Self- Coherent Optical OFDM, an Interesting Alternative to Direct or Coherent Detection

S. Adhikari[1], S. L. Jansen[2], M. Alfiad[3], B. Inan[4], V. A. J. M. Sleiffer[3], A. Lobato[5], P. Leoni[5], W. Rosenkranz[1]

[1] *Chair for Communications, Christian-Albrechts-Universität zu Kiel, Germany, asu@tf.uni-kiel.de,*
[2] *Nokia Siemens Networks, Munich, Germany,*
[3] *COBRA institute, Eindhoven University of Technology, The Netherlands,*
[4] *Institute of Communications Engineering, Technical University of Munich, Munich, Germany,*
[5] *University of the Federal Armed Forces, Munich, Germany.*

ABSTRACT

Recently, coherent optical orthogonal frequency division multiplexing (CO-OFDM) has been considered for the next generation 400-Gb/s long haul data transmission. For long haul transmission systems coherent detection is beneficial compared to direct detection as it provides higher sensitivity. Though CO-OFDM offers a virtually unlimited tolerance against linear impairments, phase noise represents major challenge that must be compensated for.

Thus, phase noise compensation (PNC) technique must be applied in the digital signal processing (DSP), which is already limited in speed and processing capabilities. Conversely, self coherent optical (SCO-) OFDM is an interesting alternative which does not require any PNC in the DSP. Furthermore, no local oscillator (LO) is required at the receiver. In this paper, an overview of the recently seen self coherent techniques will be given. Generally, self coherent detection is realized by sending an optical carrier along with the data signal like in direct detection systems. At the receiver, however, the optical carrier is extracted from the signal with the use of filters with very narrow bandwidth and used as an LO using heterodyne or homodyne detection. The performance of such a system depends on the filter bandwidth that is used to extract the carrier.

Keywords: orthogonal frequency division multiplexing, self-coherent, phase noise, Fabry-Perot tunable filter, optical communication.

1. INTRODUCTION

The vision of providing ubiquitous high-speed access to information has led to extensive research in advanced modulation formats. Exhibiting the advantage of scalability to higher level modulation formats and well defined spectrum useful for realizing next generation agile optical networks [1], orthogonal frequency division multiplexing (OFDM) is emerging as a promising modulation technique. With the rekindled interest in coherent receivers, much of the effort has been focused on the digital signal processing (DSP) which is a key technology for realizing 400 Gb/s and beyond optical transmission system.

Recently, 101.7 Tb/s conventional coherent optical OFDM (CCO-OFDM) transmission with a spectral efficiency of 11 b/s/Hz has been demonstrated that employs coherent detection and DSP [2]. Though coherent detection offers a reception sensitivity that is higher than the direct detection (DD) receiver, it is eminently prone to laser phase noise. Scaling to higher quadratic-amplitude modulation (QAM) constellations makes the signal more sensitive to laser phase noise raising stringent requirements on the laser linewidth. In [2], the authors use RF-pilot along with pilot subcarriers to mitigate the effect of phase noise. The RF-pilot based phase noise compensation (RF-PNC) was first introduced in [3] where phase-noise compensation is realized by placing a RF-pilot (RFP) tone in the center of the OFDM transmit spectrum, which is subsequently used at the receiver in order to undo phase noise impairments.

Implementing RF-PNC technique in speed and processing limited DSP is challenging and increases the requirements of the DSPs. An interesting alternative is self coherent optical (SCO-) OFDM. SCO-OFDM is similar to the RF-PNC concept for CCO-OFDM, except that the pilot is extracted in optical domain and used as local oscillator (LO) using heterodyne or homodyne detection to reverse the phase noise effect. No phase noise compensation is required in the DSP, consequently reducing the DSP complexity. No LO is required at the receiver, reducing the cost of an extra LO. Such a system not only compensates for transmitter laser linewidth but also effortlessly compensates phase noise generated by fiber nonlinearities [4].

In this paper, the different schemes for implementing self- coherent detection are discussed. Then, the paper focuses on the technique based on tunable Fabry-Perot based filters for optical carrier extraction with SCO-OFDM system. Some experimental results are then presented in back-to-back setup and after 400 km of transmission to compare the SCO-OFDM to CCO-OFDM. It is conjectured that the performance of SCO-OFDM can be improved by the usage of narrow bandwidth filters and optimum carrier-to-signal power ratio.

2. IMPLEMENTATION OF SELF COHERENT DETECTION

Several concepts for insertion and extraction of optical carrier/pilot have been proposed as seen in Table 1. In 2005, Miyazaki [5] published the first ever concept of self coherent detection where a homodyne detection using a polarization-modulation technique to generate a pilot carrier orthogonally polarized to the data signal in the transmitter and a LiNbO (LN)-based pilot-carrier combining module in the receiver was demonstrated [4-6]. One drawback in this scheme is that the spectral efficiency is 50% less compared to an intradyne system. In [7], 33% increase in spectral efficiency in self homodyne technique was shown using interleaved polarization division multiplexed.

Table 1: Self Coherent Implementation Schemes

SN	Reference	Carrier insertion technique	Carrier extraction technique	Modulation Format
1	[4-6]	Co-propagated pilot tone orthogonally polarized relative to signal	Polarization beam splitter and optical band pass filter	16-QAM
2	[7]	Co-propagated pilot tone *interleaved* polarization division multiplexed	Polarization beam splitter and optical band pass filter	16-QAM
3	[8]	Zero padding near dc and biasing IQ-MZM in a way to generate optical pilot	*Electrical* band pass filter	OFDM
4	[9]	RF carrier and phase modulation	*Optical* band pass filter	OFDM
5	[10]	Virtual carrier with the use of frequency shifter and IQ-MZM biased at null	Waveshaper	OFDM
6	[11]	Zero padding near dc and biasing IQ-MZM in a way to generate optical pilot	Circulator and *Fabry-Perot filters*	OFDM

In 2007, Louchet illustrated the fist coherent OFDM based self heterodyne system, where the carrier/ clock is extracted with an electrical band pass filter, amplified and used for down conversion [8]. Zero padding near dc components for OFDM is done to separate the signal from the carrier. In [9], the carrier is extracted in optical domain with the help of band pass filter and used for homodyne detection. In [5], the OFDM signal is generated as for coherent system, however the optical carrier is suppressed and a virtual carrier is created by frequency-shifting the laser to one side of the OFDM band. Compared to DD-OFDM, this scheme improves the spectral efficiency. At the receiver a Waveshaper is used to divide the signal to two tributaries; the OFDM signal and the virtual carrier. A polarization controller is used in one of the path to align the polarization of the extracted carrier to the signal before going into the optical hybrid. For all of the schemes discussed above for OFDM, the IQ-demultiplexing in the receiver was done in electrical IQ mixing. In [11], we realized the first SCO-OFDM experiment with IQ demultiplexing in optical domain while employing Fabry-Perot-tunable filters for the extraction of the optical carrier. The experimental setup and comparison of this scheme to CCO-OFDM is discussed in the following sections.

3. EXPERIMENTAL SETUP FOR FABRY-PEROT FILTER BASED SCO-OFDM

In the experiments, an arbitrary waveform generator (AWG) is used at a sampling rate of 10 GSamples/s to generate a continuous baseband signal. The OFDM baseband waveform is calculated offline and uploaded into the AWG. A low-pass filter (LPF) after the AWG with 4.4 GHz bandwidth is used to suppress any aliasing products. For the generation of the OFDM signal, a 256 FFT size is used, from which 148 subcarriers are effectively used as data. The modulation format is a non-rectangular 8-QAM (as seen in the inset of Fig. 1 (b)) on each subcarrier. 64 subcarriers around the DC are padded with zeros to make place for the insertion of an optical carrier/ pilot-tone. A cyclic prefix overhead of 6.25% is used to increase ISI tolerance. The net and nominal data rates are ~14.9 Gb/s and ~15.3 Gb/s, respectively.

A laser is used at the transmitter to generate a continuous wave (CW) signal that is subsequently modulated with the OFDM signal by an IQ-Mach–Zehnder modulator (IQ-MZM). Similar to the CO-OFDM modulation format discussed in [7], the IQ-MZM is biased such that the optical carrier is not totally suppressed at the transmitter. The transmission link consists of 5 spans of 81.4-km standard single mode fiber (SSMF) without any dispersion compensation. After every span, an erbium-doped fiber amplifier (EDFA) is used for amplification. At the receiver as seen in Fig.1 (a), a cascade of two FP-TF filters is employed to separate the carrier from the OFDM signal. The FP-TF is a narrowband bandpass filter that transmits the optical carrier and rejects the OFDM signal. In this experiment FP-TF filters are chosen as bandpass filter because of their high Q-value and narrow bandwidth. The Q-value of the filter is important as it enables a narrow guardband between the optical carrier and the OFDM signal making the separation easy. The first and second FP-TFs have 3-dB bandwidth of 250 MHz and 460 MHz, respectively. The Q-value is approximately 20.5 dB. With these filters a guardband of 1.3 GHz was used in the experiment to easily filter out the optical carrier at the receiver.

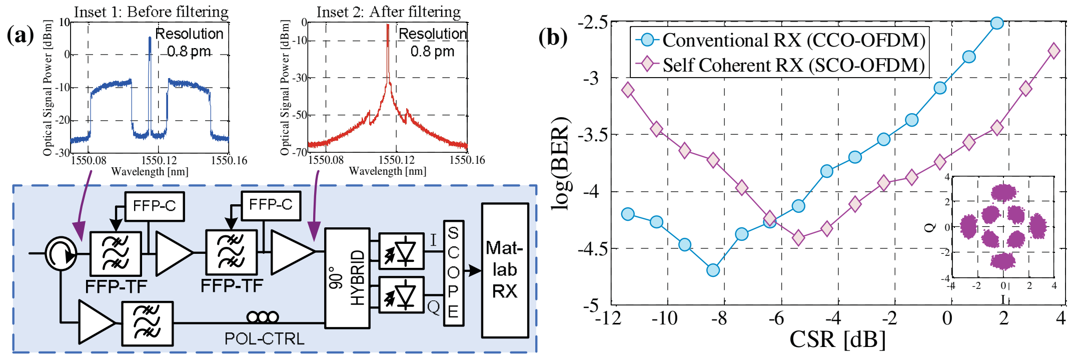

Fig. 1: (a) Schematic of self coherent optical (SCO-) OFDM system with Inset 1: optical spectrum before FFP-TF series and Inset 2: optical spectrum after FFP-TF series; FFP-TF/C: fiber Fabry-Perot-tunable filter/controller, (b) BER as a function of CSR.

In Inset 1 and 2 of Fig. 1(a), the optical spectrum of the signal before and after filtering is shown respectively. Clearly, after the second FP-TF, the OFDM signal leaking into the filtered carrier is suppressed to around 50 dB adding up to a total suppression of 35 dB (measured at a resolution of 0.8 pm). Note that the center wavelength of the FP-TF must be perfectly aligned with that of the laser. In order to cope with laser drifts, an automated feedback loop is realized to actively tune the center frequency of the FP-TF to the optical carrier using an external Fabry-Perot controller (FP-C).

A circulator is implemented to recover the reflected OFDM signal from the FP-TF. The polarization of the extracted optical carrier and optical OFDM signal are then aligned with polarization controller. Homodyne detection is realized with a 90° optical hybrid. The succeeding balanced photo detectors (BPD) convert the received optical signal to electrical in-phase (I) and quadrature-phase (Q) signals. At the receiver, after homodyne detection, the signal is sampled with a real-time oscilloscope and processed off-line. The bandwidth of the oscilloscope is 16 GHz and the sampling frequency is 50 GSamples/s.

In this paper, the performance of SCO-OFDM is compared to that of CCO-OFDM with RF-PNC scheme. For the CCO-OFDM system, an external cavity laser (ECL) with 100-kHz typical linewidth is used as LO and the OFDM signal is directly fed into the 90° hybrid.

4. EXPERIMENTAL RESULTS AND DISCUSSION

For SCO-OFDM measurements, the optical power of the filtered carrier and OFDM signal at the input of 90° hybrid is kept at 7 dBm and 0 dBm, respectively, which was found to be the optimum value. Similarly, for CCO-OFDM the optimal optical power of the LO and OFDM signal is found to be 15 dBm and 0 dBm, respectively. These values are kept constant for all the following measurements. Both in SCO-OFDM and CCO-OFDM employing RF-PNC, an optical carrier (or pilot-tone) is sent along with the OFDM signal. This optical carrier is used at the receiver for phase noise compensation. For SCO-OFDM, the optical carrier is extracted from the OFDM signal for homodyne detection. While for CCO-OFDM the optical carrier is heterodyne detected and digitally used as a pilot-tone for phase noise compensation [3]. For both modulation formats, the power of the carrier with respect to the power of the OFDM signal, called carrier-to-signal ratio (CSR), has a strong influence on the system performance. Note that, this value is referred to as pilot-to-signal power ratio (PSR) in [3]. In Fig. 1 (right), the influence of this CSR on the bit-error-rate (BER) performance is shown in a back-to-back configuration. The optical signal-to-noise ratio (OSNR) in this measurement is kept constant at 12 dB and 15 dB for CCO-OFDM and SCO-OFDM, respectively. The optimum CSR for CCO-OFDM and SCO-OFDM is located at -8.4 dB with BER at 2.0 × 10-5 and -5.4 dB with BER at 3.9 × 10-5, respectively. When the CSR is below the optimum, the optical carrier is too weak and amplified spontaneous emission (ASE) noise limits the effectiveness of phase noise compensation. For high CSR, the relative power of the OFDM signal becomes too low and hence the performance gets worse. For all the following measurements, the CSR values are set to the optimum value.

Fig. 2(a) depicts the back-to-back BER performance as a function of the OSNR. The required OSNR for a BER of 10-3 is 9.8 dB and 12.5 dB for CCO-OFDM and SCO-OFDM, respectively. The 2.7-dB difference between CCO-OFDM and SCO-OFDM is largely caused by the fact that in SCO-OFDM, the extracted optical carrier is impaired by ASE noise and is used for coherent detection. This noisy carrier leads to distortions in the real and imaginary parts of the constellation. While in conventional CO-OFDM, the pilot tone is used for digital phase noise compensation and a clean LO, that induces only phase noise, is used for coherent detection. In addition, the bandwidth of the FP-TF used in SCO-OFDM is significantly wider than the digital filter that is implemented for CCO-OFDM phase noise compensation. The wider the filter bandwidth, the more noise is

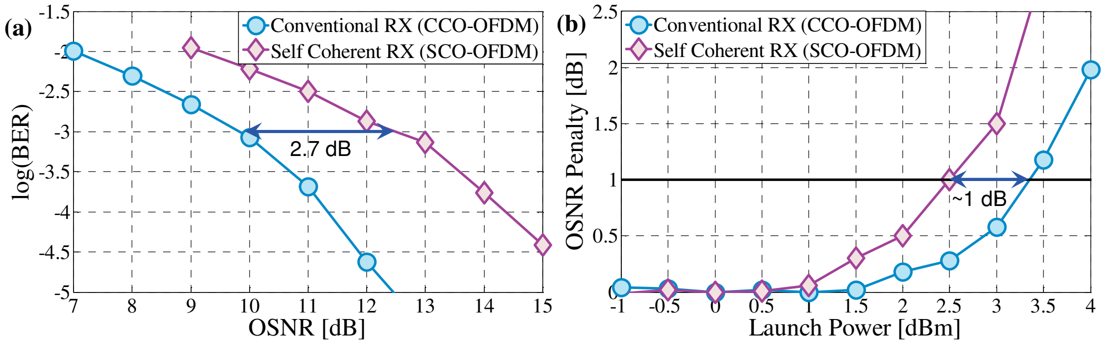

Fig. 2: (a) BER as a function of OSNR for back-to-back scenario, (b) Required OSNR penalty as a function of the launch power after 400km transmission.

added to the carrier. Subsequently, it can be inferred that with the use of lower bandwidth, the performance will get better as shown in [4]. Finally, Fig. 2(b) shows the nonlinear tolerance of CCO-OFDM and SCO-OFDM after 400-km transmission. The launch power is varied from -1 dBm to 4 dBm. The y-axis of the plot depicts the OSNR penalty for a BER of 10-3. As expected for low launch powers no OSNR penalty is present. As the launch power is increased, the nonlinearities come into play. Allowing a 1-dB penalty in required OSNR, the maximum tolerable launch power is found to be 3.4 dBm and 2.5 dBm for CCO-OFDM and SCO-OFDM, respectively.

5. CONCLUSIONS

In this paper, we have looked onto different possible ways of achieving self-coherent optical detection. We have delved in deeper into self coherent detection with IQ demultiplexing with the use of FP-TF for extracting the optical carrier. Because of its high Q-value, the bandwidth of the guardband between the carrier and OFDM signal can be relaxed. The guardband of only 1.3 GHz was used in the experiment. Compared to conventional CO-OFDM employing RF-PNC scheme, a 2.7 dB OSNR penalty is observed and a reduction of ~1 dB in nonlinear tolerance. Finally, by reducing the bandwidth of FP-TF, the performance of SCO-OFDM can be further improved.

REFERENCES

[1] S. L. Jansen, S. Adhikari, B. Inan, D. Borne, "Application scenarios for optical OFDM", SPPcom, 2010 (invited).

[2] D. Qian, M. Huang, E. Ip, Y. Huang, Y. Shao, J. Hu, T. Wang, "101.7 Tb/s (370x294-Gb/s) PDM-128QAM-OFDM Transmission over 3x55-km SSMF using Pilot-based Phase Noise Mitigation", *in Proc. OFC*, PDPB5, 2011.

[3] S. L. Jansen, I. Morita, T. C. W. Schenk, N. Takeda, H. Tanaka, "Coherent Optical 25.8-Gb/s OFDM Transmission Over 4160-km SSMF," *J. Lightwave Technol.*, vol. 26, no. 1 pp. 6–15, Jan. 2008.

[4] P. Johannisson, M. Sjodin, M. Karlsson, E. Tipsuwannakul, P. Andrekson, "Cancellation of Nonlinear Phase Distortion in Self-Homodyne Coherent Systems", *IEEE Photon. Tech. Letters,* Vol. 27, no. 11, 2010.

[5] T. Miyazaki, F. Kubota, "PSK self-homodyne detection using a pilot carrier for multibit/symbol transmission with inverse-RZ signal", *IEEE Photon. Tech. Letters,* Vol. 17, no. 6, 2005.

[6] M. Nakamura, Y. Kamio, T. Miyazaki, "Linewidth-tolerant real-time 40-Gbit/s 16-QAM self-homodyne detection using a pilot carrier and ISI supression based on electronic digital processing", *Opt. Letters*, Vol. 35, no.9, 2011.

[7] M. Sjodin, E. Agrell, P. Johannisson, G. W. Lu, P. Andrekson, M. Karlsson, "Filter Optmization for Self-Homodyne Coherent WDM Systems Using Interleaved Polarization Division Multiplexing", *J. Lightwave Technol.*, vol. 29, no. 1 pp. 6–15, Jan. 2008.

[8] H. Louchet, A. Richter, "Novel Scheme for High-Bit-Rate Coherent-OFDM Transmission without PLL", *in Proc. ECOC*, P087, 2007.

[9] L. Xu, J. Hu, D. Qian, T. Wang, "Coherent Optical OFDM Systems Using Self Optical Carrier Extraction", *in Proc. OFC*, paper OMU4, 2008.

[10] B. Schmidt, Z. Zan, L. Du, A. Lowery, "100 Gb/s Transmission using Single-Band Direct Detection Optical OFDM", *in Proc. OFC*, PDPC3,2009.

[11] S. Adhikari, S. L. Jansen, M. Alfiad, B. Inan, A. Lobato, V. A. J. M. Sleiffer, W. Rosenkranz, "Experimental Investigation of Self Coherent Optical OFDM Systems Using Fabry-Perot Filters for Carrier Extraction", in Proc ECOC, 2010.