Electronic Dispersion Compensation for 10 Gb/s, 1550nm Optical Links

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Executive Summary

Recognizing industry's need for the entire component level infrastructure to be upgraded to support higher system capacity, the Optical Internetworking Forum (OIF) authorized their Physical and Link Layer (PLL) Working Group to begin a new project, referred to as Electronic Dispersion Compensation (EDC) for 10Gb/s 1550nm Links. The goal of the project is to initiate the standardization of new optical links that benefit from the technical and economic advantages of EDC, extending the reach of present Optical Transport Network (OTN) 10Gb/s technology from 1600ps/nm (80km) to 2400ps/nm (120km). The output of this project is a set of recommended application codes that has been provided by the OIF to the ITU, based on modeled and measured data validating the ability of EDC to support 2400ps/nm links. The OIF's unique ability to leverage the EDC integrated circuit expertise and optical expertise allowed these application codes to be developed within nine months. These application codes provide the basis for the electro-optic interfaces enabling the next generation of lower-cost, high performance networks.

Introduction

The mission of the Optical Internetworking Forum (OIF) is to foster the development and deployment of interoperable products and services for data switching and routing using optical networking technologies. This requires addressing multiple issues related to optical internetworking at the carrier, system vendor, and component vendor levels. This integrated approach strengthens the OIF's ability to fulfill its mission.

Recognizing industry's need for the entire component level infrastructure to be upgraded to support higher system capacity, the OIF authorized the PLL Working Group to begin a new project, referred to as EDC for 10Gb/s 1550nm Links. The goal of the project is to initiate the standardization of new optical links that benefit from the technical and economic advantages of EDC, extending the reach of present OTN 10Gb/s 1600ps/nm (80km) technology to 2400ps/nm (120km). The output of this project is a set of recommended application codes, provided by the OIF to ITU-T Study Group 15.

The EDC for 10Gb/s 1550nm Links Project

The Electronic Dispersion Compensation (EDC) for 10Gb/s over 1550nm Links Project presents comprehensive feasibility demonstrations of links that use fully adaptive Electronic Dispersion Compensation allowing up to 120km of G.652 fiber or dispersion of 2400ps/nm. In addition, this project also provides discussions on transmitter and receiver parameter specifications within such links, and provides the associated compliance testing requirements and methodology for system, chip and transponder suppliers. The use of adaptive EDC allows for highly cost-effective and robust ITU-T application codes for extended reach links, with cumulative dispersion of at least 2400ps/nm.

Electronic Dispersion Compensation has been recognized as a technology that can mitigate power penalties associated with optical link budgets. The sources of the power penalty include inter-symbol interference (ISI) due to fiber chromatic and polarization mode dispersion, transmitter impairments, and non-ideal transmitter or receiver bandwidth (optic or electronic) limitations. Fully-adaptive EDC allows for easy-to-use, plug-and-play links.

Adaptive equalization is a mature field within signal processing and many different adaptive equalization algorithms and architectures have been studied over the last four decades. Clearly, EDC can be mass-produced using standard semiconductor processing, leading to attractive end-to-end link economics. A few of the well-known classical architectures include:

- Feed-forward equalizer (FFE),
- Decision Feedback Equalizer (DFE),
- Fixed Delay Tree Search (FDTS),
- Maximum Likelihood Sequence Estimation (MLSE).

The OIF's unique ability to leverage the EDC integrated circuit expertise and optical expertise found in the PLL Working Group allowed for the rapid development of and data aggregation for the application codes presented in this paper. Further, liaisons between the OIF and IEEE 802.3aq Group, and OIF and ITU-T Study Group 15 working group enabled real-time integration of the ITU's perspectives, as well as the EDC-relevant work done in the IEEE.

The following sections discuss the application codes reviewed by the OIF PLL Working Group, and the test configurations and test methodology that were used in obtaining the performance data for the different application codes under evaluation.

Application Codes

The OIF-recommended application codes support 120km interfaces, allowing cost-effective implementations of existing technologies adhering to specifications in ITU-T G.959.1.1, through the use of EDC. The application codes under review for this project are as follows:

- Booster amplifier after transmitter, no FEC, APD-based receiver
- Booster amplifier after transmitter, FEC, APD-based receiver
- Pre-amplified receiver, no FEC, PIN-based receiver
- Pre-amplified receiver, FEC, PIN-based receiver

Test Methodology and Results

A standardized testing methodology was established to enable apples-to-apples comparisons between experimental results using different optical or electronic components in the links. These experimental results include using *fully-adaptive* EDC at the receiver for all the application codes under discussion. In each case, only a single wavelength in the 1528-1565 nm range ("C-band") was used. The optoelectronic receiver front-end, in particular the trans-impedance amplifier, was typically selected to be sufficiently linear. The transmitted data pattern was selected to be a pseudo-random binary sequence of length 2^{31}-1. The transmission metric is dispersion versus receiver sensitivity at bit error rates (BER) of 10^{-12} and 10^{-6}, where it is understood that the BER of 1e-6 corresponds to a FEC based application code.

Experimental results also included the following:

- A data rate of 10.7Gb/s to allow the use of plural application codes, even without FEC,
- An SBS tone for booster application codes

- Receiver decision threshold optimization at every data point, at every bit error rate.

Baseline Transmitter and Receiver Characteristics

Key transmitter parameters were established to serve as a baseline against which different PLL members, each using different transmitter-, receiver, or EDC-technology, could reference. Two modulator technologies, lithium niobate-based Mach-Zehnder (MZ) and InP-based electroabsorption (EA), are considered the primary paths for the transmitter. These baseline parameters are as follows:

- Extinction Ratio > 9dB. This requirement is consistent with the current ITU G.959.1.1 specification.
- Output power from transmit source > 0dBm. Note that in both application codes, an amplifier may be external or internal to the source to achieve the required launch power into the fiber.
- Transmitter chirp. While the transmitter chirp-parameter, α, is easy to define for a MZ structure, it is not as straightforward to define for an EA modulator. This is because α varies dynamically with the modulator bias. To circumvent this and to provide a benchmark for comparisons between different types of modulators, different "chirp conditions" were recognized and incorporated into testing:

    - "zero-chirp" – the modulator bias condition enables a path penalty (PP) < 1.8dB over 1200ps/nm of fiber, at 9.95Gb/s, without dispersion compensation (DC),
    - "standard chirp" – the modulator bias condition enables PP < 1.8dB over 1600ps/nm, at 9.95Gb/s, without dispersion compensation,
    - "strong chirp" – the modulator bias condition enables PP < 1.8dB over 2000ps/nm, at 9.95Gb/s, without dispersion compensation.

The baseline receiver parameters, including decision threshold and crossing point, were based on the recently approved OIF Implementation Agreement, "Interoperability for Long Reach and Extended Reach 10 Gb/s Transponders and Transceivers", OIF-LRI-01.0 (www.oiforum.com/public/impagreements.html)

Test Configurations and Methodology

For both booster-based and pre-amplified receiver application codes, members applied a standard test methodology to generate "normalized" experimental results. Prior to incorporating EDC in the receive chain, the following steps were taken:

1. Link characterization at the nominal reach (1200ps/nm, 1600ps/nm, or 2000ps/nm) based on the corresponding transmitter chirp for that nominal reach,
2. Record Eye through fiber,

3. Record Optimal Receiver threshold,
4. Record Path Penalty.

Steps 2-4 were then repeated with an EDC-enabled Rx chain for 2400ps/nm of fiber

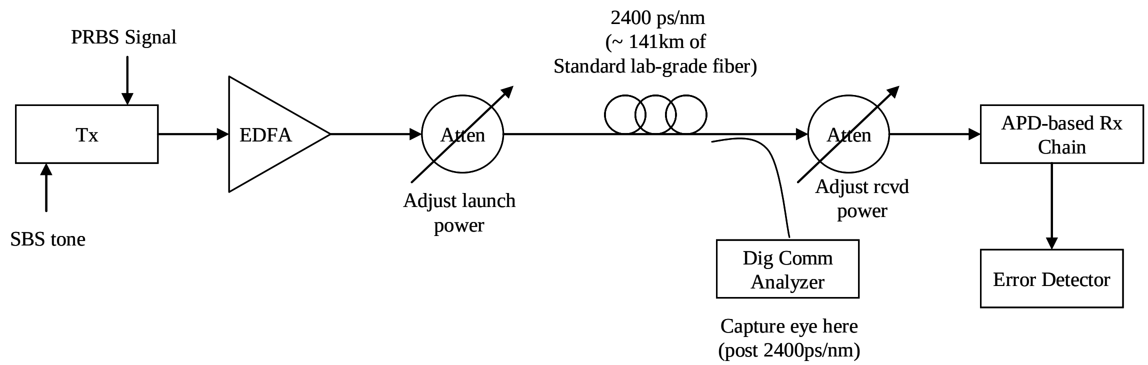

Figure 1: Test Configuration for the "booster"-based application codes. The output power is adjusted between +11dBm and +14dBm.

As can be seen in Figure 1, an attenuator is used at the output of the EDFA to adjust the launch power, between +11dBm and +14dBm. Following the attenuator is a length of fiber equivalent to 2400ps/nm of dispersion. A second attenuator adjusts the received power into an APD-based receiver chain, with or without EDC.

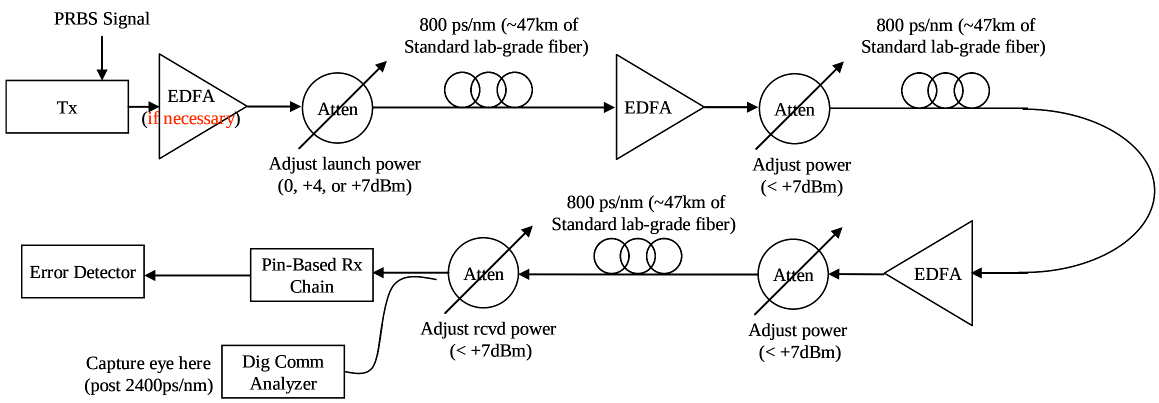

Figure 2: Test configuration for the "pre-amplified"-based application codes

Note that Figure 2's setup is not a "true" pre-amplified link configuration. However, this configuration was selected to allow companies that might not have a sufficiently high-sensitivity pre-amplified receiver to still provide comparable experimental data. This configuration is intended to provide a sufficiently high power to account for the total link attenuation but the resulting optical signal-to-noise ratio (OSNR) at the receiver might not be truly representative of the OSNR for preamplifier-based application codes.

Typical Results – "Booster" Application Codes

Figure 3 shows experimental results for the booster-based configuration without FEC, following the test configuration of Figure 1. The source transmitter here is EAM-based and the data rate is 10.7Gb/s. The laser is chirped such that the path penalty without EDC is <1.8dB over 1600ps/nm of fiber at 9.95Gb/s. The inclusion of EDC in the link allows transmission over 2400ps/nm of fiber without penalty.

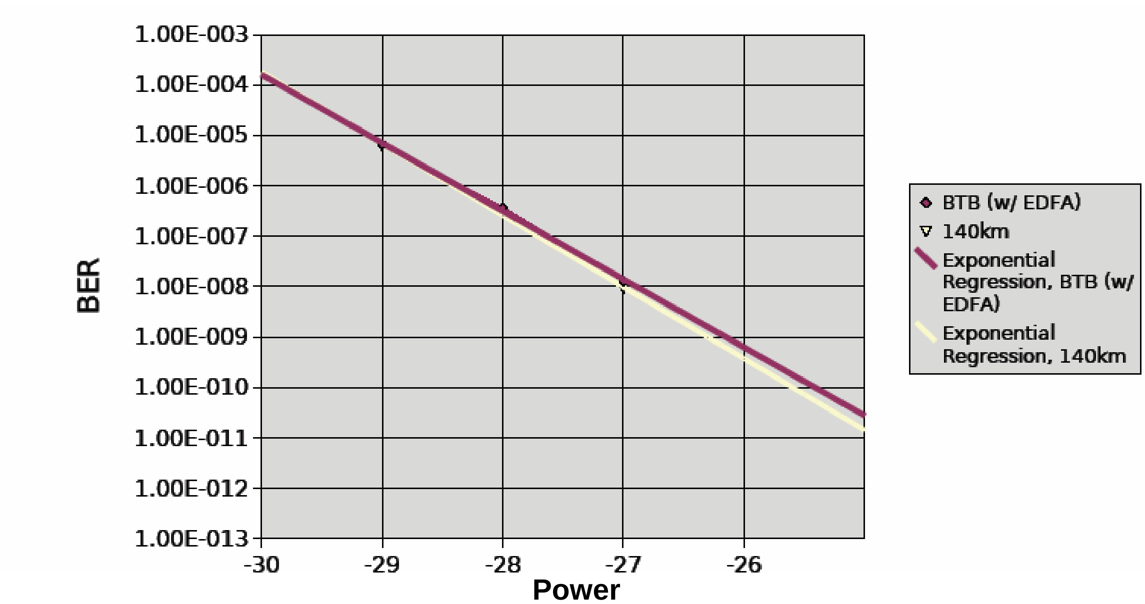

Figure 3: 2400ps/nm transmission at 10.7Gb/s results for the booster-based configuration without FEC using an EAM-based transmitter and EDC.

Typical Results – "Pre-Amplified" Application Codes

Figure 4 shows experimental results for the pre-amplified receiver-based configuration without FEC, following the test configuration of Figure 2. The source transmitter here is EAM-based and the data rate is 10.7Gb/s. The laser is chirped such that the path penalty without EDC is <1.8dB over 1600ps/nm of fiber at 9.95Gb/s. The inclusion of EDC in the link allows transmission over 2400ps/nm of fiber with only 1dB of path penalty.

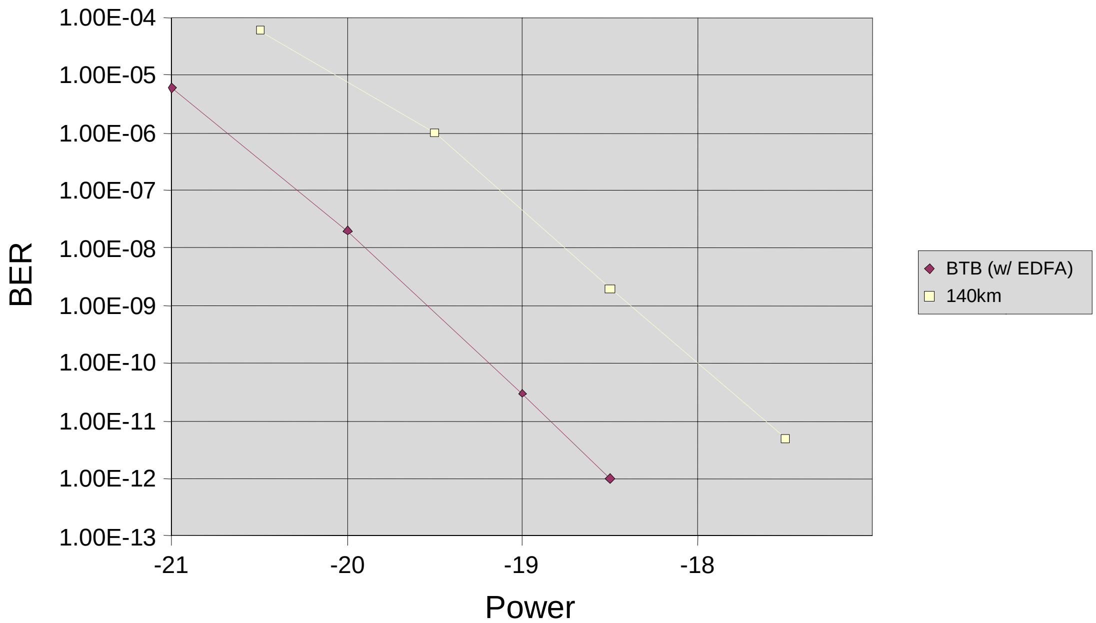

Figure 4: 2400ps/nm tranmission at 10.7Gb/s results for the pre-amplified receiver configuration without FEC using an EAM-based transmitter and EDC.

Summary

The EDC for 10Gb/s 1550nm Links Project initiates the standardization of new optical links that benefit from the technical and economic advantages of EDC, extending the reach of present OTN 10Gb/s 1600ps/nm (80km) technology to 2400ps/nm (120km). The output of this project is a set of recommended application codes that has been provided by the OIF to the ITU, based on modeled and measured data validating the ability of EDC to support 2400ps/nm links. Future work within the OIF will focus on extending the reach of present technology, with EDC, to 3200ps/nm (160km).