Efficient Echo-Cancellation Algorithms for Full Duplex Coherent Optical Systems

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Abstract: A digital echo-cancellation method to identify and mitigate reflection impairments in full duplex coherent optical links is proposed. More-than 6 dB improvements in echo power tolerance are experimentally verified in a 32-GBd full-duplex DP-QPSK link.

1. Introduction

To support the continuously growing demands on higher communication speed and better quality of service, coherent optical technology [1], widely used in long haul and metro as well as data center interconnections, is migrating closer to access networks [2]. Coherent detection for access networks enables the superior receiver sensitivity that allows for extended power budget and efficiently utilizing the spectral resource, which benefits future network upgrades. To reduce the power consumption and thereby meet the size and cost requirements for access applications, the optical industry is investing a lot on the developments of low-complexity and cost-effective application-specific integrated circuits (ASIC) and photonic systems. Besides these efforts, there is also a growing need for bidirectional transmission over a single fiber in most existing operators' optical infrastructures to support single-fiber topologies, keep the cost down, and facilitate the redundancy for protecting optical links. These needs stimulate the study of full duplex coherent optics [3] that not only doubles the capacity of fiber in access networks but also reduces the requirements in the number of ports for bi-directionally operated devices. Due to higher receiver sensitivity, coherent systems are more tolerable to a small amount of reflections and backscattering, but this condition can be assumed only in healthy optical distribution networks with angle-polished connectors (APC). In other cases, strong reflections may occur in damaged fiber connections, aged devices, free space optics-based wavelength selective switches [4], or optical circulators under low-temperature operations. The influence becomes stronger when the back reflections take place where the received signals are relatively weak, such as the input/output ports of the transceivers. Having an approach that mitigates optical reflections will be of great importance to extend the use case scenarios and relax the link requirements for full duplex coherent optics.

Echo cancellation (EC) has already been adopted by full duplex data over cable service interface specifications (DOCSIS®) technology [5], which is proved to be effective to eliminate the interference between the downlink (DL) and uplink (UL). However, the phase randomness and multi-dimension nature of coherent optics may lead to higher complexities. The coherent optical signals suffer from stronger phase noise, carrier frequency offsets, and polarization rotations. Thus, optical reflections are in a chaotic state additive to the main signal, decreasing the signal-to-interference-plus-noise ratio. It is more challenging to separate echo from the coherent optical signals. Moreover, coherent signal recovery is usually blind without training or pilot signals, which further complicates the estimation of the echo signals. In this work, a set of digital-signal-processing (DSP) techniques is proposed to mitigate the echo interference in the full duplex coherent optical systems. The method could extract the echo from the received data after a coarse signal recovery. Then, based on the estimated channel-status and phase information, echo signal is reconstructed and subtracted from the interfered signals. In the simulations and experiments of a 32-GBd dual-polarization quadrature-phase-shift-keying (DP-QPSK) system, the EVM floor is improved from around 30% to less-than 15% with a more-than 6-dB gain in tolerance towards the power of echo.

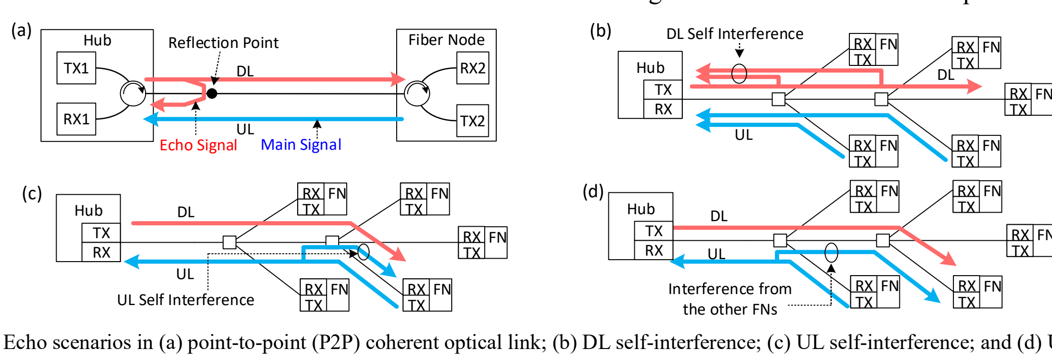

Fig. 1. Echo scenarios in (a) point-to-point (P2P) coherent optical link; (b) DL self-interference; (c) UL self-interference; and (d) UL echo interference from other FNs. DL: downlink, UL: uplink, FN: fiber node, TX: transmitter, RX: receiver.

2. Reflection Scenarios and Operation Principles

Taking the access point-to-point (P2P) coherent link between a hub and a fiber node (FN) as an example, we show the formation of the echo interference in Fig. 1(a). A reflection point leads to a part of the DL optical signal returning back to the hub. More complicated cases are shown in Fig. 1(b) to (d). In the DL transmission in Fig. 1(b), the hub may receive multiple reflections at different locations of the fiber link with different delays, phases, and reflection strengths. In the UL, the first case is UL self-interference as shown in Fig. 1(c), which is composed of the copies of UL signals reflected at different parts of the network. The second case is the UL interference across the fiber nodes, where the receiver at one FN may receive the reflected signals from the other FNs as shown in Fig. 1(d). Different from self-interference, which is known and trackable to the transmitter sending it, interferences from other transmitters are very hard to be eliminated by DSP. In the real case, scheduling among different transmission groups can be used to avoid echo interference across fiber nodes. This paper mainly discussed one-point echo cancellation in P2P coherent links as shown in Fig. 1(a).

The operation principle of the DSP procedures is shown in Fig. 2. There are three main blocks: the conventional coherent signal recovery DSP chain, the DSP chain to separate and roughly demodulate the echo signal, and the echo-signal reconstruction part to rebuild the inverted echo signal and use it to cancel out the echo to obtain a cleaner main signal. It can be observed that the EC is equivalent to adding a forward feedback loop on the original coherent DSP chain. The function can be skipped without interrupting the conventional signal recovery process. After the phase recovery, the data is duplicated and one of the copies is sent to the echo-signal extraction block. Then, a decision will be made and the difference between the symbols with and without decision is the un-equalized, phase-rotated echo signal (UPES) plus noise. The constant modulus algorithm (CMA) is applied to demultiplex the polarizations of UPES and compensate for the channel response. In the following, fourth-power Viterbi-to-Viterbi phase recovery is implemented to recover the phase of the echo signal. The channel information and trace of the phase rotations are stored in the system's memory, which will be used for rebuilding the echo signal in the next step. Echo signal reconstruction is based on the fact that the echo signal is the copy of the originally transmitted signal (OTS) suffering from extra delays, phase noise, and channel filtering. So, if the OTS is obtainable from the hub itself, given the necessary channel status information, the inverse of the echo can be reconstructed. In echo re-construction, the OTS is firstly phase pre-distorted and a synchronization is needed to make sure that there is no timing mismatch between the OTS and phase rotations. Then, the channel response is imposed on the phase distorted OTS. This step can be accomplished by taking the output of a least-mean-square (LMS) adaptive filter, with the phase distorted OTS as the input and UPES plus noise as the reference. Then the inversely rebuilt echo signal is added to the output data stream from the phase recovery stage to complete the echo cancelling.

In order to reconstruct the echo signal in a coherent system, it is important to effectively compensate the channel response, de-multiplex the polarizations, and retrieve the phase changing information for both original and echo signals using blind algorithms. Chromatic dispersion also needs to be compensated under long-distance fiber transmissions. Another important point is that EC doesn't need to be activated all the time. By estimation, with EC DSP, the computing complexity is expected to be increased by 2 to 3 times, which comes at an expense of increasing on-chip power consumption and processing latency. Thus, when the influence of the reflection is tolerable, the EC loop can be partly or totally shut down. However, since it can coarsely recover the echo signal, the proposed algorithm could also be used to monitor the strength of the back reflections.

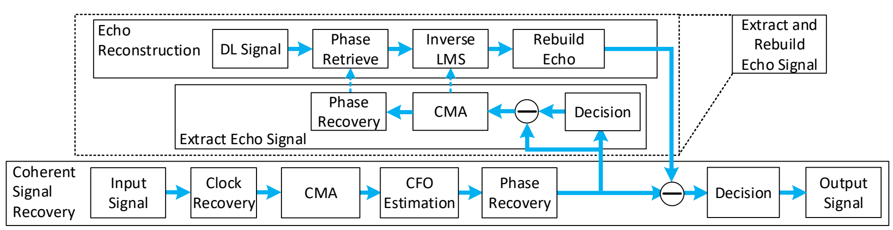

Fig. 2. DSP procedures of echo cancellation. CMA: constant modulus algorithm; CFO: carrier frequency offset; LMS: least mean square

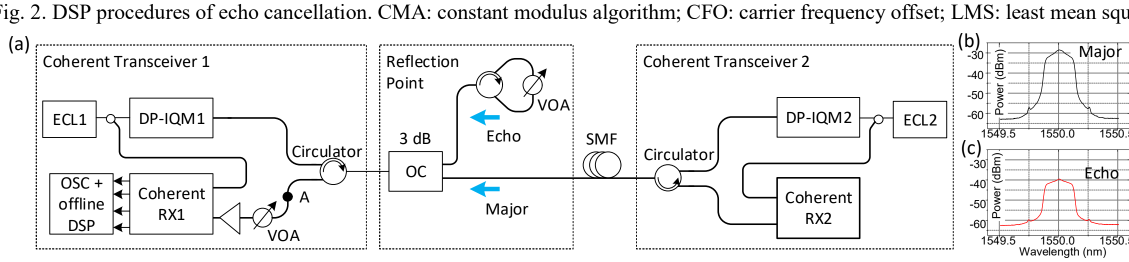

Fig. 3. (a): experimental system diagram; (b): optical spectrum of major signal at A; and (c) optical spectrum of echo signal at A. ECL: external cavity laser; OC: optical coupler; VOA: variable optical attenuator; DP-IQM: dual polarization IQ modulator.

3. Experimental Results

To validate the performance, both simulations and experiments have been conducted. The system setup is shown in Fig. 3(a), which is based on a P2P coherent transmission link connecting two transceivers. Each transceiver is composed of a dual-polarization in-phase and quadrature modulator (DP-IQM) and a coherent receiver. A circulator based tunable fiber reflector is introduced in the middle of the link between Transceiver 1 and the 20-km single-mode fiber to emulate a reflection point close to the hub side. Offline DSP is used to recover the signals and cancel the echo interference. The modulation format used for both DL and UL is the 32-GBd DP-QPSK. The main signal comes from Transceiver 2 in the UL transmission while the echo is from the reflected DL signal in Transceiver 1. The DL and UL data streams are independently generated. The optical spectra for main and echo signals before entering Coherent Receiver 1 are shown in Fig. 3(b) and (c) respectively.

Defining the received signal to echo ratio (RSER) as the power ratio between the received main signal and echo, the simulated performance of the signal's error vector magnitude (EVM) versus signal to noise ratio (SNR) is shown in Fig. 4(a). The experimental results of EVM and bit error rate (BER) versus optical signal-to-noise ratio (OSNR) are shown in Fig. 4(b) and (c) respectively. It is observed that the trends between the experiments and simulations are matched well. When the SNR is less than 15 dB, the gain brought by the EC is limited because the low SNR degrades the performance of both main and echo signal recoveries. The simulated EVM results versus RSER are shown in Fig. 4(d) with a SNR of 25 dB. The experimental EVM and BER versus RSER when OSNR is around 32 dB are shown in Fig. 4(e) and (f) respectively. Under the small RSER, the improvements are limited because the strong interference from the echo seriously affect the performance of the first-stage coarse signal recovery. As RSER increases, the EVM of the signal after EC approaches the signal's EVM without echo to some extent. But a small gap is observed which may be caused by the residual echo signal and DSP penalties in echo extraction as well as its reconstruction. A 7.2-dB improvement on the RSER tolerance is observed under an EVM threshold of 20%. There are no significant performance degradations with 20-km fiber transmission for the main signal. The trends of simulations and experiments are matched very well. The selected constellations of the signal without EC, the estimated echo signal, and the signal after EC are shown in the inset of Fig. 4(e).

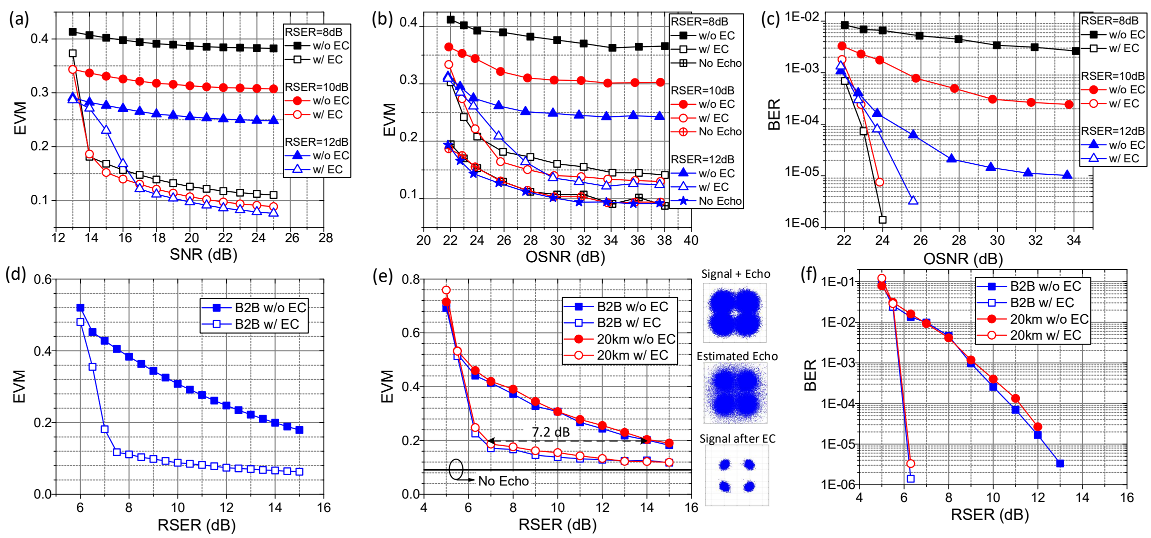

Fig. 4. (a): simulated EVM versus SNR; (b): measured EVM versus OSNR; (c) measured BER versus OSNR; (d) simulated EVM versus RSER; (e) measured EVM versus RSER; and (f) measured BER versus RSER. RSER: received signal to echo ratio.

4. Conclusions

In this work, for the first time, we developed an echo-cancellation method to mitigate the single-point reflection impairments in a P2P full duplex coherent optical system. After estimating and eliminating the echo interference, signal quality is significantly improved. Experimental results show the EVM floor is reduced from around 30% to less-than 15% in a 128-Gbps full duplex P2P coherent link, which agrees the simulation model well.

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