DIGITAL SIGNAL PROCESSING TECHNIQUES FOR MULTI-CORE FIBER TRANSMISSION USING SELF-HOMODYNE DETECTION SCHEMES

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ABSTRACT

We discuss digital signal processing (DSP) techniques for self-homodyne detection (SHD), multi-core fiber (MCF) transmission links, and related technologies. We focus on exploiting the reduced phase noise of self-homodyne multi-core fiber (SH-MCF) systems to enable DSP resource savings and describe digital receiver architectures that mixes signal and local oscillator in the digital domain.

***Index Terms*—** Coherent optical communications, optical communications DSP, self-homodyne optical systems, multi-core fiber.

1. INTRODUCTION

The advancement of ultra-high speed analog to digital converters (ADCs) and the increase in density of logical resources in integrated circuits according to Moore's law, have enabled commercialization of coherent modulation formats in lightwave communication systems. ADCs are able to sample the optical waveform at frequencies of 10's of GHz which means digital signal processing (DSP) at speeds commensurate with optical line-rates may be used to both demodulate and compensate for transmission impairments [1]. Previously, such DSP techniques were successfully applied to radio and wired communication systems, where typical signal bandwidths allow much lower sampling frequencies and reduced computational requirements. Indeed, many of the DSP techniques applicable to optical communications have been previously used in radio communication; however the different nature of the transmission medium still presents new challenges.

Recently, the introduction of multi-core fiber (MCF) and space-division multiplexing (SDM) has enabled a huge increase of the available transmission bandwidth [2]. Hence, to maintain the highest possible line rates, enable potential energy savings and lower the cost per bit, it becomes attractive to investigate transmission schemes that exploit the characteristics of SDM systems to reduce the DSP requirements or compensate for high laser phase noise. One of such techniques is self-homodyne detection (SHD). In SHD, an unmodulated pilot-tone (PT) is transmitted along with the signal and used as the local oscillator (LO) at the receiver instead of using a narrow linewidth, free-running laser as in intradyne (ID) coherent detection [3].

Here, we describe the structure of an optical coherent receiver with DSP back-end before introducing SHD and its applicability to MCF based SDM systems. Next, we review a digital receiver architecture for SHD SDM systems, SHD related technologies and present an experimental study of the reduction of the carrier phase (CP) estimation rate. Finally, we summarize the main conclusions of this paper.

2. DSP FOR OPTICAL COMMUNICATIONS

The electromagnetic field travelling inside an optical fiber can be modelled as a Jones vector:

$$\begin{pmatrix} \tilde{X} \\ \tilde{Y} \end{pmatrix} = \begin{pmatrix} \tilde{A}_k e^{j\phi_x(t)} \\ \tilde{B}_k e^{j\phi_y(t)} \end{pmatrix} \tag{1}$$

where $\tilde{X}$ and $\tilde{Y}$ are the complex envelopes of the two orthogonal polarizations, $\phi_{x,y}(t)$ is the laser phase noise, and $\tilde{A}_k$ and $\tilde{B}_k$ the modulation complex numbers for each symbol k, which define a 4 dimensional space. In the frequency domain, the output of the optical fiber will be:

$$\begin{pmatrix} \tilde{X}' \\ \tilde{Y}' \end{pmatrix} = M \begin{pmatrix} \tilde{X} \\ \tilde{Y} \end{pmatrix} + N(\omega) \tag{2}$$

where $N(\omega) = [\tilde{n}_x(\omega)\, \tilde{n}_y(\omega)]^T$ is a complex Gaussian noise added by active optical components to both polarizations. Neglecting fiber nonlinearities, the transfer function M of a small section of an optical fiber can be modeled as [4, 5]:

$$M = \alpha e^{-j\frac{\beta_2}{2}L\omega^2} \prod_{i=1}^{S} K_i\, U_i \tag{3}$$

where:

$$K_i = \begin{pmatrix} 1 & 0 \\ 0 & k_i \end{pmatrix} \tag{4}$$

$$U_i = \begin{pmatrix} e^{j(\phi_i+\omega\tau_i)/2} & 0 \\ 0 & e^{-j(\phi_i+\omega\tau_i)/2} \end{pmatrix} \begin{pmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{pmatrix} \tag{5}$$

where α is the attenuation coefficient, β_2 is the group velocity dispersion parameter of the fiber, L is the length of the fiber, $k_i \in (0,1)$ accounts for the polarization dependent loss (PDL), τ_i is the differential group delay (DGD) between polarizations, and ϕ_i and θ_i define the rotation of the state of polarization (SOP). A general fiber model will consist of a concatenation of many sections $K_i U_i$ where the parameters change randomly, but letting $S = 1$ in (3), a one-section model is adequate for the first-order, instantaneous values of the parameters [4].

A polarization and phase-diverse coherent optical receiver, such as the one depicted in Figure 1(a), consists of an opto-electric front-end that linearly maps the optical field into a sequence of samples, followed by a DSP back-end. The opto-electronic front-end consists of a free-running laser acting as LO, two optical hybrids, 4 balanced photodiodes, and 4 analog to digital converters (ADCs) [1].

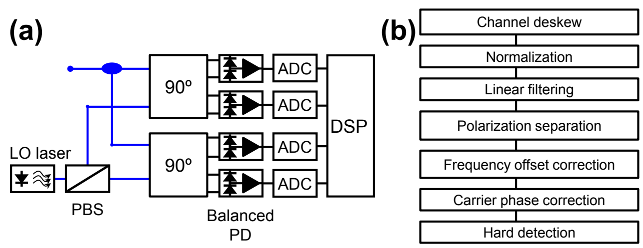

Fig. 1: (A) Components of a polarization-diverse ID coherent optical receiver. (B) Diagram of the subsystems of a typical DSP architecture for coherent optical communication systems.

The samples of the detected signal can be represented as:

$$\tilde{X}_I = \Re\mathfrak{e}\{\tilde{X}'\tilde{E}_{lo}^*\} = \Re\mathfrak{e}\{\tilde{A}'_k[n]e^{-j\omega_{off}n+j\phi'_x[n]} + \tilde{n}_x[n]\} \quad (6)$$

$$\tilde{X}_Q = \Im\mathfrak{m}\{\tilde{X}'\tilde{E}_{lo}^*\} = \Im\mathfrak{m}\{\tilde{A}'_k[n]e^{-j\omega_{off}n+j\phi'_x[n]} + \tilde{n}_x[n]\} \quad (7)$$

$$\tilde{Y}_I = \Re\mathfrak{e}\{\tilde{Y}'\tilde{E}_{lo}^*\} = \Re\mathfrak{e}\{\tilde{B}'_k[n]e^{-j\omega_{off}n+j\phi'_y[n]} + \tilde{n}_y[n]\} \quad (8)$$

$$\tilde{Y}_Q = \Im\mathfrak{m}\{\tilde{Y}'\tilde{E}_{lo}^*\} = \Im\mathfrak{m}\{\tilde{B}'_k[n]e^{-j\omega_{off}n+j\phi'_y[n]} + \tilde{n}_y[n]\} \quad (9)$$

where $\tilde{X}'$ and $\tilde{Y}'$are the impaired signal components, ω_{off} is the frequency offset between the transmitter laser and the LO, and $\phi'_{x,y}(n)$ accounts for the phase noise, which is the added contribution of the transmitter and receiver phase noises. Consequently, the main impairments that must be compensated at the receiver DSP are dispersion, SOP rotation, DGD and PDL, ω_{off} and phase noise.

A general implementation of the DSP back-end consists of the following stages [1], as shown in Figure 1(b). Firstly, deskew corrects for the temporal delay offsets that arise from imperfections in the opto-electric front-end. Next, a normalization stage ensures the signal quadrature components have zero DC offset and that the amplitude is constant whatever the optical input power, within the receiver's dynamic range. The linear filtering compensates for chromatic dispersion and other *a-priori* known linear effects. After that, the polarization components are separated with a 2x2 multiple-input-multiple-output (MIMO) equalizer, usually updated via the least-mean squares (LMS) algorithm. To compute the error term of the equalizer during convergence, the constant modulus algorithm (CMA) or the radially directed equalizer (RDE) algorithm may be used for M-phase-shift keyed (PSK) or M-quadrature amplitude modulation (QAM) signals, respectively. Once the equalizer has converged, the error can be computed using the output of the hard-decision. Notably, the MIMO equalizer not only compensates for rotations of the SOP, but also DGD and PDL [6]. After equalization, the ω_{off} between the transmitter and the LO lasers is estimated and compensated for. Finally, the CP is estimated and the constellation aligned before hard-detection.

3. SELF-HOMODYNE SYSTEMS AND MULTI-CORE FIBER

The previous section introduced ID coherent optical receivers where the LO is a free-running laser. However, in SHD systems the transmitted PT used as LO is tapped from the light source before the optical modulator. Hence, SHD leads to cancellation of laser phase noise allowing the use of low-cost, broad linewidth transmission lasers. Also, tolerance to fiber nonlinearities may be increased [7]. In terms of DSP, the detected samples have null ω_{off} so this DSP stage is unnecessary for SHD receivers. The disadvantages of SHD are the loss of some spectral efficiency due to the need to allocate transmission capacity for the PT. Also, since phase noise cancellation may be degraded if the PT and signal path lengths are not well matched, path length alignment may be required as well as tracking of the SOP of the LO before the optical hybrid.

SHD techniques for optical systems have been extensively researched. In the early implementations, the information carrying signal was polarization-multiplexed with the carrier, as shown in Figure 2(a). This scheme showed tolerance to both phase noise [3] and fiber nonlinearities [7], at a cost of 50% spectral efficiency (SE). To partially compensate for the loss of spectral efficiency, interleaving techniques can be used, reducing the loss of spectral efficiency to only 33% [8].

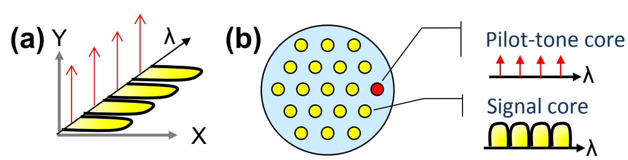

Fig. 2: Signal and PT transmission schemes: (a) polarization-division-multiplexing and (b) space-division-multiplexed.

With the introduction of multi-core fibers, the availability of multiple spatial channels allows transmitting the PT in a dedicated core, using the remaining cores for data-bearing signals, as shown in Figure 2(b). This yields a SE loss inversely proportional to the number of cores. For example for a 19-core fiber the SE will be reduced by 5.3% compared to an equivalent ID system using all cores for data signals [9].

3.1. Digital self-homodyne receiver

Early polarization-multiplexing based SHD experiments required accurate tracking of the SOP for correct de-multiplexing of the signal and LO before the single-polarization optical hybrid. In this section, we describe and experimentally validate a novel approach, named digital self-homodyne reception, which combines ID detection in a polarization-diverse optical hybrid to realize polarization tracking and phase noise cancellation in the DSP domain [10].

The digital self-homodyne receiver works as follows: consider a polarization-multiplexed PT signal detected in a polarization-diversity ID receiver, assuming the signal and PT components aligned with the X and Y polarizations of the receiver, respectively. The detected complex currents for the X and Y polarizations are proportional to $r_x = e_s \cdot e_{lo}*$ and $r_y = e_{pt} \cdot e_{lo}*$, with e_s , e_{lo} and e_{pt} as the complex envelopes of the signal, LO and PT, respectively, and * denoting complex conjugate. The data signal component, r, may be recovered by taking:

$$r = r_x \cdot r_y* = e_s \cdot e_{pt}* \cdot |e_{lo}|^2 \tag{10}$$

The first and second terms on the right-hand side of (10) correspond to the signal with phase noise cancellation by the PT. The third term is the LO power, which is assumed constant. The mixing operation may be performed in the electrical domain, with analog mixers at the output of the balanced photo-detectors, or via DSP, such as the receiver considered in this section. If the signal and PT components are misaligned with the X and Y polarizations of the receiver, we may assume that this alignment can be achieved via DSP.

Figure 3 shows the experimental setup for a demonstration of such a receiver. Transmission was performed using a 530 kHz linewidth ECL or a 2.8 MHz linewidth DFB. The generated lightwave was followed by a polarization controller (PC) and a prototype PT vector modulator (PTVM) [11]. In the latter, the transverse magnetic (TM) and transverse electric (TE) components of the input field were split by a polarization beam splitter (PBS) at the input. The TM component was modulated by an embedded IQ modulator and recombined with the TE component by a polarization beam combiner (PBC) to generate the polarization-multiplexed pilot tone signal. Adjusting the PC at the PTVM input controlled the ratio between the powers of the PT and signal components, which was kept at 1 for SHD and suppressing the PT to generate single polarization signals with ID.

Figure 4 shows the back-to-back dependence of the BER on the OSNR with QPSK and 16QAM signals, using ECL or DFB lasers for transmission and also as the LO for ID measurements. For QPSK when using ECL lasers, we obtained approximately 5 dB penalty for digital self-homodyne detection with respect to intradyne detection for a bit-error rate (BER) of 10^{-4}, in agreement with results from previous related experiments [12]. This penalty may be partially attributed to the pilot tone contribution to the total signal power, which amounts to 3 dB. The remaining penalty may be attributed to the limited filtering of the PT [8, 13] as well as limitations of the polarization alignment algorithm. When using DFB lasers, we were unable to obtain a valid signal

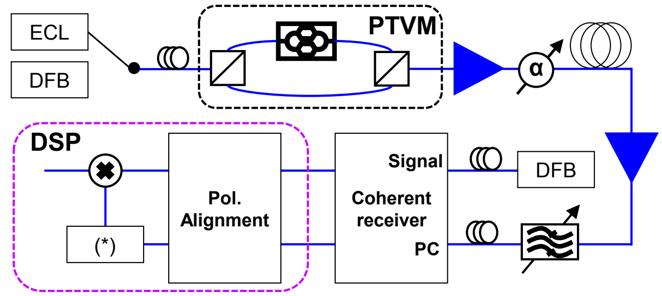

Fig. 3: Experimental setup and diagram of the digital self-homodyne receiver.

with intradyne detection. Nonetheless, SHD yielded a penalty of less than 0.4 dB with respect to the ECL case. Similarly, Figure 4(b) shows the back-to-back dependence of the BER on the OSNR with 16QAM signals and ECL lasers. With this modulation format, self-homodyne detection yielded a 6.1dB penalty with respect to ID. The limitations of the polarization alignment algorithm become particularly significant in this case. In fact, we were unable to obtain a valid signal with self-homodyne detection and DFB lasers. However, increasing the PT power to a ratio 2 allowed recovering the original signal albeit with significant distortion.

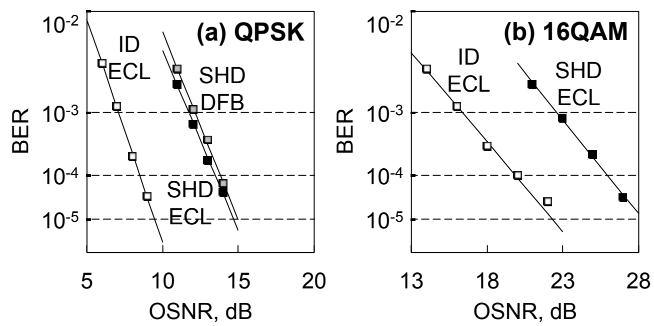

Fig. 4: Back-to-back performance using ID and SHD with (a) QPSK and ECLs or DFBs for transmission and LO and (b) 16QAM with ECLs for transmission and LO.

3.2. Self-homodyne related schemes

In this subsection, we review several techniques that, not being strictly SHD, share some of its benefits like phase noise cancellation.

The first such technique is named Spatial Super-channels (SSC) [14]. SSC exploits the fact that the several cores of a multi-core fiber will have the same amount of certain impairments, referred as common-mode impairments. One transmitter laser is split and shared among all channels, and at the receiver, again one LO is split and shared for all receivers, as shown in Figure 5. In [14], negligible penalty was demonstrated when using core-joint DSP with one “master channel” polarization X on core 1 to correct for the phase of polarizations X/Y on cores 1 and 2. This relates to SHD in the sense that the core to core signal coherence of SHD in MCF fibers can also be exploited to realize core-joint DSP and thus reduce the total cost per bit compared to

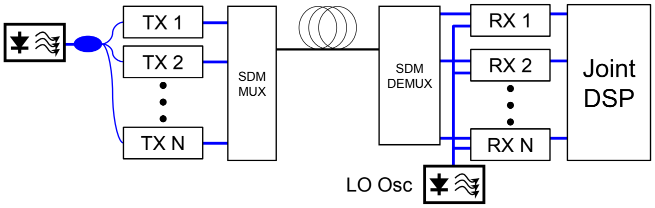

Fig. 5: Diagram of the experimental setup for a SSC in an MFC.

an equivalent single-mode fiber (SMF) or ribbon-fiber transmission system.

Another scheme that enables core-joint DSP for ω_{off} and CP is the Shared Carrier Receiver (SCR) [12], depicted in Figure 6. SCR systems share the transmitter laser among all the cores and additionally transmit this PT in a dedicated core. At the receiver, the PT signal is received with an intradyne coherent receiver and the frequency offset and phase digitally extracted. These estimated values are then used to simplify the required DSP for all the information bearing cores which share the same transmitter laser, at a cost of a SE reduction inversely proportional to the number of cores.

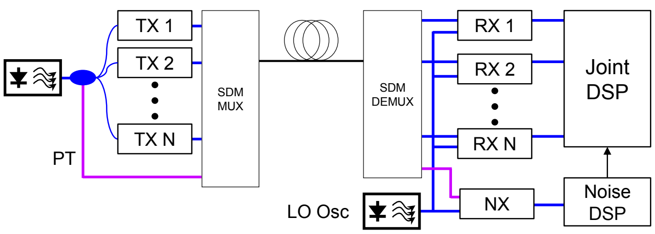

Fig. 6: Diagram of the shared-carrier receiver scheme.

Finally, a technique named Digital Coherence Enhancement (DCE) enables the use of high-linewidth lasers as LOs [15, 16] by estimation of the laser phase noise using an extra optical hybrid and balanced photodiodes. Although it has been demonstrated only for high-linewidth, locally generated LO lasers, it can be applied to multi-core fiber transmission with core-joint DSP where this LO can be transmitted in a dedicated core as described.

4. REDUCED CARRIER PHASE ESTIMATION RATE FOR SELF-HOMODYNE SYSTEMS

In a self-homodyne system where the signal and PT's optical paths lengths are properly aligned, cancellation of phase noise allows for a relaxed rate at which the CP should be estimated. In this section, we experimentally verify that the reduction of the CP can be decreased by several orders of magnitude [17].

Figure 7 shows the experimental setup for single-polarization QPSK, 25 Gbaud, SHCD MCF transmission. The transmitter consisted of 125 DFB rack-mounted lasers with frequencies between 189.5 and 195.7 THz on the 50 GHz ITU-T grid. The average linewidth was found to be 3.8 MHz. After polarization control and attenuation, the lightwaves were combined in arrayed waveguide gratings (AWGs) and coupled together. These carriers were then split in a 2x2 splitter with one output port used for signal modulation and the other for the PT path. The remaining input port of the splitter was used for injecting a phase-modulated signal for path-length alignment. The carriers in the signal path were deinterleaved (Int) and two MZM IQ modulators were used for decorrelated odd/even channels. After modulation, odd and even channels were combined and amplified, and then split again to be injected into the MCF with a free-space coupling. The MCF was a trench-assisted homogeneous 19-core fiber with average loss and dispersion of 0.23 dB/km and 19.5 ps/nm/km, respectively. Crosstalk ranged from 23 dB for the center core to 27 dB for the core carrying the PT, and the fiber length was 10.1 km [2].

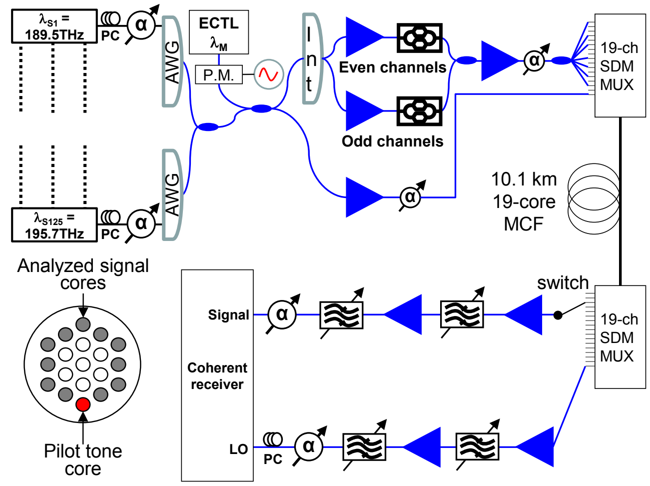

Fig. 7: Experimental setup for the transmission study of SHD, single-polarization signals over a 19-core fiber.

Using the experimental setup of Figure 7, 3 traces, each containing 2 MSample, were acquired for each of the 11 outermost cores and each of the 125 wavelength channels per core. Only the outermost cores were processed in order to equalize the impact of inter-core crosstalk. These traces were processed with an offline digital processor (DP) as described in section 2 and implemented in MATLAB for easy prototyping. In order to remove the impact of the parameter estimation rate of the normalization, CD compensation and CMA equalization stages, estimation updates for these blocks were performed on a block-by-block basis. The Viterbi & Viterbi (V&V) algorithm was used for the CP recovery stage, and the unwrapped CP estimation buffer was updated only once every N blocks. Consequently, the same estimated CP angle is used for N consecutive blocks. Figure 8 shows the averaged BER as a function of N (the number of skipped blocks) for V&V estimation block sizes of 32, 64, and 128 samples for both SHD and ID detection. The ID measurements used the same experimental set-up, but bypassing the MCF for the LO to decorrelate it from the signal to replicate an ID system with an equivalent linewidth. For SHD, Figure 8 shows that for low values of N (high CP estimation update rates), longer estimation sequences perform better, because V&V estimator is able to remove more noise. As the estimation update rate decreases (larger N), the performance degrades more rapidly for longer estimators. This is due to the fact that a longer estimator is less able to track the phase changes caused by residual linewidth and thus the probability of cycle slips increases. However, up to a value of N = 10^3, the BER penalty is less than 2×10^{-6} for all the three estimation block sizes considered. In the ID case, Figure 8 reveals a rapid BER degradation due to phase-noise induced cycle slips, due to the presence of uncompensated laser phase noise.

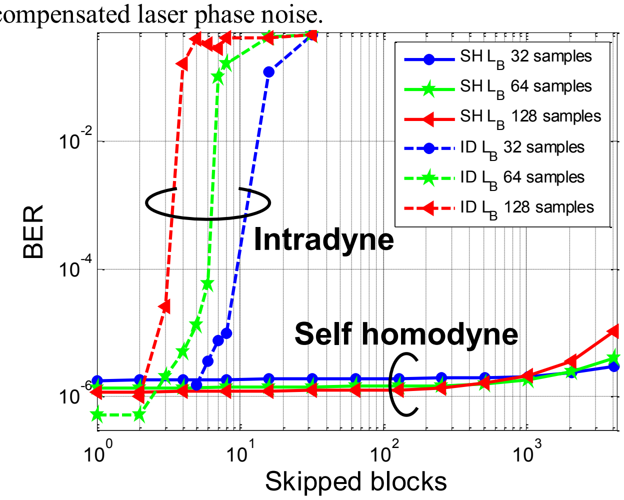

Fig. 8: Experimental results of the carrier phase reduction rate for MCF self-homodyne systems.

5. SUMMARY

We have reviewed intradyne and self-homodyne coherent optical receivers and described the principal stages of DSP required to receive both. We also described potential savings of DSP resources from adopting self-homodyne detection and/or joint DSP techniques and we reported the benefits of a digital self-homodyne receiver using both a transmitted polarization-multiplexed pilot-tone and intradyne coherent receiver. Finally, we described experimental measurements of reduced carrier phase reduction rate when using self-homodyne detection in multi-core fibers.

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