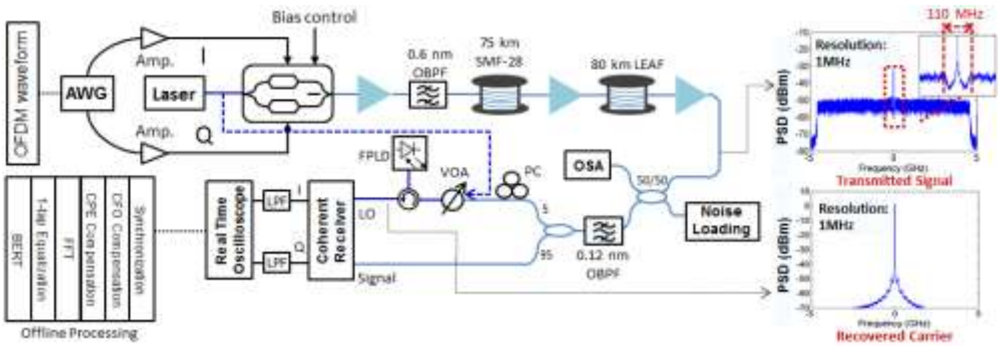


Fig. 2: Experimental setup. Spectra of the transmitted OFDM signal (upper) and the recovered carrier (lower).

Fig. 2 shows our experimental setup. The waveform samples of the base band OFDM are calculated offline based on a PRBS of 2^{17}-1 and QPSK constellation mapping. Then the electrical waveforms are generated by an arbitrary waveform generator (AWG) operating at 10 GS/s which then drives an I-Q modulator. An IFFT size of 256 was used. 22 high frequency subcarriers are set to zero to avoid electrical filtering induced penalty at the receiver side. Eight-sample cyclic prefix (CP) is placed before and after each OFDM symbol, resulting in symbol rate of about 36.8 MSym/s for each subcarrier. To study the ultimate performance of ILCR, OFDM signals with different pilot tone guard band spectral widths (2, 6, 14, and 20-sub-channels wide) were generated.

A laser with 1 kHz linewidth emitting at 1557.4 nm was used in the transmitter. The I-Q modulator was biased slightly away from the transmission null points for both I and Q to generate the carrier tone. The resulting carrier-to-signal power ratio was around -10 dB.

The transmission link consisted of two spans with total transmission distance of 155 km (comprising 75 km standard single mode fibre (SSMF-28) and 80 km large effective area fibre (LEAF)). The optical power launched into the transmission link was -2 dBm.

At the receiver side, ASE-generated noise loading was used to adjust the optical signal-to-noise ratio (OSNR). The single-polarisation OSNR after two-span transmission was -34 dB. A 0.12-nm optical band pass filter (OBPF) was used to filter out the out-of-band noise. A 95/5 coupler split the filtered signal into the coherent receiver and our ILCR module, which consists of a variable optical attenuator (VOA), a polarization-maintaining optical circulator, and a discrete-mode semiconductor laser [8] with a free-running linewidth of 200 kHz. The laser was biased at 146 mA and the output signal was used as the LO of the coherent receiver. After coherent detection, a low pass 5.8-GHz filter (LPF) was used to suppress the aliasing product as well as the wide band noise. The signal was then sampled by a 32-GHz, 80-GS/s real time oscilloscope before offline processing.

An 8% training overhead was used for symbol synchronization, CFO estimation, and channel estimation. The common phase error (CPE) was estimated from the OFDM centre tone after being digitally filtered by a 35-MHz 5thorder Bessel LPF. Finally the bit error ratio (BER) was calculated.

The spectrum of the OFDM signal with a two-channel wide carrier tone guard band after transmission with the noise loading turned off, is shown as the upper inset in Fig. 2. The spectrum of the corresponding recovered carrier at an injection power of -57 dBm is shown in the lower inset. It can be seen that a clear carrier was recovered even in this case, in which the guard band occupies merely two channel slots.

4. Experimental Results and Discussions

The performance of ILCR-based OFDM signals for different injection powers is shown in Fig. 3. The measurements were taken at a single-polarization OSNR of 26 dB. The signal quality is evaluated based on the average error vector magnitude (EVM) for the demodulated OFDM-QPSK signal. RF-pilot OFDM signals with different guard band widths were compared using our carrier recovery technique as well as the traditional DSP-based heterodyne carrier estimation technique [3]. The EVM using the heterodyne technique was 15.1% and is plotted as the green dashed curve in Fig. 3. Heterodyne detection was performed using the same semiconductor laser which was operating in a free running mode. It can be seen from this figure that ILCR based OFDM provides better performance at low injected powers and from the constellation diagrams that ILCR based OFDM provides smaller phase noise after demodulation. At low injection powers, the performance of the signal with different guard band widths converges. This is because the subcarriers are well suppressed once the locking bandwidth is sufficiently small and thus a further decrease in the locking range does not lead to any further improvement. To study the performance limitations due to the limited suppression of the data signals in ILCR, we performed an experiment in which the clean carrier is used for injection locking of the LO – our implementation is shown as the dashed blue line in Fig.1. Here, CW light from the transmitter was tapped and directed to the ILCR module. The result is plotted in Fig. 3 as closed squares. When the injection power is low, the performance is identical to our previous experiment, demonstrating that our ILCR scheme retrieves a clean carrier with full suppression of the data signal. As the injected power increases, the data signal is not fully suppressed by the ILCR which leads to a penalty, as demonstrated in Fig. 3.

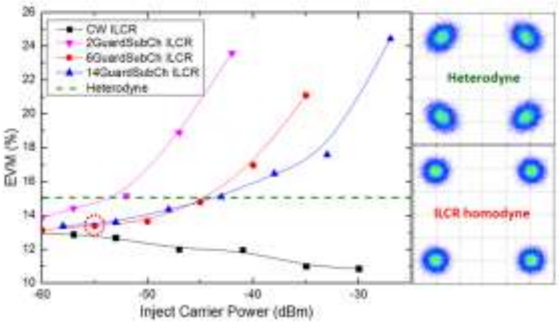
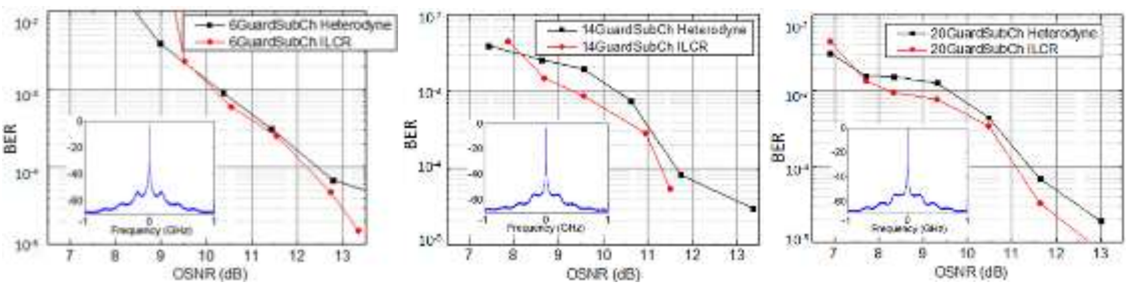


Fig. 3: Performance of the ILCR-based OFDM signals under different injection power at OSNR of 26 dB.

The BER as a function of single-polarization OSNR is shown in Fig. 4 for guard bands occupying 6, 14, and 20 sub-channels. The injection power was kept at about -55 dBm for all the measurements. The insets show the spectrum of the recovered carrier at OSNR of 14 dB. Generally, the ILCR based OFDM outperforms the heterodyne approach in the high OSNR regime and becomes worse at very low OSNR. This is because the recovered carrier is corrupted by the noise when the OSNR becomes very low. As shown in Fig 4 (b) and (c), the ILCR based OFDM brings 0.9 and 1.2 dB OSNR benefit for 14 and 20 sub-channel wide guard bands at a BER of 10^{-3}, respectively. The performance of ILCR with a 6 sub-channels guard band is comparable to heterodyne in the OSNR range from 9.5 dB to 12 dB and only showed better performance at higher OSNR. This is because the suppression of the low frequency subcarriers for the recovered carrier is insufficient (as seen in the inset of the figure), which counteracts the benefit brought by ILCR homodyne detection.



(a) (b) (c)

Fig. 4: BER performance of the heterodyne OFDM and ILCR OFDM with different number (a) 6, (b) 14, (c) 20-channels wide guard band. Insets: ILCR recovered carrier at OSNR of 14 dB.

5. Conclusion

We demonstrated all optical carrier recovery based on single laser injection locking for RF-pilot OFDM. As expected for a homodyne method as compared to a conventional heterodyne detection, better performance (about 1 dB OSNR benefit demonstrated here) was achieved (for OFDM signal with 14 and 20 guard bands (reducing the capacity by 5-8% only) together with significantly reduced DSP load.

6. References

[1] Xiang Liu and Fred Buchali, “Intra-symbol frequency-domain averaging based channel estimation for coherent optical OFDM,” Optics Express, **16**, 21944-21957 (2008).

[2] William Shieh, “OFDM for Flexible High-Speed Optical Networks,” JLT, **29**, 1560-1577 (2011).

[3] Sander L.Jansen, Itsuro Morita, Tim C.W. Schenk, Noriyuki Takeda, and Hideaki Tanaka, “Coherent Optical 25.8-Gb/s OFDM Transmission Over 4160-km SSMF”, JLT **26**, 6-15 (2008).

[4] B. Inan, S. Randel, S. L. Jansen, A. Lobato, S. Adhikari, N. Hanik, “Pilot-Tone-based Nonlinearity Compensation for Optical OFDM Systems”, in Proc. ECOC, 2010, paper Tu.4.A.6.

[5] S. Adhikari, S. Sygletos, A. D. Ellis, B. Inan, S. L. Jansen, and W. Rosenkranz, "Enhanced Self-Coherent OFDM by the Use of Injection Locked Laser," in Proc. OFC, 2012, paper JW2A.64.

[6] David S. Wu, Radan Slavík, Guiseppe Marra, David J. Richardson, “Direct Selection and Amplification of Individual Narrowly Spaced Optical Comb Modes Via Injection Locking: Design and Characterization”, JLT, **31**, 2287-2295 (2013).

[7] A. E. Siegman, “29” in *Lasers*, Anthony E. Siegman, (University Science Books, 1986).

[8] John O’Carroll, Richard Phelan, Brian Kelly, Diarmuid Byrne, Liam P. Barry, and James O’Gorman, “Wide temperature range 0 < T < 85 °C narrow linewidth discrete mode laser diodes for coherent communications applications”, Optics Express, **19**, B90-B95, (2011).