Recent Advances in Carrier Phase Recovery Algorithms

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Abstract: We review the most recent advances in carrier phase estimation algorithms for coherent optical communications, with special emphasis on multi-carrier modulation systems and on the interplay between linear and nonlinear phase noise sources.

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1. Introduction

It is nowadays unanimously accepted that the commercial success of coherent optical transceivers has been largely enabled by the staggering advances in digital signal processing (DSP) registered during the last decade [1]. Notably, the carrier recovery subsystem has been one of the main hurdles posed by early analog coherent optical systems [2], which has been efficiently solved by DSP in modern digital coherent transceivers.

In this paper, we review the progress that has been recently made on carrier phase recovery algorithms for coherent optical communications, starting from their evolution in single-carrier systems, to the more recent applications in multi-carrier modulation and their exploitation for nonlinear phase noise mitigation.

2. A Revision of Impactful CPR Algorithms for Single-Carrier Systems

It is worth noting that the first carrier phase recovery (CPR) approaches applied to coherent optical communications have been deeply inspired by existent CPR solutions that find wide applicability in many radio-frequency systems, which is a natural consequence of the more mature development of these systems. This has been the case for the well-known Viterbi-Viterbi CPR algorithm [3], which has clearly dominated as the leading CPR algorithm for the first generation of QPSK-modulated coherent optical systems. However, soon thereafter, coherent optical communications have registered extremely fast progress on spectral efficiency needs, leading to the use of more advanced CPR algorithms [4], [5], compatible with high-order modulation formats.

This has set the turning point on CPR-related research, leading to a clear departure from its legacy RF heritage, and consequently to the development of novel CPR algorithms, now tailored to the specificities of the optical transmitter, channel and receiver. In that regard, one of the key newly-developed CPR methods that has found notable success and wide commercial deployment is the blind phase search (BPS) algorithm, originally proposed by T. Pfau *et al.* [6] in what remains today as one of the most highly-cited papers in this research field. Arguably, the success of the BPS algorithm can be attributed to its modulation format generality allied with an algorithmic simplicity and efficient hardware implementation, which has led many coherent transceiver manufacturers to include this algorithm into their DSP stack.

However, when applied as a standalone CPR algorithm, BPS may lead to excessive computational effort, due to the need to cover a very wide angular range. This has led to the advent of a plethora of dual-stage CPR methodologies, typically combining a first-stage low-complexity coarse phase estimation with a second-stage fine-tuned CPR, which is aimed to correct for the residual phase noise left behind in the first stage [7], [8].

Note that the aforementioned algorithms are ideally meant to operate in a fully blind manner, i.e. without any a priori knowledge of the transmitted signal. However, this leads to a phase ambiguity at the CPR output, where the estimated carrier phase cannot be unequivocally associated with a quadrant in the IQ plane. In order to avoid this phase ambiguity issue, a set of pilot symbols should be regularly placed within the signal frame, serving as an absolute phase reference. This has led to the wide adoption of pilot-based CPR [9], [10], typically operating as a first-stage phase estimation

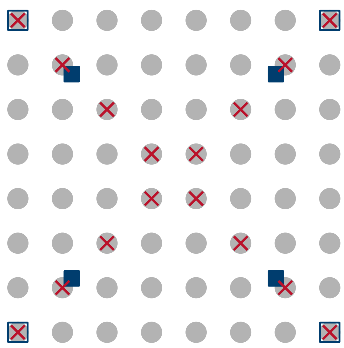

Fig. 1: Illustration of different allocation strategies for pilot symbols over 64QAM. □: pilots placed at the outer QAM symbols; ■: pilots placed at the average QAM energy; ×: pilots with QAM amplitude modulation.

subsystem [11], simultaneously enabling an initial low-complexity coarse phase estimation and an absolute phase reference for angular and timing synchronization.

The main drawback of pilot-based CPR lies in an additional overhead reserved for CPR pilots, which effectively reduces the achievable information rate (AIR) [12]. To partially circumvent this limitation, a modified pilot-based CPR has been proposed in [13], where only the phase component of the pilot symbols is pre-conditioned, while their amplitude component can still be modulated, thus reducing the AIR loss. An illustration of the different pilot-based CPR strategies is provided in Fig. 1, considering the example of a 64QAM constellation template.

3. Advanced CPR Algorithms for Multi-Carrier Systems

Following a thriving development phase that led to the invention of a large variety of CPR algorithms for single-carrier coherent optical systems, the research initiatives in this field have been recently slowing down, mainly owing to two key factors: i) the wide availability of cost-effective low-linewidth lasers and ii) the ever-increasing baudrates (already surpassing 100 Gbaud) that facilitate the carrier recovery task. Under such circumstances, the main technical issue that is currently being actively addressed by the research community is associated with the impact of equalization-enhanced phase noise (EEPN), which results from the interplay between the distributed phase noise (Tx and Rx) and the chromatic dispersion (and mitigation) effect [14].

Consequently, the research efforts on CPR have been progressively shifting towards multi-carrier transmission systems, where the use of multiple low-baudrate subcarriers severely limits the performance of traditional CPR approaches originally designed for single-carrier systems. Due to the lower baudrate of each of the contributor subcarriers, we are again posed with the challenge that legacy single-carrier systems initially had, even if equipped with low-linewidth lasers. Typically, this problem is tackled by employing joint CPR [15]–[17], which enables to increase the effective baudrate of the CPR subsystem. In Fig. 2, we display a simplified diagram of the difference between per subcarrier CPR, Fig. 2.a, and joint CPR, Fig. 2.b. While in the former we achieve a phase noise estimate for each of the N subcarriers, the latter yields a single phase estimate, which is usually obtained from the averaging of each of the individual estimates. However, this joint approach to CPR demands that all subcarriers experience the same distributed phase noise, which is a condition that may not always hold true, namely when the signal is transmitted over a dispersive channel, causing a walk-off between different subcarriers. To maximize the performance of joint CPR under such conditions, a chromatic dispersion-aware CPR for multi-carrier systems has been recently proposed in [16], [17], which relies on a differential phase noise estimate between a pair of reference subcarriers, thereby enabling to distinguish between transmitter and receiver phase noise contributions.

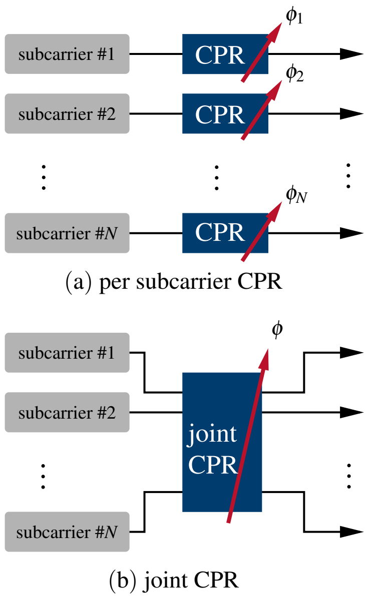

Fig. 2: Diagram of independent (per subcarrier) vs. joint CPR in multi-carrier systems.

4. Open Issues and Current Research Challenges

Despite the remarkable progress that has been made in this area, there are still several open issues and challenges that deserve the attention of our research community in the near future. A prominent practical challenge is related to the expected evolution of the scope of coherent optical communications, progressively moving from point-to-point to point-to-multipoint applications [18]. In such scenarios, a major upcoming challenge is associated with the improvement of joint CPR architectures in low-baudrate multi-carrier systems where not all contributors are impacted by the same distributed laser phase noise. On a different direction, and despite the significant research efforts that have been recently made, it still remains unclear what are the ultimate limits of CPR performance in long-haul systems impaired by fiber nonlinearities. In particular, it has been shown that the CPR subsystem is able to at least partially compensate for the nonlinear phase noise (NLPN) effect [19]–[22], provided that sufficient temporal resolution is available. However, when applied with multi-carrier modulation at low baudrate per subcarrier, the practical NLPN mitigation capabilities that have been recently reported are still well behind the upper performance bound of NLPN-free systems [21], [22]. Therefore, the development of nonlinearity-aware low-complexity CPR solutions still remains an open research topic. On the same line, there is also an active ongoing discussion on whether the dependence of nonlinear interference noise on the geometric and/or probabilistic shaping of the transmitted signal [23] can actually be partially or even fully avoided by the optimization of the CPR subsystem [24].

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