Superchannel CPE with Wyner-Ziv Cooperation for Band-Limited Interconnects in Multi-DSP Receiver

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Abstract

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Introduction

The demand of Tb/s-class high-speed data rates in optical communications has necessitated high-throughput technologies, such as superchannel transmissions[1–10], where parallel subcarrier transmitters send independent data with different wavelengths to increase total throughput without expanding baud-rates per subcarrier. A number of superchannel receiving algorithms have been proposed in literature; e.g., joint-channel carrier phase estimation (CPE)[2], multi-input multi-output (MIMO) equalization[3], Han–Kobayashi/dirty-paper coding[10], and multi-channel digital backpropagation[4]. Such joint-channel processing showed a significant advantage in mitigating both linear and nonlinear inter-channel cross-talk, compared to conventional per-channel digital signal processing (DSP).

However, the joint-channel DSP requires a significant amount of data exchange among neighboring subcarrier receivers. When the superchannel receiver is configured by parallel discrete-chip subcarriers, sharing subcarrier data for joint-channel DSP will be challenging. In this paper, we consider practical scenarios having bandwidth-constrained inter-chip communications for partial cooperation. To exploit the band-limited interconnects, we propose to use Wyner–Ziv (WZ) cooperation approach[11–15] for joint-channel CPE. The proposed method makes use of correlated phase estimates at parallel subcarrier receivers as side information to improve the estimation accuracy. The WZ cooperation can efficiently decrease the required amount of data transfers by 90% by utilizing the underlying correlation, achieving an increase of 0.16 b/s/Hz spectral efficiency (SE) and 0.25 dB gain.

Wyner–Ziv cooperative CPE

Fig. 1 illustrates a schematic of the superchannel receiver under consideration. The superchannel receiver is implemented with N parallel subcarrier receiver chips, each of which consists of optical-to-electrical front-end (including polarization diversity and analog-to-digital converter) and standard DSP blocks (including dispersion compensation, CPE, polarization recovery, etc.). Because the DSP blocks are implemented in discrete chips, the usual MIMO processing across subcarrier receivers is difficult to realize unless high-speed interconnects are established among DSP chips. In this paper, we consider narrow-band inter-chip connections to improve CPE accuracy by utilizing phase noise correlation.

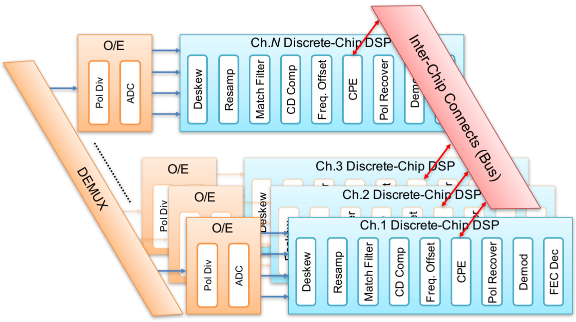

Fig. 1: Superchannel receiver using multiple discrete DSP chips and band-limited interconnects for cooperative MIMO processing.

The phase noise may come from various physical/hardware impairments including fiber nonlinearity as well as laser linewidth. Our experimental measurements[2] indicated that the phase noise at different subcarriers can be mutually correlated, which can be exploited by a joint-channel CPE to improve estimation accuracy. Based on the measurement results, we assume a multivariate Wiener process to model the correlated phase noise at multiple subcarriers as follows:

$$\Delta\boldsymbol{\theta}_k \triangleq \boldsymbol{\theta}_k - \boldsymbol{\theta}_{k-1} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{R}_{\mathrm{ch}}), \qquad (1)$$

$$\boldsymbol{R}_{\mathrm{ch}} = \sigma_{\mathrm{p}}^2\big((1-\rho)\boldsymbol{I}_N + \rho\mathbf{1}_N\mathbf{1}_N^{\mathrm{T}}\big), \qquad (2)$$

where $\boldsymbol{\theta}_k = [\theta_{k,1}, \ldots, \theta_{k,N}]^{\mathrm{T}} \in \mathbb{R}^N$ denotes the N-channel phase vector at symbol index k, $\mathcal{N}(\cdot,\cdot)$ denotes the Gaussian distribution, $\boldsymbol{R}_{\mathrm{ch}} \in \mathbb{R}^{N\times N}$ is the channel covariance matrix, ρ is a correla-

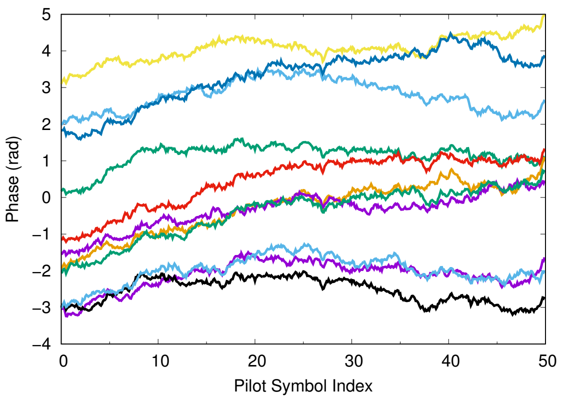

Fig. 2: Example of carrier phase changes for 11 superchannels ($\Delta\nu = 1$MHz, $\rho = 0.6$, 32GBd, 1% pilot).

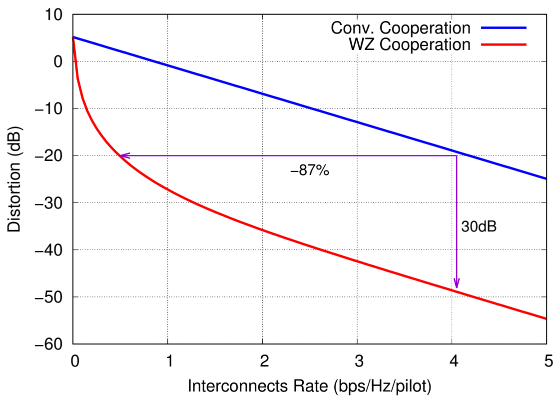

Fig. 3: Distortion of WZ-coded data representation as a function of interconnect bandwidth.

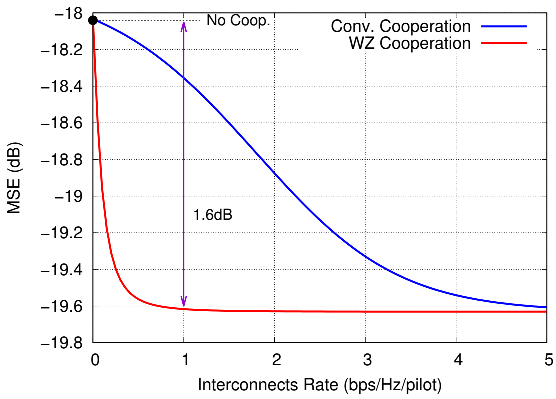

Fig. 4: MSE of cooperative CPE as a function of interconnect bandwidth.

tion factor, $\boldsymbol{I}_N$ is a size-N identity matrix, and $\mathbf{1}_N$ is a size-N all-ones vector. The phase noise variance is assumed to have its effective linewidth $\Delta\nu$ as follows: $\sigma_{\mathrm{p}}^2 = 2\pi\Delta\nu T_{\mathrm{s}}$ for a baud rate of $1/T_{\mathrm{s}}$. Fig. 2 depicts a realization example of 11-channel phase evolution sampled at pilot symbols (1% insertion) for a correlation factor of $\rho = 0.6$ and an effective linewidth of $\Delta\nu = 1$MHz at a baud rate of 32GHz. We can observe that the phase at different subcarriers behaves similarly, that can be useful for phase estimation. We use Gaussian process (GP) interpolation based on distributed pilots across both subcarriers and time dimensions, by introducing an analogous joint-channel CPE technique[2].

In order to share initially estimated phase values at pilot symbols with all subcarrier receivers over band-limited interconnects, we introduce the WZ cooperation[11–15], which has been widely used for distributed sensor networks and video streaming. Because estimated phases are mutually correlated, the conditional entropy of unknown phase values at different subcarriers can be small, indicating the possibility of more efficient representation with a smaller amount of data according to the WZ coding[11]. For correlated Gaussian signals, the rate-distortion function of $R = \frac{1}{2}\log_2^+(((\sigma_{\mathrm{p}}^2+\sigma_{\mathrm{e}}^2)^2 - \rho^2\sigma_{\mathrm{p}}^2)/D(\sigma_{\mathrm{p}}^2+\sigma_{\mathrm{e}}^2))$ is achievable with WZ codes, where σ_{e}^2 and D denote estimation error and distortion, respectively.

Performance results

Here, we evaluate the benefit of the WZ-based cooperative CPE for superchannel receivers. Fig. 3 shows the achievable distortion as a function of bandwidth of inter-chip connections. We consider 11-channel 32GBd dual-polarization 64-ary quadrature-amplitude modulation (DP-64QAM) at a signal-to-noise ratio (SNR) of 10 dB for an effective linewidth of 1MHz and a correlation of 0.9, with 1% pilot insertion ratio. For comparison, uniform quantization to represent estimated phase values is taken place as a conventional cooperation to share the estimates. It is observed that the WZ cooperation can significantly reduce the distortion of data representation for the whole range of interconnect bandwidth, in comparison to the conventional data sharing.

Fig. 4 shows the mean-square error (MSE) of the phase noise estimation for the cooperative CPE method given distorted side information as a function of interconnect data rates. We can see that about 1.6 dB MSE reduction is achieved by the cooperative CPE using side information gathered from the other subcarrier receivers. More importantly, the WZ cooperation requires much lower data rates for interconnects than the conventional cooperation does.

In Fig. 5, we show how much the improved MSE can contribute to the improvement of the achievable SE in terms of generalized mutual information (GMI) for DP-64QAM transmission after the cooperative CPE, as a function of interconnects bandwidth. It was verified that the accurate CPE algorithm with the WZ cooperation can improve the GMI by greater than 0.1 b/s/Hz even

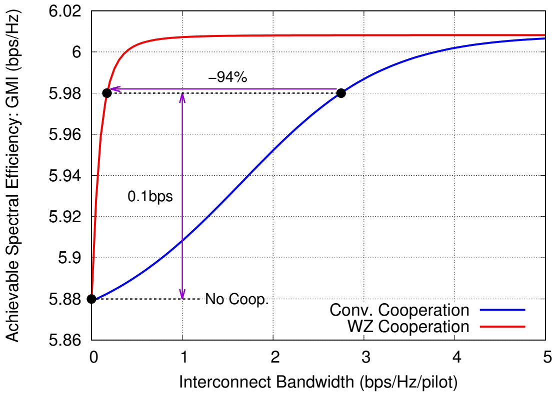

Fig. 5: GMI of DP-64QAM transmission with cooperative CPE as a function of interconnect bandwidth.

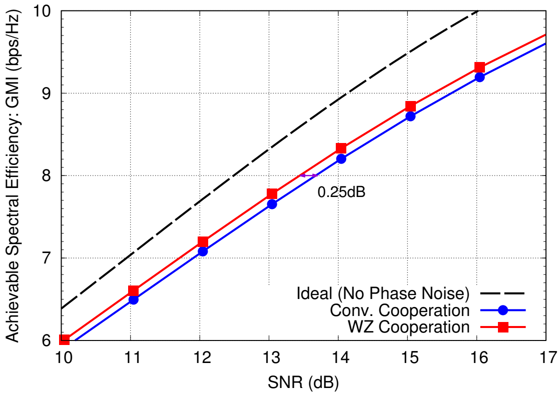

Fig. 6: GMI vs. SNR with cooperative CPE for an interconnect rate of 1 b/s/Hz/pilot.

at a narrow bandwidth below 0.5 b/s/Hz/pilot. To achieve 0.1 b/s/Hz gain over the non-cooperative CPE (i.e., zero interconnects bandwidth), the WZ cooperation can reduce the required bandwidth by 94% compared to the conventional method. When we plot the achievable SE versus channel SNR in Fig. 6, we can find that the 0.1 b/s/Hz GMI improvement in turn corresponds to a maximum of 0.25 dB SNR gain.

Conclusions

We considered bandwidth-constrained interconnects among multiple discrete subcarrier DSP chips for cooperative CPE. It was verified that the WZ cooperation can significantly decrease the required data rates for interconnects. More than 1 dB MSE gain was achieved by the WZ-cooperation CPE. Correspondingly, the achievable SE can be improved by 0.16 b/s/Hz and the required SNR is reduced by 0.25 dB. The proposed concept is potentially useful for various joint-carrier processing of the next-generation superchannel receivers having a massively large number of subcarrier DSPs to realize ultra high-speed optical communications.

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